Perception for the Next Generation of Mobile Robots for Industrial Applications

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Perception for the Next Generation of Mobile Robots for Industrial Applications

1. The AASS MRO Lab @Örebro University
2. Mobile Robotics & Olfaction Lab Profile
3. Accurate and Efficient Long-term World Modelling 3D NDT-OM for Mapping
5. Highly Reliable People Recognition Flash Camera People Tracking
6. Current Developments
7. Summary
8. Literature
The AASS MRO Lab
@Örebro University
Mobile Robotics & Olfaction Lab

Profile

AASS

The AASS Mobile Robotics & Olfaction Lab in 2015*
- 14 Ph.D. students, 10 senior researchers
- 7 ongoing projects, funding > 1.0M€/y

Research Area 1:
Mobile Transport Robots for Industrial Applications
- 3D perception, robot vision and navigation
- autonomous and safe long-term operation in the real world
- extensive technology transfer through collaborative projects with industrial partners
- autonomous forklifts, wheel loaders, mining vehicles, service robots on airports, in hospitals and for cleaning
- leader in Europe, key player world-wide

Research Area 2:
Mobile Robot Olfaction
- gas sensing with sensor systems in open sampling configuration (from electronic to mobile nose)
- gas sensor networks for air pollution monitoring, mobile robots for surveillance of landfill sites, gas leak localization, gas-sensitive flying robots
- world-leading in mobile robot olfaction

*18 Feb 2015
General Focus ...

- **perception systems** for mobile robots (fundamentals of autonomous operation and environmental monitoring)
### General Focus ...
- perception systems for mobile robots (fundamental autonomous operation and environmental monitoring)

### Objective ...
- theoretical and practical foundations of long-term operation of mobile robots in unconstrained, dynamic environments
1. **General Focus ...**
   - perception systems for mobile robots (fundamentals of autonomous operation and environmental monitoring)

2. **Objective ...**
   - theoretical and practical foundations of long-term operation of mobile robots in *unconstrained, dynamic environments*
1. General Focus ...
   - perception systems for mobile robots (fundamentals of autonomous operation and environmental monitoring)

2. Objective ...
   - theoretical and practical foundations of long-term operation of mobile robots in unconstrained, dynamic environments
1. **General Focus ...**
   - perception systems for mobile robots (fundamentals of autonomous operation and environmental monitoring)

2. **Objective ...**
   - theoretical and practical foundations of mobile robots in unconstrained, dynamic environments

3. **Approaches are Characterized by ...**
   - fusion of different sensor modalities
1. General Focus ...
   - perception systems for mobile robots (fundamentals of autonomous operation and environmental monitoring)

2. Objective ...
   - theoretical and practical foundations of long-term operation of mobile robots in unconstrained, dynamic environments

3. Approaches are Characterized by ...
   - fusion of different sensor modalities
   - timely integration into industrial demonstrators
1. Project History

- **2004**: 3D-P4Mining
- **2005**: NSAL
- **2006**: SLAM Benchmark (Toyota)
- **2007**: Project History
- **2008**: 3D-P4Mining
- **2009**: SLAM Benchmark (Toyota)
- **2010**: 3D-P4Mining
- **2011**: 3D-P4Mining
- **2012**: 3D-P4Mining
- **2013**: 3D-P4Mining
- **2014**: 3D-P4Mining
- **2015**: 3D-P4Mining
- **2016**: 3D-P4Mining
- **2017**: 3D-P4Mining
- **2018**: 3D-P4Mining
Mobile Robots for Logistics
2. **Logistics**
   - "moving goods from Point A to Point B" [URL]

2. **Intralogistics**
   - "the art of optimizing, automating, integrating, and managing the logistical flow of material goods with the flow of information pertaining to those goods [...] It can also encompass the logistical flow of materials within an entire supply chain ..." [URL]
Roboticics for Logistics

- Mining
  - (e.g., Atlas-Copco)

- Construction
  - (e.g., Volvo CE)

- Logistics
  - (e.g., Kollmorgen)

- Robots for flexible and efficient transport systems
2. Robotics for Logistics

- Robots for flexible and efficient transport systems
  ... also in hospitals, supermarkets, etc.
Robotics for Logistics – Open Problems

- Autonomous Industrial Vehicles: Where we are and what is missing.

  » Core requirements that point to shortcomings in SoA
     (distilled from experience in collaboration with several industrial partners)
2. Robotics for Logistics – Open Problems

- Deployment
  - **Dep1**: Avoid the need to hand-craft AGV paths for each new setting
  - **Dep2**: At least speed profiles should not be fully specified
  - **Dep3**: AGV system should avoid deadlocks automatically
  - **Dep4**: Perceptual functions should not rely on additional infrastructure
Robotics for Logistics – Open Problems

- Deployment
- Non-holonomic vehicles
  - V1: Automatic trajectory generation for non-holonomic vehicles (even without considering obstacles and coordination)
  - V2: Sophisticated mechanical structures (e.g. articulated vehicles, detachable trailers, ...)
  - V3: Payload can change manoeuvring capabilities and dynamics
Rob4Log

1. Robotics for Logistics – Open Problems
   - Deployment
   - Non-holonomic vehicles
   - Efficiency and safety
     - **ES1**: Reliable perception at high speeds (up to 30–40 km/h)
     - **ES2**: Generation of collision-free trajectories at high speeds
     - **ES3**: Autonomous vehicles in shared spaces should behave in a way comparable to human-operated vehicles
     - **ES4**: Actions of human drivers should be taken into account
2. Robotics for Logistics – Open Problems

- Deployment
- Non-holonomic vehicles
- Efficiency and safety
- Dynamic nature of the environment
  - **Dyn1**: Perceive dynamic objects, identify different types of dynamics, and learn how they are spatially distributed
  - **Dyn2**: Spatial information about dynamics should also be used for localization
  - **Dyn3**: Spatial information about dynamics should also be used for planning
Robotics for Logistics – Open Problems

- Deployment
- Non-holonomic vehicles
- Efficiency and safety
- Dynamic nature of the environment

**Automated planning capabilities**

- **AP1**: Automated planning at different levels of abstraction
- **AP2**: System should be able to refine existing plans in response to new requests (e.g., changed deadlines, new goals, or newly perceived obstacles)
- **AP3**: Task allocation/vehicle coordination should provide flexible solutions, e.g., sets of collision-free trajectories instead of precise temporal instants
- **AP4**: Reasoning tasks should be integrated with execution monitoring
Accurate and Efficient Long-term World Modelling

3D NDT-OM for Mapping
3. **3D NDT-OM ↔ 3D NDT**
   - 3D NDT (**Normal Distribution Transform**) [Magnusson et al., JFR 2007]
3D NDT-OM ↔ 3D NDT

- 3D NDT (Normal Distribution Transform) [Magnusson et al., JFR 2007]
  - Initially used only for registration
3D NDT(-OM) Mapping

- Research question
  - How to create and maintain compact, consistent world models from (rich) 3D data?
  - Many issues needed to be addressed
    - general research direction since about 3 years
  - One key issue was that recursive updates were not possible

- addressed in ICRA 2013 paper and IJRR 2013 article
3D NDT(-OM) Mapping, Recursive Update

- addressed in ICRA 2013 paper and IJRR 2013 article
  - formulation provides natural multi-resolution support
3D NDT-OM Mapping

- Research question
  - How to create/maintain compact, consistent world models from 3D data?
- Many issues needed to be addressed (general research direction since 3y)
- One key issue was that recursive updates were not possible
- Another issue is map maintenance in dynamic environments
3D NDT-OM Mapping

- Research question
  » How to create/maintain compact, consistent world models from 3D data?
- Many issues needed to be addressed (general research direction since 3y)
- One key issue was that recursive updates were not possible
- Another issue is map maintenance in dynamic environments
3D NDT-OM for Dynamic Environments

- Research question
  - How to maintain compact, consistent world models learned from 3D data?
- Combine NDT with robust, probabilistic SoA approach
3D NDT-OM for Dynamic Environments

- Research question
  - How to maintain compact, consistent world models learned from 3D data?
- Combine NDT with robust, probabilistic SoA approach
  - needs specific sensor model
3D NDT-OM for Mapping in Dynamic Environments

Resulting in a consistent final map of the environment. See full video at http://youtu.be/2IS0CbaThA0
Results, Large-Scale Industrial Environment

- ARLA milk storage facility

after 10 minutes ...

NDT

NDT-OM

NDT-OM (with free cells)
3. Results, Large-Scale Industrial Environment

- ARLA milk storage facility

after 130 minutes (NDT-OM) ...
Highly Accurate Navigation with Non-Holonomic Vehicles

3D NDT-OM for Navigation

![Graph showing ATE vs Resolution]
Monte Carlo Localization with NDT-OM

- standard Monte Carlo localization
- use NDT map for measurement update instead of grid map
  - exploit that NDT is a likelihood model
- compare grid-MCL and NDT-MCL (2D)
4. Monte Carlo Localization with NDT-OM

- standard Monte Carlo localization
- use NDT map for measurement update instead of grid map
  - exploit that NDT is a likelihood model
- compare grid-MCL and NDT-MCL (2D)
  - absolute error
    - static environment
    - trajectory: 120m
    - grid-MCL = amcl in ROS
Monte Carlo Localization with NDT-OM

- standard Monte Carlo localization
- use NDT map for measurement update instead of grid map
  - exploit that NDT is a likelihood model
- compare grid-MCL and NDT-MCL (2D)
  - absolute error
  - closed loop tests
    - grid map resolution: 0.03m
    - NDT map resolution: 0.5m
NDT-MCL

Normal Distributions Transform
Monte Carlo Localization

Jari Saarinen
Henrik Andreasson
Todor Stoyanov
Achim Lilienthal
Monte Carlo Localization with NDT-OM

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### Monte Carlo Localization with NDT-OM

- standard Monte Carlo localization
- use NDT map for measurement update instead of grid map
  - exploit that NDT is a likelihood model
- compare grid-MCL and NDT-MCL (2D)
  - absolute error
  - closed loop tests
    - grid map resolution: 0.03m
    - NDT map resolution: 0.5m
That's not the whole story however ...  
- calculate kinematically drivable paths with lattice-based motion planner for each vehicle  
- post-process paths with continuous path smoother \( \rightarrow \) continuous drivable path  
- generate trajectories by associating speed profiles consistent with dynamic and coordination constraints
Highly Reliable People Recognition

Flash Camera People Tracking
People Tracking with the Stereo-Flash Camera

- highly reliable detection and tracking of humans is required
- robust performance is key
  - under different weather/illumination conditions
  - independent of body pose
- industrial work sites allow to make specific assumptions
People Tracking with the Mono-Flash Camera

- Hardware

- NIR Imaging Sensor
- Wide-angle Lens: 120° FOV
- NIR Bandpass Filter: Center Wavelength: 940nm, Bandwidth: 10nm
- 16 x NIR LEDs: Center Wavelength: 940nm
People Tracking with the Mono-Flash Camera

- Hardware

![Diagram of the Mono-Flash Camera System]

- **NIR Imaging Sensor**
- **Wide-angle Lens**
  - 120° FOV
- **NIR Bandpass Filter**
  - Center Wavelength: 940nm
  - Bandwidth: 10nm
- **16 x NIR LEDs**
  - Center Wavelength: 940nm

---

![Graph showing Relative Sensitivity/Emission/Transmission vs. Wavelength]

- **Visible**
- **Near-infrared (NIR)**

**Graph legend**:
- Green: Relative Spectral Sensitivity (Imaging Sensor)
- Red: Relative Spectral Emission (IR-LEDs)
- Black: Relative Spectral Transmission (Bandpass Filter)
- Blue: Solar Radiation Spectrum at Sea Level
People Tracking with the Mono-Flash Camera

- Hardware
- Image Acquisition
People Tracking with the Mono-Flash Camera

- Hardware
- Image Acquisition
- Algorithm

3 main processing steps:

1.) Detection of Reflectors
   Image acquisition and feature based detection of reflective material

2.) Reflector Classification and Localization
   Supervised learning based classification into vest- and non-vest features, estimation of object distance and 3D projection

3.) Tracking
   Tracking of detected groups of reflectors over a series of input image pairs using a particle filter
People Tracking with the Mono-Flash Camera

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- Image Acquisition
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People Tracking with the Mono-Flash Camera

- Hardware
- Image Acquisition
- Algorithm
  - Monocular distance estimation

**Feature Descriptors**

\[ r = [r_1, r_2, r_3, ..., r_N] \]

**Random Forest Regressor**

**3D Projection**

**Regressor Models**

**Random Forest Classifier**

**Vest Probabilities**

**Thresholding**

**Vest Features**

**Classifier Model**

**Scenario 1**

- True Distance
- Estimated Distance

**Scenario 2**

- True Distance
- Estimated Distance

**Scenario 3**

- True Distance
- Estimated Distance

**Scenario 4**

- True Distance
- Estimated Distance
People Tracking with the Stereo-Flash Camera

- Camera Setup

1 Color Camera
For visualization purposes

2 NIR Camera Units

NIR Camera
Wide-angle Lens
Bandpass Filter
16 x NIR LEDs
People Tracking with the Stereo-Flash Camera

- Camera Setup
- Image Acquisition
People Tracking with the Stereo-Flash Camera

- Camera Setup
- Image Acquisition
People Tracking with the Stereo-Flash Camera

- Camera Setup
- Image Acquisition

The **ideal case**: no secondary NIR light sources

The **non-ideal case**: secondary NIR light sources cause background illumination
People Tracking with the Stereo-Flash Camera, Algorithm

Image Segmentation
- Detect image regions containing reflectors

Localization
- Obtain a 3D position estimate for each detected reflector

Classification
- Discriminate reflectors of safety clothing from arbitrary other reflectors

Tracking
- Assign individual reflectors to tracked persons and maintain a filtered state for position and speed
People Tracking with the Stereo-Flash Camera
People Tracking with the Stereo-Flash Camera

- Advantages of the flash camera approach
  - High robustness to various illumination conditions
  - Accurate detection under partial occlusion
  - Robust towards body pose variation

- Current Limitations
  - Tracking performance decreases under frequent interaction between persons
  - Algorithm allows to detect reflective safety vests but not specifically humans

- Future Work
  - Refine detections by using information from the color camera
Summary
MR&O Lab Profile

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### 7. MR&O Lab Profile

- **Mobile Robots for Logistics**

![Mining](image1)

(e.g., Atlas-Copco)

![Construction](image2)

(e.g., Volvo CE)

![Logistics](image3)

(e.g., Kollmorgen)
MR&O Lab Profile

Mobile Robots for Logistics

Accurate and Efficient Long-term World Modelling
  - 3D NDT-OM for Mapping
MR&O Lab Profile

Mobile Robots for Logistics

Accurate and Efficient Long-term World Modelling

Highly Accurate Navigation with Non-Holonomic Vehicles
  - 3D NDT-OM for Navigation
  - Monte Carlo Localization with NDT (NDT-MCL)
MR&O Lab Profile

Mobile Robots for Logistics

Accurate and Efficient Long-term World Modelling

Highly Accurate Navigation with Non-Holonomic Vehicles

Highly Reliable People Recognition
- Flash Camera People Tracking
Current Developments
8. **Autonomous Picking & Palletizing 2014 – 2015 (3m)**

- Motivation:
  Mobile manipulation system for autonomous commissioning
Autonomous Picking & Palletizing 2014 – 2015 (3m)

- **Motivation:**
  Mobile manipulation system for autonomous commissioning

- **Contribution:**
  Prototype of a mobile manipulation system for autonomous commissioning
Autonomous Picking & Palletizing 2014 – 2015 (3m)

- First Demo: [MP4]
### Autonomous Picking & Palletizing 2014 – 2015 (3m)

- **Research Platform APPLE:**
  - for autonomous commissioning in intralogistics settings
  - nonholonomic mobile base (7)
  - lightweight arm, LBR iiwa (3)
  - under-actuated gripper with active surfaces, Velvet Fingers (2)
  - NIR safety camera, RefleX (6)
8. **Autonomous Picking & Palletizing 2014 – 2015 (3m)**

- **Research Platform APPLE:**
  for autonomous commissioning in intralogistics settings

- **Pallet Detection:**
  - uses Asus Xtion Pro Live (5)
  - rough estimate of pallet position given (pre-defined pickup zone)
  - Signed Distance Function (SDF) tracker for "visual surveillance" with a given SDF model of the pallet
  - trajectory is recomputed on the fly (may include reverse driving)
8. Current Developments

- Developing Research Directions
  - HRI for Intralogistics Robots
8. Technology Transfer
   - Industrial prototype of flash camera
8. **Technology Transfer**
   - Industrial prototype of flash camera
   - First tests at customer site of SAUNA system
EU Topic Group ROB4LOG

- Topic Group of Logistics and Freight Transportation (ROB4LOG)
  - Robotics in Logistics and Transport
    - http://web.ita.es/eurobotics
Literature
Robot Vision in Changing Environments


9. **3D NDT, Registration**


9. **3D NDT, Non-Registration**

  *Comparative Evaluation of the Consistency of Three-Dimensional Spatial Representations used in Autonomous Robot Navigation.*  

  *Comparative Evaluation of Range Sensor Accuracy for Indoor Mobile Robotics and Automated Logistics Applications.*  

  *Automatic Appearance-Based Loop Detection from 3D Laser Data Using the Normal Distributions Transform.*  

  *Path Planning in 3D Environments using the Normal Distributions Transform.*  
9. **3D NDT OM**


9. **NDT Localization**


MALTA/SAVIE/SAUNA System


Autonomous Industrial Vehicles: Where we are and what is missing.

9. **Motion Planning and Execution**

  *A Lattice-Based Approach to Multi-Robot Motion Planning for Non-Holonomic Vehicles.* 

  *Drive the Drive: from Discrete Motion Plans to Smooth Drivable Trajectories.* 
### Sensing-While Moving, Pile Handling


9.

**RobLog, System**


### RobLog, SDF Tracker

  **Improved Local Shape Feature Stability Through Dense Model Tracking.**  

- Daniel R. Canelhas, Todor Stoyanov, Achim J. Lilienthal.  
  **SDF Tracker: A Parallel Algorithm for On-line Pose Estimation and Scene Reconstruction From Depth Images.**  
9. RobLog, Decision Making

  Probabilistic Relational Scene Representation and Decision Making Under Incomplete Information for Robotic Manipulation Tasks. 

- R. Mojtahedzadeh, A. Bouguerra and A. J. Lilienthal. 
  Automatic Relational Scene Representation for Safe Robotic Manipulation Tasks. 

  Robotics and Autonomous Systems (RAS), Special Issue on Emerging Spatial Competences: From Machine Perception to Sensorimotor Intelligence. 
  To appear.
IR Flash Industry Safety Camera


Thanks for your attention!

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5. **Summary**

- **Lab Profile**
- **Lab Projects**
- **Results 2013**
  - NDT-OM

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![Point cloud](image1)

![NDT representation](image2)

\[ \sim 300,000 \Rightarrow \sim 4,000 \]
5. Summary

- Lab Profile
- Lab Projects
- Recent Results
  - NDT-OM
5. **Summary**

- **Lab Profile**
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  - NDT-OM
    - included into the controller of Kollmorgen
5. **Summary**

- **Lab Profile**
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  - NDT-OM
  - NDT-D2D Registration

![Diagram with charts and graphs](image-url)
5. **Summary**

- **Lab Profile**
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  - NDT-OM
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  - NDT-MCL
5. Summary

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5. **Summary**

- **Lab Profile**
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- **Recent Results**
  - NDT-OM
  - NDT-D2D Registration
  - NDT-MCL
  - SDF Tracker /
  - Improved Depth Features
5.

- Lab Profile
- Lab Projects
- Recent Results
  - NDT-OM
  - NDT-D2D Registration
  - NDT-MCL
  - SDF Tracker / Improved Depth Features
5. Summary

- Lab Profile
- Lab Projects
- Recent Results
  - NDT-OM
  - NDT-D2D Registration
  - NDT-MCL
  - SDF Tracker / Improved Depth Features
    - RobLog System (Qubica)
5. **Summary**

- **Lab Profile**
- **Lab Projects**
- **Recent Results**
  - NDT-OM
  - NDT-D2D Registration
  - NDT-MCL
  - SDF Tracker / Improved Depth Features
  - Flash Camera for Reflective Vest/People Tracking
    - → industrial prototype (Optronics)
5. Summary

- Lab Profile
- Lab Projects
- Recent Results
  - NDT-OM
  - NDT-D2D Registration
  - NDT-MCL
  - SDF Tracker / Improved Dep
  - Flash Camera for Reflective
  - Gasbot 1.0 / 2.0
5. **Summary**

- **Lab Profile**
- **Lab Projects**
- **Recent Results**
  - NDT-OM
  - NDT-D2D Registration
  - NDT-MCL
  - SDF Tracker / Improved Depth
  - Flash Camera for Reflective
  - Gasbot 1.0 / 2.0
    - market analysis
    - pre-study (Robotdalen)
5. Conclusions

- Lab Profile
- Lab Projects
- Recent Results

**Conclusions – From the Lab to Industrial Prototypes**
- tests under real-world conditions
- establish trustful relation (time)
  - understanding mutual goals / conditions
- postdocs (less pressure to publish)
- short-term adaptation of research strategy
- persistence regarding long-term research strategy