German Research Center for Artificial Intelligence

Document D-16-03

Proceedings of the RIC Project Day

Workgroups *'Locomotion & Mobility'* and *'Navigation & Planning'*

Frank Kirchner (Editor)

Florian Cordes, Leif Christensen (Associate Editors)

09/2016

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German Research Center for Artificial Intelligence
Deutsches Forschungszentrum für Künstliche Intelligenz
DFKI GmbH

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Prof. Wolfgang Wahlster
Director

Proceedings of the RIC Project Day

Workgroups 'Locomotion & Mobility' and 'Navigation & Planning'

Frank Kirchner [1,2] (Editor)

Florian Cordes [1], Leif Christensen [1] (Associate Editors)

(1) DFKI GmbH, Robotics Innovation Center, Robert-Hooke-Straße 1, 28359 Bremen, Germany
(2) Universität Bremen, Arbeitsgruppe Robotik, Robert-Hooke-Straße 1, 28359 Bremen, Germany

09/2016

Document D-16-03 des

Deutschen Forschungszentrums für Künstliche Intelligenz (DFKI)

Abstract

This document is the current edition of a publication series which records the topics, discussions and efforts of the workgroups at the DFKI Robotics Innovation Center (RIC). Each edition contains presentation slides and posters of a project day which is organized by two workgroups.

Workgroups provide a platform for cross-project communication and knowledge transfer. They are formed by peers dedicated to a specific topic. Each workgroup has one administrator. In 2008, the workgroups started to present their results and efforts in an open presentation format called brown-bag talk. From 2009 onwards, these presentation were held at so-called project days. Since 2014, a project day consists of two main parts: an oral session and a poster session. Both sessions are documented in a proceedings using the DFKI Document format.

Zusammenfassung

Dieses Dokument enthält die aktuelle Ausgabe einer Tagungsbandserie, welche die Themen, Diskussionen und Bemühungen der Arbeitsgruppen am DFKI Robotics Innovation Center (RIC) protokolliert. Jede Ausgabe enthält Vortragsfolien und Poster eines Projekttages, der von je zwei Arbeitsgruppen gestaltet wird.

Arbeitsgruppen widmen sich einem bestimmten Themengebiet und stellen eine Plattform dar, um über Projekte hinaus zu kommunizieren und Wissen zu transferieren. Jede Arbeitsgruppe wird von einem sogenannten Kümmerer administriert. Im Jahr 2008 begannen die Arbeitsgruppen ihre Ergebnisse und Arbeiten in einem offenen Vortragsformat – dem sogenannten 'Brown Bag Talk' – vorzustellen, welches ein Jahr später in die Form von Projekttagen überführt wurde. Seit 2014 besteht ein Projekttag nicht nur aus Vorträgen, sondern beinhaltet zudem Posterpräsentationen. Beide Formate werden seitdem in einem Tagungsband in Form eines 'DFKI Document' festgehalten.

Contents

1 Editorial

This proceedings document records the last year's efforts of two thematic workgroups of the DFKI-RIC.

Workgroups are formed by peers and provide a means for cross-project communication on a deep content level and facilitate knowledge transfer amongst the peers. In 2008 we first started forming workgroups on specific topics around robotics and AI research. Among them were topics as 'system design & engineering', 'machine learning', 'planning & representation' as well as 'frameworks & architectures' and 'man-machine interaction'. These workgroups were established with the intention to provide a platform for interested DFKI-RIC personnel for discussing the state of the art, recent achievements, and future developments in the respective fields.

Over time the workgroups gathered a collection of material in form of presentations, short papers, and posters which were worthwhile to be presented also to the rest of the institute. Due to this development, in 2009, we started to have a project day once every quarter. Each project day provided a platform for two of the workgroups to present their material and to discuss it with the colleagues of the institute. Nowadays, the project day is organized as a half-day workshop with oral presentations, poster sessions, and a free sandwich lunch for everybody who attends.

The current document format compiles the material of the workgroups presented during a project day into a single, citable document of unified format. The future might bring further ideas and changes to enhance the presentation quality of this material.

Frank Kirchner

This year's third project day presented the material of the workgroups 'Locomotion & Mobility' and 'Navigation & Planning'.

The aim of the workgroup 'Locomotion & Mobility' is to provide a forum for discussions on the topic of locomotive capabilities of mobile robots. This includes the improvement of existing locomotion capabilities as well as brainstorming new types of locomotion and the review of state of the art in robot locomotion. In general the meetings of the workgroup are focussed on land bound systems with wheels, tracks, legs and hybrid legged-wheel or wheeled-leg locomotion systems. However, swimming, diving and flying systems are in the interest of the group members as well. The electro-mechanical focus on the topic of locomotion in former years gave way for a discussion that centers more around control and behavior generation for kinematically complex robots.

The purpose of the workgroup 'Navigation & Planning' is to discuss ideas and develop concepts as well as algorithms that allow mobile robots to behave in or even interact with the surrounding world in a meaningful manner. Apart from purely reactive systems, a fundamental requirement for a mobile robot is the capability to localize itself in a defined reference frame by interpreting heterogeneous (often exteroceptive) sensor input and relating it to some sort of environment representation. Another fundamental requirement of deliberative robots is the capability to reason on this representation, for example by planning a path from the current location to some goal, taking into account all the knowledge it has on its own movement capabilities and the environment. Handling different kind of maps (one distinct view on the environment representation) is a topic that comes naturally along when dealing with these navigational aspects of mobile robots and is therefore part of the agenda of this workgroup. Striving towards the goal of long term autonomy in robotic systems, a growing part of the topics in the workgroup are dealing with the robustness of navigational algorithms on real systems and their adaptivity to the sometimes harsh real world and its dynamic changes, especially when dealing with space or underwater environments. Another strong topic in the workgroup arises from dealing with teams of heterogeneous and also reconfigurable robots, where high level planning is needed to exploit the capabilities of such teams to the extent where their benefit as a whole is greater than the sum of their parts. The range and selection of this year's presentations reflect quite well the ongoing discourse of the above mentioned topics in the workgroup 'Navigation & Planning' in the last year.

We would like to thank the authors of this project day for their contributions and for the effort to provide their material in a standardized format.

Florian Cordes, Leif Christensen

2 'Locomotion & Mobility'

2.1 'Introduction Project Day 2016: Workgroup Locomotion & Mobility' (LM-T-01)

Florian Cordes[(1)]

(1) DFKI GmbH, Robotics Innovation Center, Robert-Hooke-Straße 1, 28359 Bremen, Germany
(2) Universität Bremen, Arbeitsgruppe Robotik, Robert-Hooke-Straße 1, 28359 Bremen, Germany

Contact: `florian.cordes@dfki.de`

Abstract

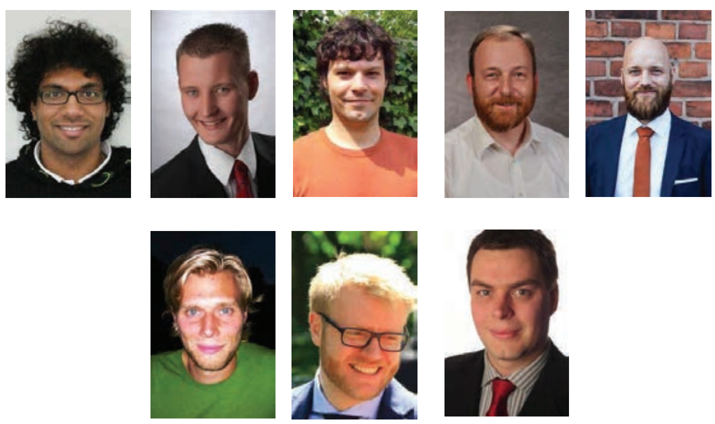
This talk introduces the main topics of the workgroup Locomotion & Mobility. Out of the five main topics (i) System Description and Comparison (ii) Test Facilities Planning (iii) Interfaces between Locomotion Control and High Level Control (iv) Tasks for Mobile Robots (v) State of the Art, mainly the topic (i) was discussed. This was done by internal presentations of experimental results, test planning and experiment procedures with the systems SherpaTT and Coyote III in the context of the projects TransTerrA and FT-Utah. Consequently, apart from one talk on the ape-like robot Charlie, the rest of this year's presentations deals with a modular test track which has been used with SherpaTT and the state of development of the robots SherpaTT and Coyote III.

Workgroup Locomotion & Mobility

DFKI Bremen & Universität Bremen
Robotics Innovation Center
Director: Prof. Dr. Frank Kirchner
www.dfki.de/robotics
robotics@dfki.de

Universität Bremen

(Regular) Participants



„Applications are Welcome!"

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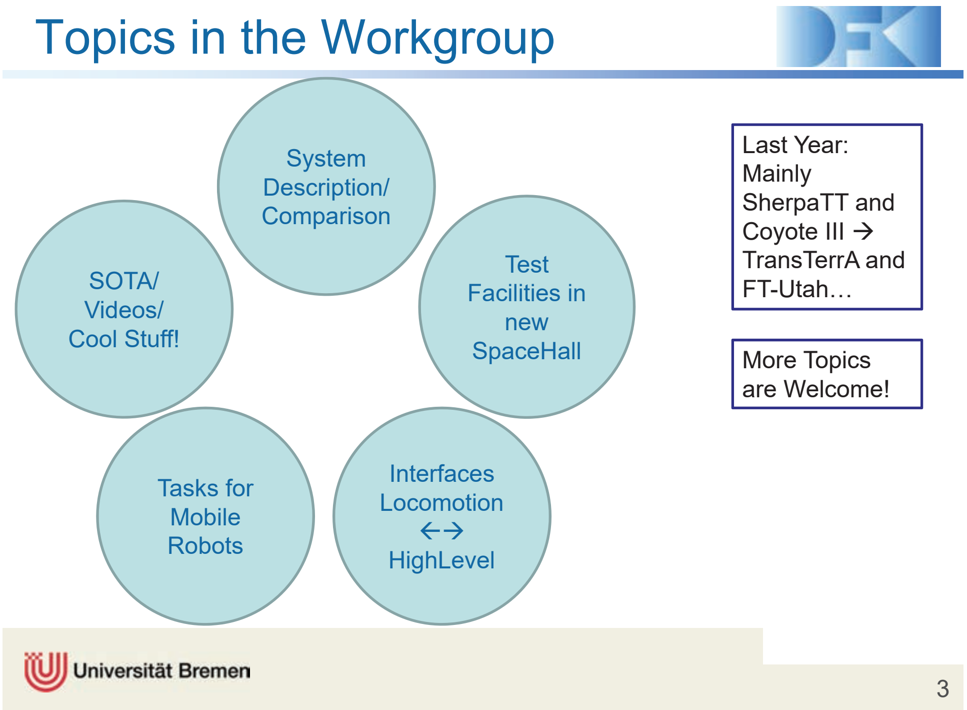

Agenda for Today

- 9:05 – 9:20
  Adaption of Charlie for the Requirements in the Project VIPE
  Daniel Kuehn

- 09:20 – 09:35
  Modular Test Parcours: Possibities, Parts, and How-To Use
  Alexander Dettmann

- 09:35 – 09:50
  SherpaTT - Recent Outdoor Tests and Plans for Utah Trials
  Florian Cordes

- 09:50 – 10:05
  Insights into the Development and Evaluation of Coyote III
  Roland U. Sonsalla

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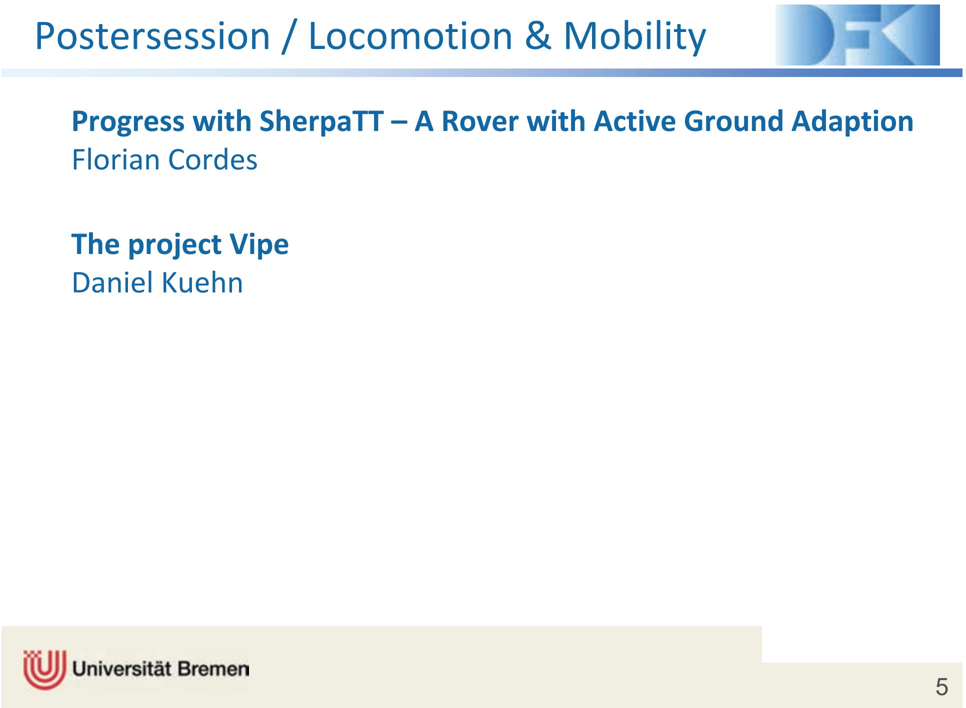

Postersession / Locomotion & Mobility
Progress with SherpaTT – A Rover with Active Ground Adaption
Florian Cordes
The project Vipe
Daniel Kuehn
Universität Bremen
5

2.2 'Modular Test Course Possibilities, Parts, and How-To Use It' (LM-T-02)

Alexander Dettmann[(1)], *Roland Sonsalla*[(3)], *Julius Moessner*[(3)]

(1) Universität Bremen, Arbeitsgruppe Robotik, Robert-Hooke-Straße 1, 28359 Bremen, Germany
(3) DFKI GmbH, Robotics Innovation Center, Robert-Hooke-Straße 1, 28359 Bremen, Germany

Contact: alexander.dettmann@dfki.de, roland.sonsalla@dfki.de

Abstract

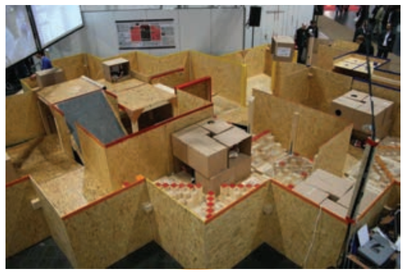
In the field of locomotion, test courses are needed to evaluate a robot's performance in challenging environments. In order to be able to execute repeatable experiments and to compare systems, the need of a standardized test setup is required. The NIST (National Institute of Standards and Technology) already published test methods for evaluationg emergency response capabilities regarding mobility. There they specify how the capability of traversing gaps, hurdles, inclines, stairs, and pitch roll ramps can be tested. In this presentation, modular elements are specified, which allow the creation of test courses according to these standards. The presented design follows a flexible building block principle, which allows easy recreation of obstacle courses due to simple geometric forms and cheap materials. In addition, it is easy to assemble and disassemble and supports large-sized robots (up to 150 kg and 2.4 m span width).

Modular Test Course

Possibilities, Parts, and How-To Use It

by Alexander Dettmann, Roland Sonsalla, and Julius Mößner

DFKI Bremen & Universität Bremen
Robotics Innovation Center
Director: Prof. Dr. Frank Kirchner
www.dfki.de/robotics
robotics@dfki.de



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Why do we need a modular test course?

- Test mobility of robots
- Repeatable experiments
- Compare systems
- Robotic challenges with high demands on mobility
  - ESA Lunar Robotics Challenge
  - DLR SpaceBot Cup
  - DARPA Robotics Challenge
  - RoboCup Rescue Robot League
- Mobility requirements
  - Slopes up to 40°
  - Stairs up to 75
  - 15 cm steps
  - Hard ground, gravel, sand pits, …
- Standard test methods for evaluating mobility required

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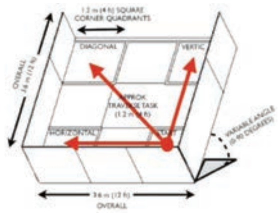
2

ASTM Standards

- Published by NIST (National Institute of Standards and Technology)
- Test Methods for Evaluating Emergency Response Robot Capabilities: Mobility
  - Gaps
  - Hurdles
  - Inclines
  - Stairs
  - Continuous Pitch Roll Ramps
  - Crossing Pitch Roll Ramps
- Specification of each obstacle type
- Realization not specified
  - \\files\research\workgroups\locomotion_mobility\presentations_and_meetings\20141008_Mobility_Tests\ASTM_Standards_on_Mobility



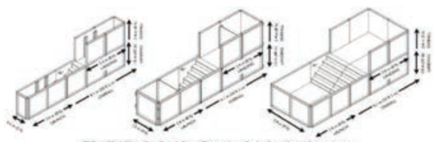


FIG. 1 Mobility: Confined Area Obstacles: Stairs/Landings Apparatuses

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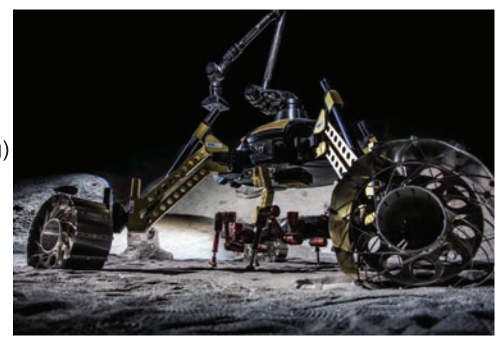
Derived Requirements

- According ASTM standards
  - Basic element of size 1200 mm x 1200 mm x 100 mm (l*w*h)
  - OSB (Frictional characteristics of dust covered floors)
- Easy to use
  - Building block principle
  - Easy assembly / disassembly
  - Extendable
- Supporting our robots
  - From Asguard (0,7 m x 0,5 m, 15 kg) to Sherpa (2,5 x 2,5 m, 150 kg)
- Easy to recreate
  - Simple geometric forms
  - Cheap materials
  - Simple manufacturing



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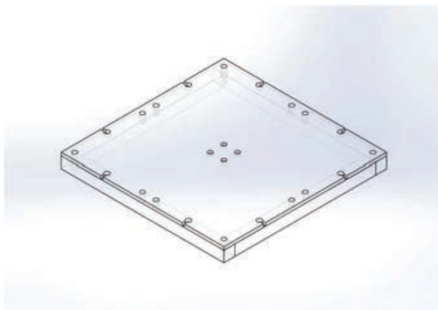
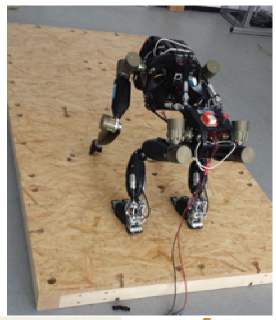
Basic Element

- Size:1200 mm x 1200 mm x 100 mm (l*b*h)
- 5 pieces
  - 2 x 1200 mm x 80 mm x 80 mm
  - 2 x 1040 mm x 80 mm x 80 mm
  - 1 x OSB-Plate 1200 mm x 1200 mm x 22 mm
- Boreholes in plate





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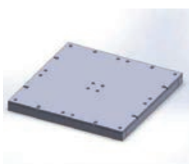
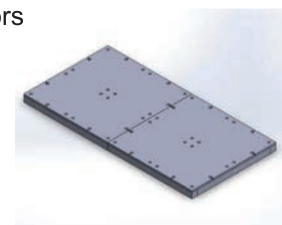
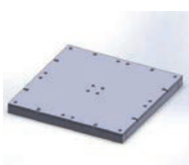
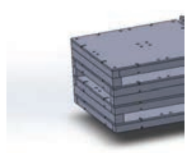
Connection Elements

- Horizontal connection via steel worktop connectors

 +  = 

- Vertical connection via wooden dowels

 +  = 

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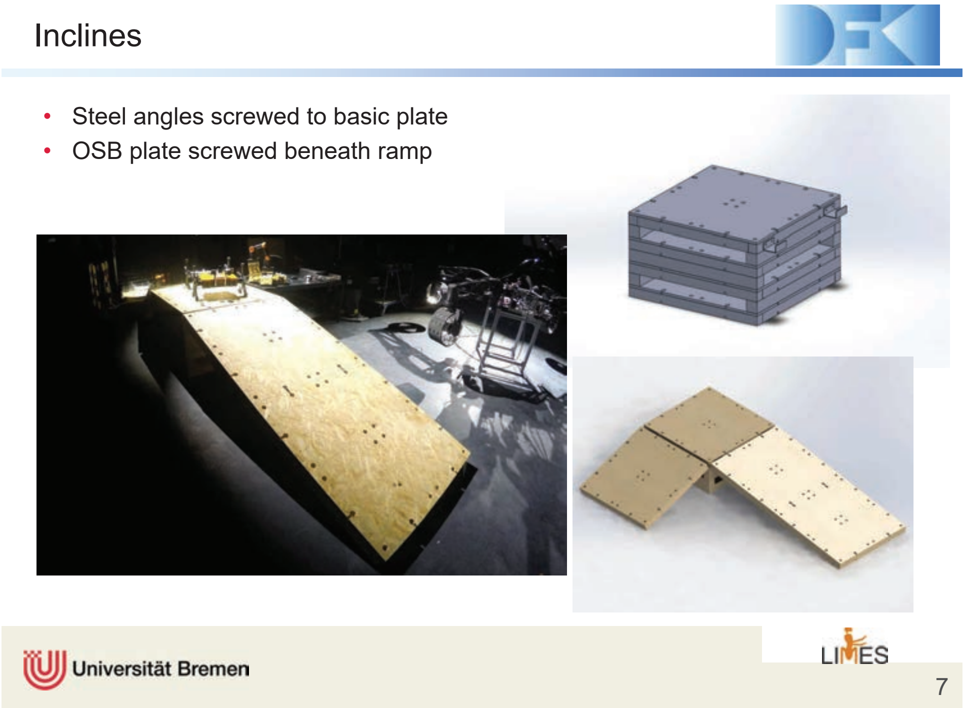
Inclines
Steel angles screwed to basic plate
OSB plate screwed beneath ramp
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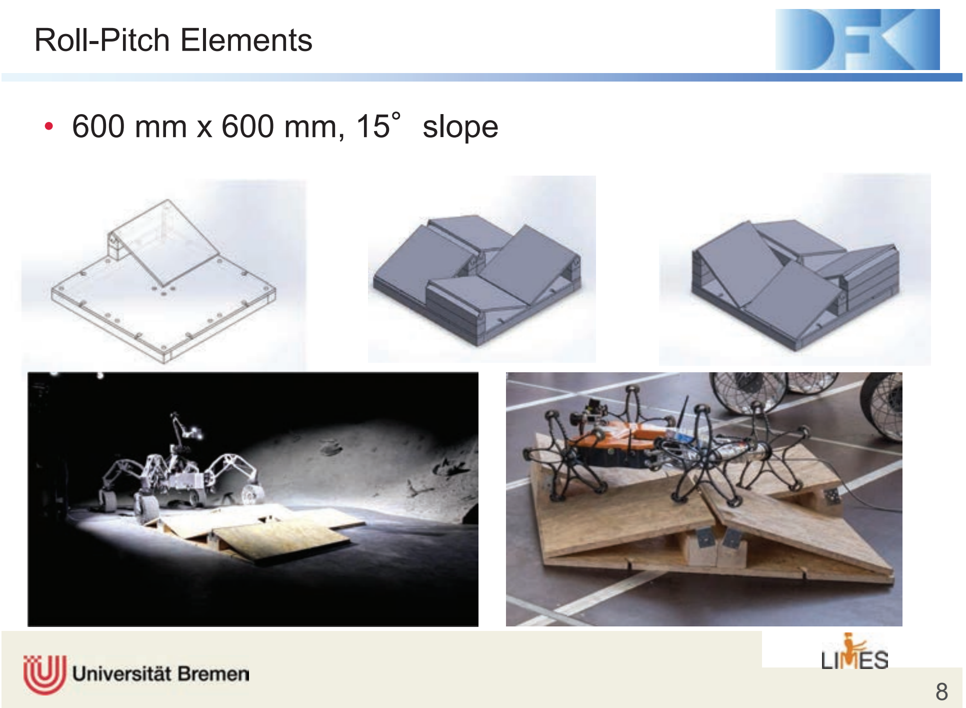
Roll-Pitch Elements
600 mm x 600 mm, 15° slope
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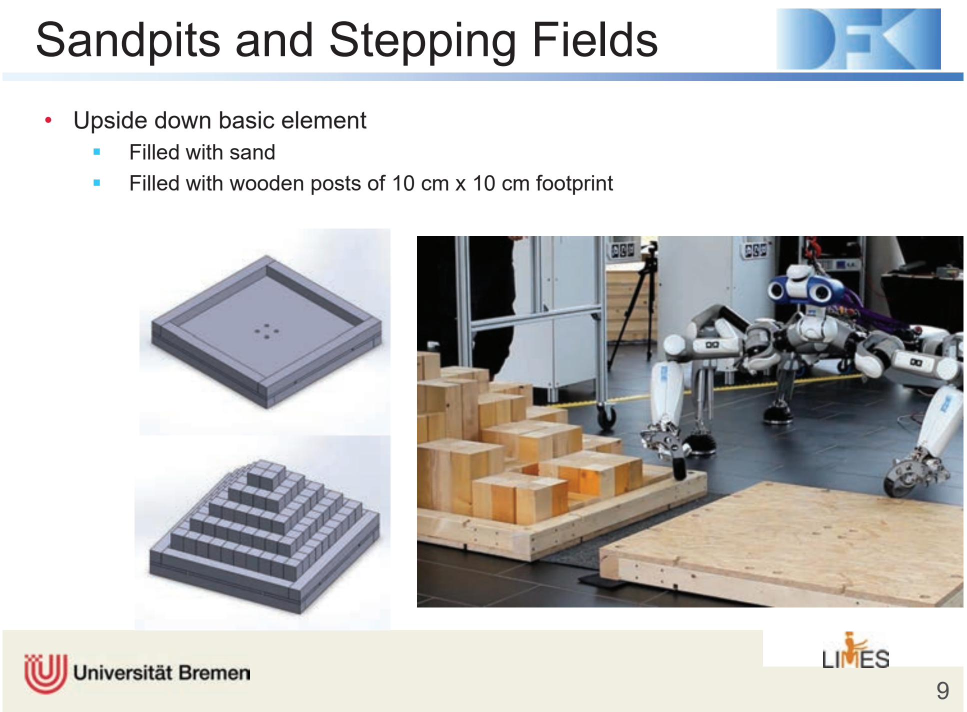
8


Sandpits and Stepping Fields
Upside down basic element
Filled with sand
Filled with wooden posts of 10 cm x 10 cm footprint
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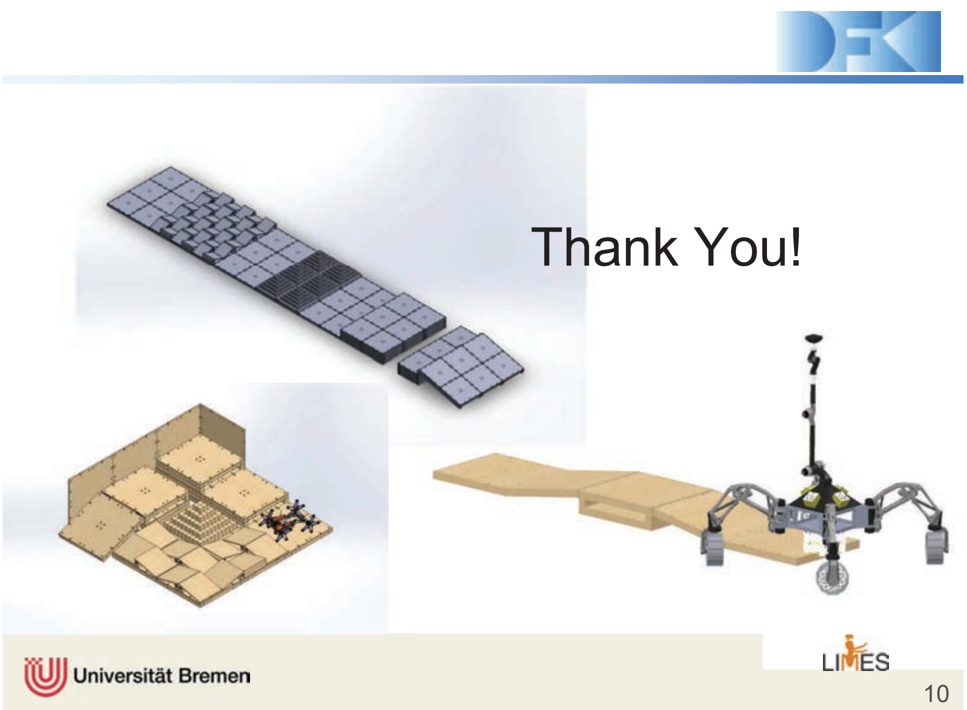
9


Thank You!
Universität Bremen
LIMES
10

2.3 'Adaption of Charlie for the Requirements in the Project VIPE' (LM-T-03)

Daniel Kuehn[(1)]

(1) DFKI GmbH, Robotics Innovation Center, Robert-Hooke-Straße 1, 28359 Bremen, Germany

Contact: daniel.kuhn@dfki.de

Abstract

In this talk the robotic system Charlie is presented, as well as the adaptions of Charlie, which are necessary to meet the requirements in the Project VIPE. The presentation started by introducing the project in general, including its partner, main, motivation, and vision.

In the following the electro-mechanical adaptions of the robot Charlie are presented. Starting with the previous state of the robot, the lateral play within legs is analyzed and it is shown, how this play is reduced by employing the improved upper and lower leg structures as well as new ankle joint actuators. The leg design is transferred from the rear legs to the front legs, whereas for the front legs the design of the one DoF hand is presented as well.

Gefördert durch:
Bundesministerium für Wirtschaft und Energie
aufgrund eines Beschlusses des Deutschen Bundestages

Projekttag

Adaption of Charlie for the Requirements in the Project VIPE

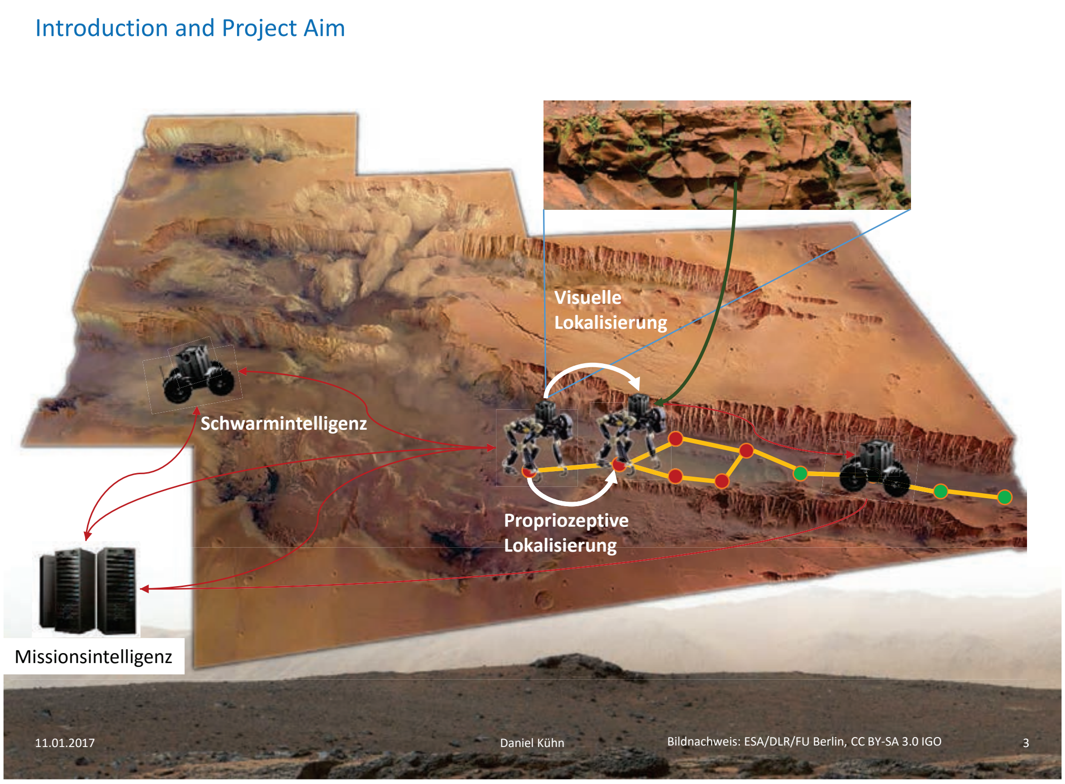
VaMEx-VIPE

Deutsches Zentrum für Luft- und Raumfahrt e.V. (DLR)
Raumfahrtmanagement | Navigation

Introduction and Project Aim

Motivation and vision:

- Vipe is part of DLR’s VaMEx II initiative
- Current Mars Rover („Spirit, „Opportunity“, „Curiosity“) fail on steep slopes or caves
- VaMEx initiative explored autonomous exploration with rovers and drones
- VIPE uses hominid robot platform to close the gap within the first VaMEx initiative
  - Charlie has to overcome different obstacles
  - Be able to perform simple manipulation tasks
- Transfer of technologies to terrestrial applications


Introduction and Project Aim
Visuelle Lokalisierung
Schwarmintelligenz
Propriozeptive Lokalisierung
Missionsintelligenz
11.01.2017
Daniel Kühn
Bildnachweis: ESA/DLR/FU Berlin, CC BY-SA 3.0 IGO
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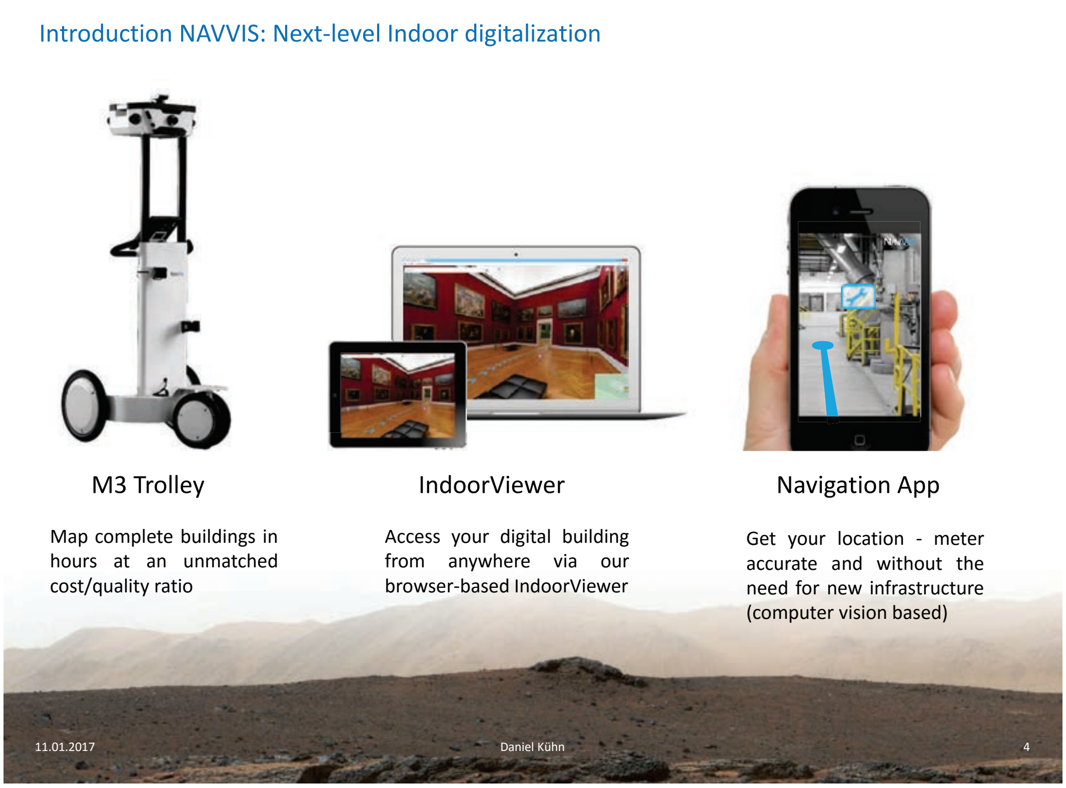
Introduction NAVVIS: Next-level Indoor digitalization
M3 Trolley
Map complete buildings in hours at an unmatched cost/quality ratio
IndoorViewer
Access your digital building from anywhere via our browser-based IndoorViewer
Navigation App
Get your location - meter accurate and without the need for new infrastructure (computer vision based)
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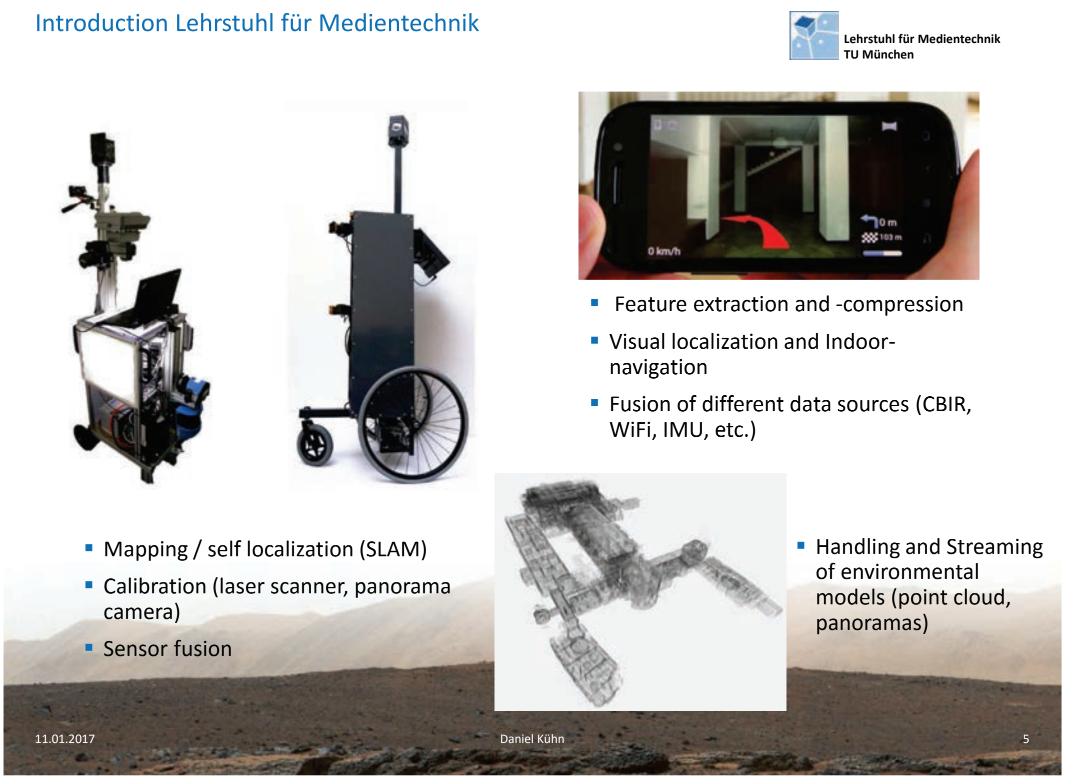
4



Introduction Lehrstuhl für Medientechnik
Lehrstuhl für Medientechnik
TU München
0 km/h
0 m
103 m
Feature extraction and -compression
Visual localization and Indoor-navigation
Fusion of different data sources (CBIR, WiFi, IMU, etc.)
Mapping / self localization (SLAM)
Calibration (laser scanner, panorama camera)
Sensor fusion
Handling and Streaming of environmental models (point cloud, panoramas)
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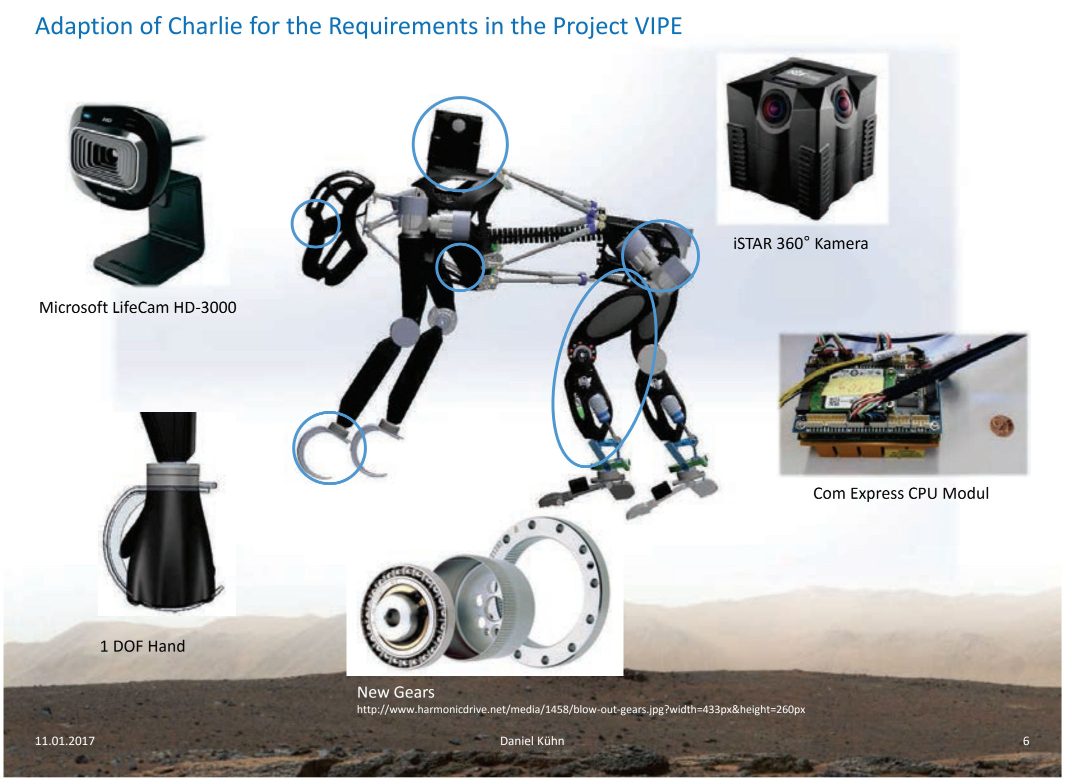
5



Adaption of Charlie for the Requirements in the Project VIPE
Microsoft LifeCam HD-3000
iSTAR 360° Kamera
Com Express CPU Modul
1 DOF Hand
New Gears
http://www.harmonicdrive.net/media/1458/blow-out-gears.jpg?width=433px&height=260px
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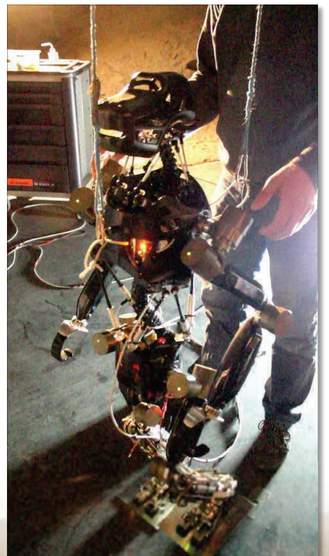
6

Previous State

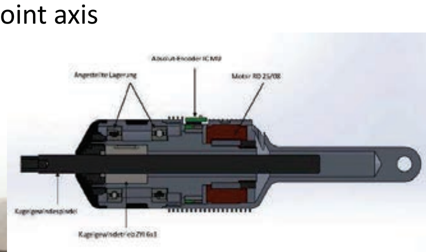
- Reduction of lateral play within legs
  - CoM can move +-30 mm in y- direction
  - Heel width: 50mm
- Mechanical play breakdown:
  1. +- 5,9 mm around the roll axis
  2. max. +- 4 mm within the hip actuators
  3. +- 19 mm elastic deflection of the leg structure
- Actions:
  - New linear actuators
  - Stiffening of the structure

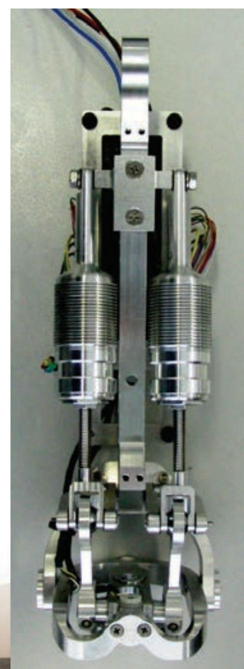


11.01.2017 Daniel Kühn 7

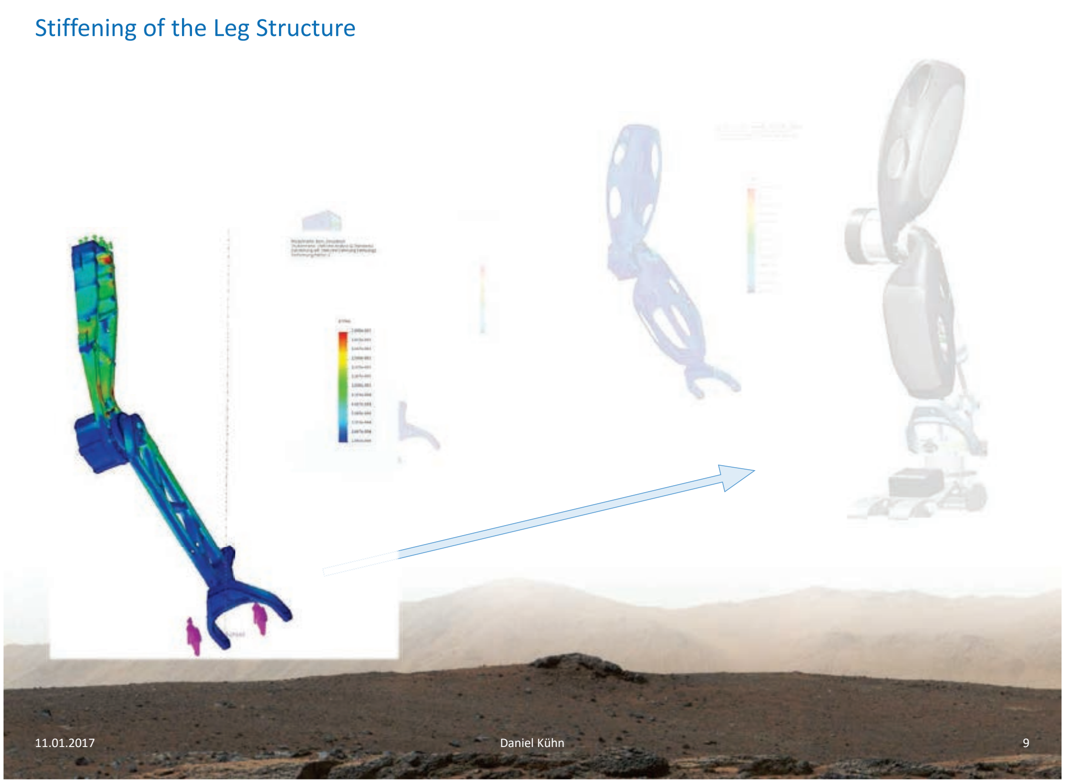
New Linear Actuator

- Weight 135 g (previously 250 g)
- Torque remains equal
- Higher linear speed
- Higher loading capacity
- Remaining axial play about 0,03 mm (previously 1 mm)
- Motor commutation with IC-MU absolute encoder
- Absolut position of the ankle joint is measured within the joint axis





11.01.2017 Daniel Kühn 8


Stiffening of the Leg Structure
11.01.2017
Daniel Kühn
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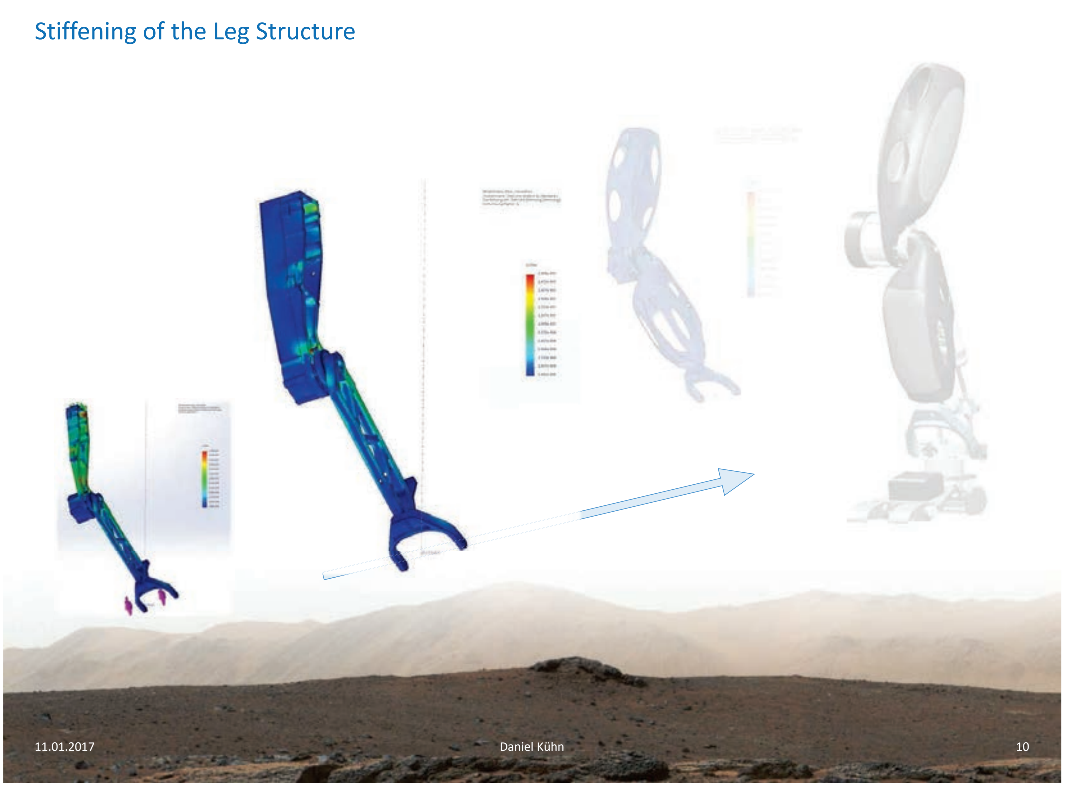
Stiffening of the Leg Structure
11.01.2017
Daniel Kühn
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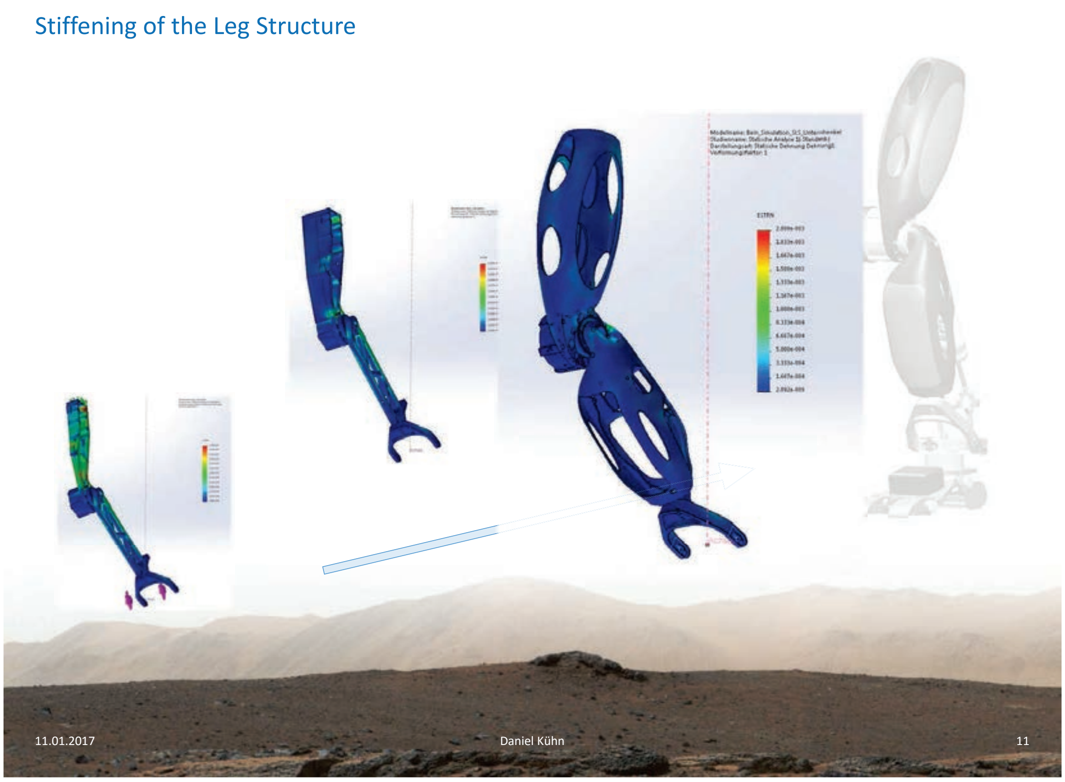
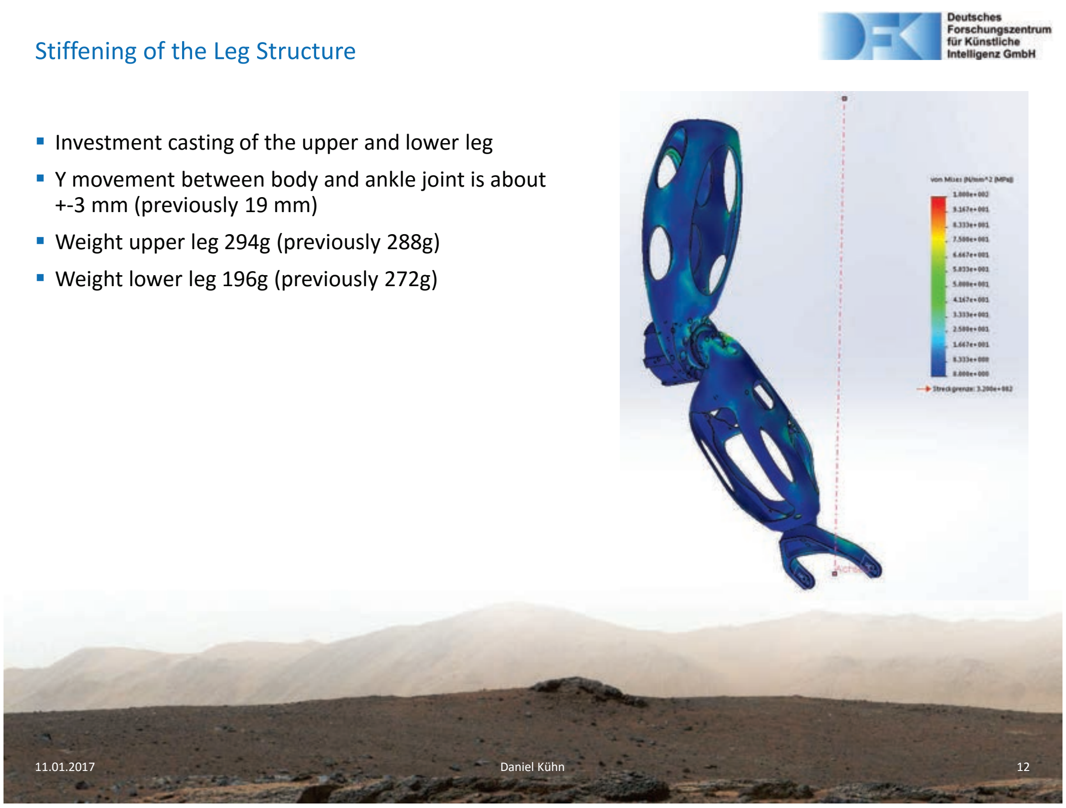
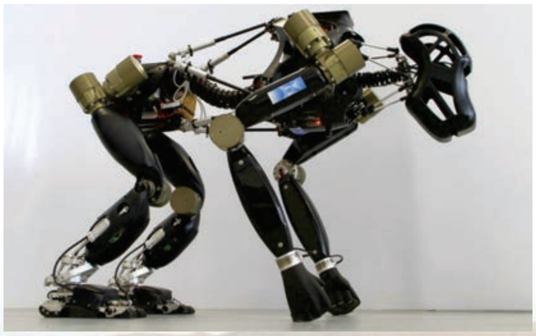

Stiffening of the Leg Structure
11.01.2017
Daniel Kühn
11


Stiffening of the Leg Structure
Deutsches Forschungszentrum für Künstliche Intelligenz GmbH
Investment casting of the upper and lower leg
Y movement between body and ankle joint is about +-3 mm (previously 19 mm)
Weight upper leg 294g (previously 288g)
Weight lower leg 196g (previously 272g)
11.01.2017
Daniel Kühn
12

Resulting Leg Design

- Design transfer from the rear legs to the front legs
- Balancing on one leg
  - Blown fuses
  - Changing gear reduction in the second and third joint
  - 1:80 → 1:100

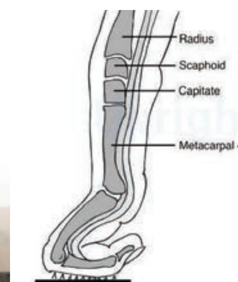


11.01.2017 Daniel Kühn 13

Hand Design

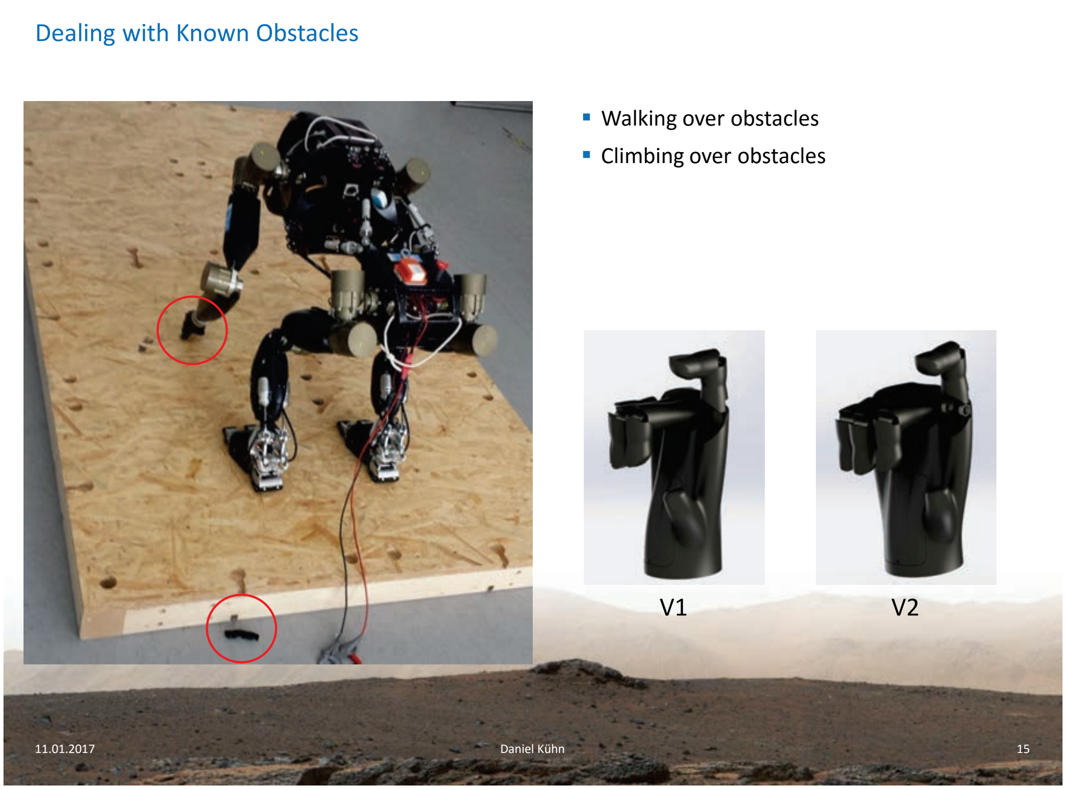
- 1 DoF hand

http://www.billybear4kids.com/Rozi/KnuckleWalker2.jpg



http://www.uprightape.net/Image%20Files/10-1b%20Knuckle.jpg

11.01.2017 Daniel Kühn 14


Dealing with Known Obstacles
Walking over obstacles
Climbing over obstacles
V1
V2
11.01.2017
Daniel Kühn
15

2.4 'SherpaTT - Recent Outdoor Tests and Plans for Utah Trials' (LM-T-04)

Florian Cordes[(1)]

(1) DFKI GmbH, Robotics Innovation Center, Robert-Hooke-Straße 1, 28359 Bremen, Germany

Contact: florian.cordes@dfki.de

Abstract

This talk encompasses two main topics: (i) a detailed presentation of the most recent outdoor tests with the system is provided and (ii) the plans for the upcoming field trials in Utah, USA are presented. The talk starts with a review on the first implementation of active ground adaption with single wheel control and then shows the simplified and updated control with combined wheel control. A method for increasing the available workspace is presented and a video of a outdoor run is shown.

In the project FT-Utah (Field Trials Utah), the robot will be used in the desert of Utah, USA. The planned experiments are presented in the second part of the talk. The talk concludes with a presentation of the next immediate steps in the work with SherpaTT.

SherpaTT – Recent Outdoor Tests and Plans for Utah Trials

Dipl.-Ing Florian Cordes
DFKI Robotics Innovation Center Bremen
Robert-Hooke Straße 5
28359 Bremen, Germany

Contents

- Motion Control System – Initial State vs. Current State
- Outdoor Tests July/August 2016
- Planned Stuff for Utah

Motion Control

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3

First Approach: Single Wheel Control

- Control of
  - Body's Roll/Pitch
  - Z-forces (gravity vector) distribution including ground contact ensurance
- Simplified Process of GAP:
  1. Calculate expected forces based on current foot print
  2. PI control refF and actF -> outputs z-offset for each wheel
  3. PI controller refRoll and actRoll -> outputs z-offset for each wheel
  4. PI controller refPitch and actPitch -> outputs z-offset for each wheel
  5. Add up all offsets and write to inverse kinematics

Offset Direction positive roll and positive pitch

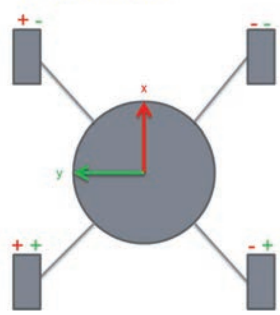

Fig: Offset directions for positive roll and pitch errors

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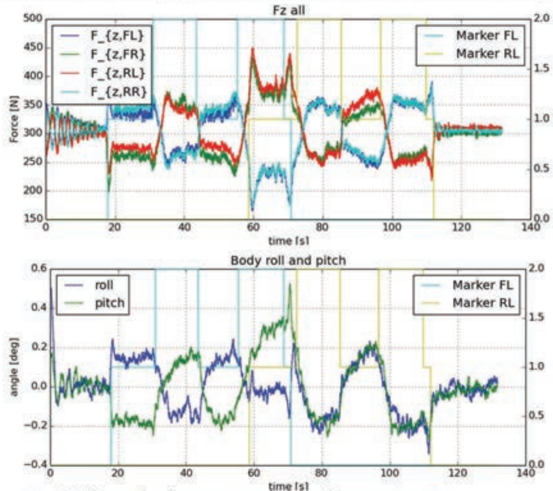
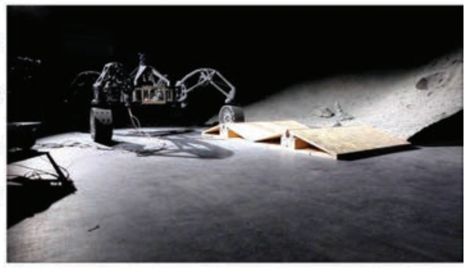
First Approach in Lab-Experiments





Video: SherpaTT on wooden obstacle course

Video: SherpaTT on artificial crater (playback-speed: 4x)

- Wheels keep ground contact, forces are +/-150N from reference
- Only small deviations in roll/pitch observable (less than +/- 0.5deg)

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Identified Drawbacks

- 3 different PI controllers acting on each wheel's z-coordinate
  - Controllers "do not know" of each other
- Adaption controller only acts on single wheel, regardless what the other wheels do
  - First implementation stage had no interconnection between the single wheels
  - Each change on one wheel affects other wheels
  - An implemented cross influence (dependent on distance, axis, …) did not yield satisfying results (introduced even more oscillations)

$$\mathbf{z}_{co} = \mathbf{CIM} \cdot \mathbf{\Delta f}$$

$\mathbf{z}_{co}$: cross offset vector
$\mathbf{CIM}$: cross influence factor matrix
$\mathbf{\Delta f}$: force error vector

$$\mathbf{CIM} = \begin{bmatrix} 0 & cim_{01} & cim_{02} & cim_{03} \\ cim_{10} & 0 & cim_{12} & cim_{13} \\ cim_{20} & cim_{21} & 0 & cim_{23} \\ cim_{30} & cim_{31} & cim_{32} & 0 \end{bmatrix}$$

cim_{ij}: influence factor wheel j onto i
$cim_{ij} = -1 \cdot cim_{ji}$

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New Approach: "Cross Offsets"

- For force leveling control (FLC)
  - Wheels front_left (FL) and rear_right (RR) as well as font_right (FR) and rear_left (RL) are pairs
  - One pair of wheels gets the same positive offset
  - 2nd pair gets same offset with negative value
  - Mean value of FLC-offsets remains zero → commanded body height is not affected by FLC

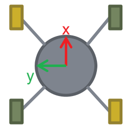

Fig: wheel pairs FL/RR and FR/RL

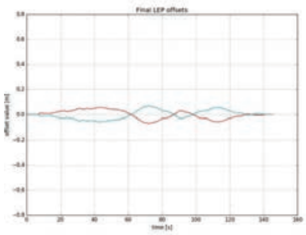

Fig: offsets from pure FLC-run. Blue: FL/RR, red: FR/RL

Video: Run through sand pit with FLC, without RPA (speed x2)

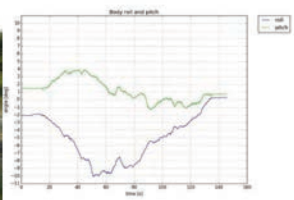

Fig: roll and pitch during FLC+RPA-run.

Contact pairs are clearly visible before activating FLC

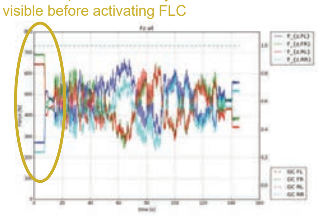

Fig: forces during pure FLC-run.

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New Approach: Roll/Pitch Control

- Roll/Pitch Adaption (RPA)
  - Angle-Axis: roll and pitch as a single angle around combined rotation axis
  - Distance of LEP to axis as scaling offset factor
  - Keeps angles between +1deg and -1deg
  - Steering-DoF is kept perpendicular to ground

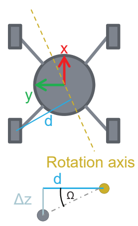

Fig: angle axis approach for RL

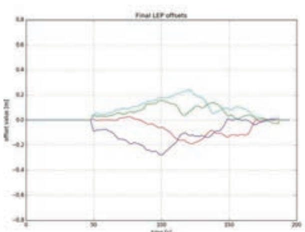

Fig: LEP-offsets in FLC+RPA run

Video: Run through sand pit with FLC+RPA (speed x2)

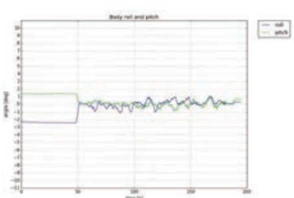

Fig: roll and pitch during FLC+RPA-run.

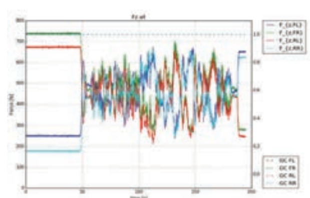

Fig: forces during FLC+RPA-run.

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New Ground Adaption Process

1. Calculate reference force based on actual foot print
2. If stuck: do Wheel Steering Support (WSS)
   - Alters reference Forces to allow steering maneuver
3. Generate offsets for Force Leveling Control (FLC)
4. Generate offets for Roll/Pitch Adaption (RPA)
5. Add up offsets
6. Check boundaries and shift offsets towards center of workspace if possible

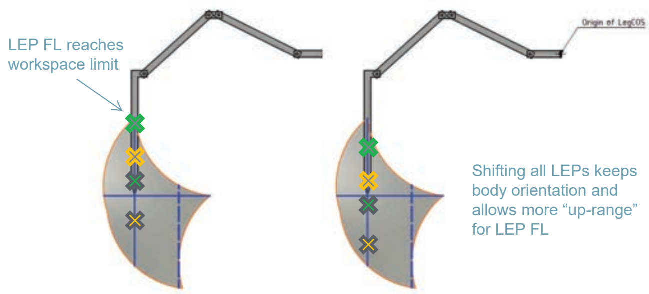

Fig: Example for simple LEP-Shifting for workspace optimization

LEP positions: ✖ FL ✖ FR ✖ RL ✖ RR

Video: Outdoor Run 2016-08-23

Video: SherpaTT in Outdoor Test Runs. Original Playback Speed

Plans for Utah

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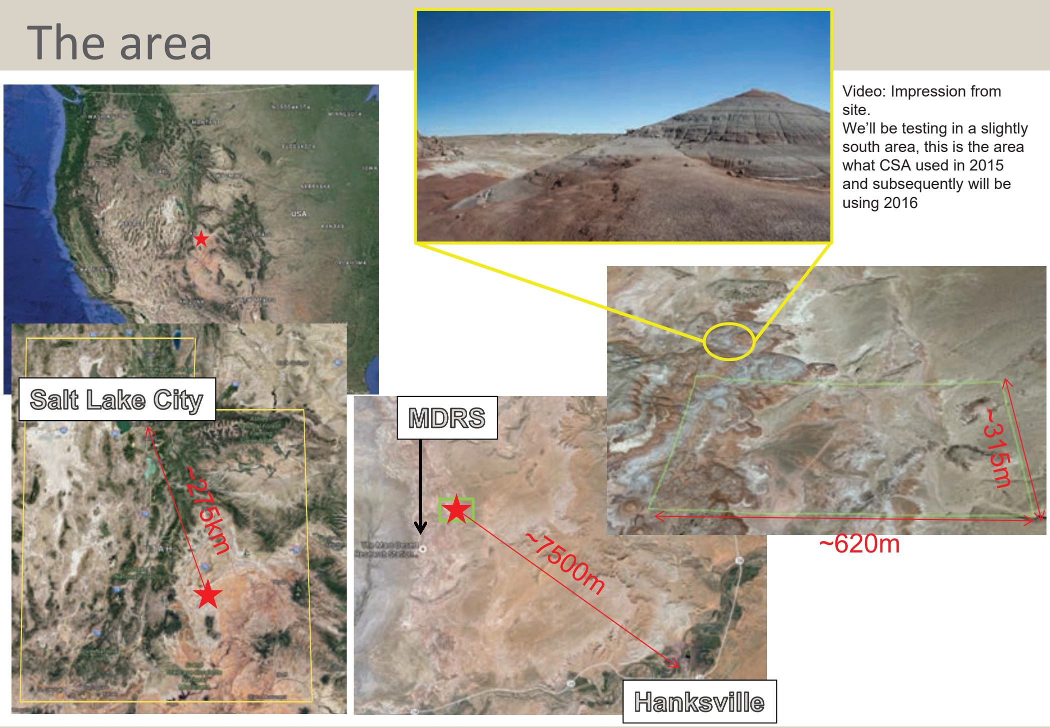
11

The area



Video: Impression from site.
We'll be testing in a slightly south area, this is the area what CSA used in 2015 and subsequently will be using 2016

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12

Planned Tests – WheelTypes and Active Suspension

- Apart from locomotion: Autonomy (Navigation, Cooperation) and Manipulation will be tested. Not scope of this presentation.
- Three sets of wheels: rigid, semi-flexible, very soft
  - Influence of wheel type on robot motion control?
  - Parameter adaption necessary? Expecting FLC to be influenced
  - Wheel traction/performance in soft soil and on rigid ground

Rigid wheel, here without grousers

New semi flexible wheel (CAD)

Very soft wheel ("DLR-Wheel")

Video: Different Surfaces Found at 2015's CSA site

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Planned Tests – Postures Supporting Active Ground Adaption

- Following a straight line path along a slope: How do postures affect the quality of path following?
  - Shifting the center of mass within the support polygon is expected to yield better distribution of forces onto the wheels
- Upslope Experiments: How do different postures affect the slope climbing capabilities?
- General locomotion capabilities in natural terrain
  - Holes, channels, small hills
  - Collect data for more precise traversability map generation

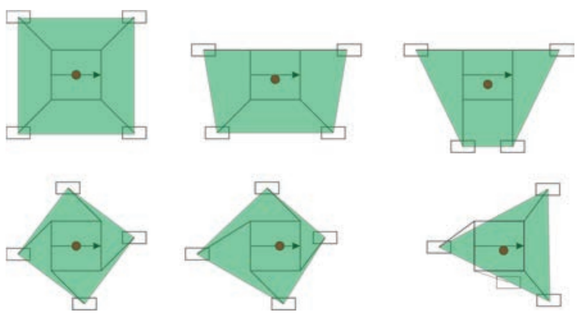

Fig.: Different possible postures for slope experiments

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Next

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Next Steps

- SherpaTT specific:
  - Implement "Force-Fuse"
    - Check Forces in x-y Plane and Stop Motion in Case of high loads
    - Avoid self-destruction
  - Advance Workspace Maximizer: Roll/Pitch body for more workspace
  - Torque control at wheels
- Utah-specific
  - Final experiment definition
  - Time schedule for experiments

Fig: broken and repaired structure

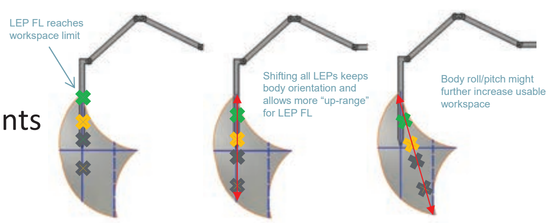

Fig: extension of workspace maximizer

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2.5 'Insights into the Development and Evaluation of Coyote III' (LM-T-05)

Roland Sonsalla[(1)]

(1) DFKI GmbH, Robotics Innovation Center, Robert-Hooke-Straße 1, 28359 Bremen, Germany

Contact: roland.sonsalla@dfki.de

Abstract

Coyote III is a micro rover with high mobility performance in unstructured terrains. Equipped with its own power source, on-board sensor suite and computer it is able to perform autonomous exploration tasks. The communication subsystem allows to cooperate with other systems. Coyote III is equipped with two standardized electro-mechanical interfaces, allowing to dock additional payload elements, such as a manipulator or standardized payload items. Due to the lightweight and robust structural design of Coyote III, it is possible to apply several kilograms of additional payload to the rover. The modular design approach allows to adapt the rover structure according to specific payload requirements. The following slides present the development history of Coyote III and its core features. Furthermore, a set of locomotion experiments performed indoors and outdoors for system evaluation and as preparation for an excessive field test in the Utah desert is presented. The environmental features to be found on the test site in Utah are investigated and visualized along with an outlook on the proposed tests in the desert with respect to the locomotive capabilities of Coyote III.

Insights into the Development and Evaluation of Coyote III

Direktor: Prof. Dr. Frank Kirchner
Universität Bremen,
DFKI Robotics Innovation Center
Robert-Hooke-Str. 1
28359 Bremen

Roland Sonsalla
22.09.2016

Universität Bremen

Introduction

Who is Coyote III?

When was Coyote III developed?

Where is Coyote III's area of operation?

What is this talk all about?

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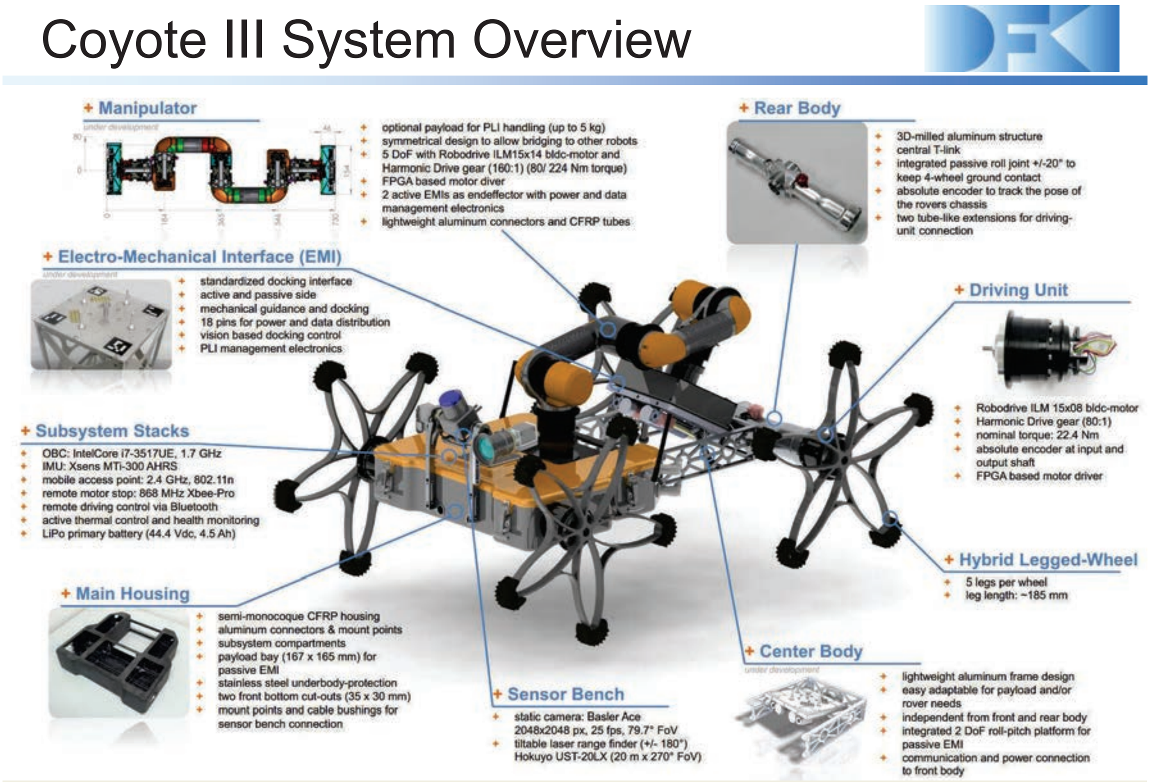
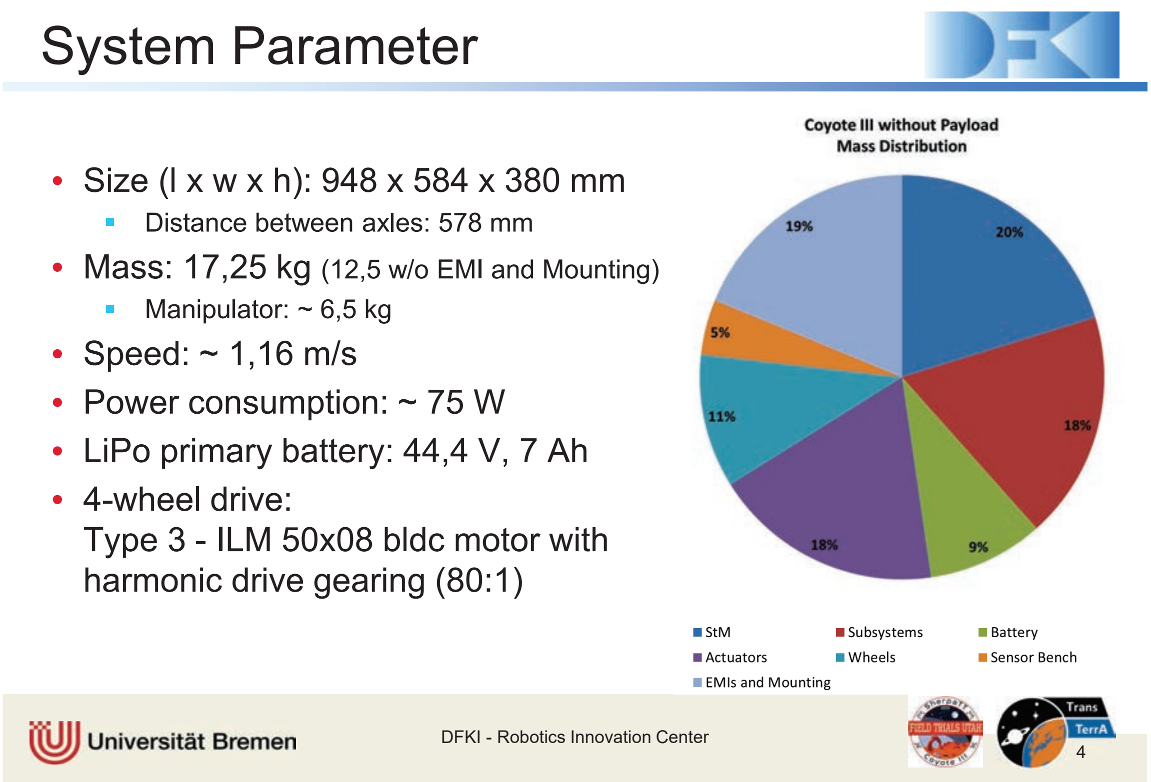

Coyote III System Overview
+ Manipulator
under development
optional payload for PLI handling (up to 5 kg)
symmetrical design to allow bridging to other robots
5 DoF with Robodrive ILM15x14 bldc-motor and Harmonic Drive gear (160:1) (80/ 224 Nm torque)
FPGA based motor diver
2 active EMIs as endeffector with power and data management electronics
lightweight aluminum connectors and CFRP tubes
+ Electro-Mechanical Interface (EMI)
under development
standardized docking interface
active and passive side
mechanical guidance and docking
18 pins for power and data distribution
vision based docking control
PLI management electronics
+ Subsystem Stacks
OBC: IntelCore i7-3517UE, 1.7 GHz
IMU: Xsens MTi-300 AHRS
mobile access point: 2.4 GHz, 802.11n
remote motor stop: 868 MHz Xbee-Pro
remote driving control via Bluetooth
active thermal control and health monitoring
LiPo primary battery (44.4 Vdc, 4.5 Ah)
+ Main Housing
semi-monocoque CFRP housing
aluminum connectors & mount points
subsystem compartments
payload bay (167 x 165 mm) for passive EMI
stainless steel underbody-protection
two front bottom cut-outs (35 x 30 mm)
mount points and cable bushings for sensor bench connection
+ Sensor Bench
static camera: Basler Ace 2048x2048 px, 25 fps, 79.7° FoV
tiltable laser range finder (+/- 180°) Hokuyo UST-20LX (20 m x 270° FoV)
+ Rear Body
3D-milled aluminum structure
central T-link
integrated passive roll joint +/-20° to keep 4-wheel ground contact
absolute encoder to track the pose of the rovers chassis
two tube-like extensions for driving-unit connection
+ Driving Unit
Robodrive ILM 15x08 bldc-motor
Harmonic Drive gear (80:1)
nominal torque: 22.4 Nm
absolute encoder at input and output shaft
FPGA based motor driver
+ Hybrid Legged-Wheel
5 legs per wheel
leg length: ~185 mm
+ Center Body
under development
lightweight aluminum frame design
easy adaptable for payload and/or rover needs
independent from front and rear body
integrated 2 DoF roll-pitch platform for passive EMI
communication and power connection to front body


System Parameter
Size (l x w x h): 948 x 584 x 380 mm
Distance between axles: 578 mm
Mass: 17,25 kg (12,5 w/o EMI and Mounting)
Manipulator: ~ 6,5 kg
Speed: ~ 1,16 m/s
Power consumption: ~ 75 W
LiPo primary battery: 44,4 V, 7 Ah
4-wheel drive:
Type 3 - ILM 50x08 bldc motor with harmonic drive gearing (80:1)
Coyote III without Payload
Mass Distribution
20%
18%
9%
18%
11%
5%
19%
StM
Subsystems
Battery
Actuators
Wheels
Sensor Bench
EMIs and Mounting
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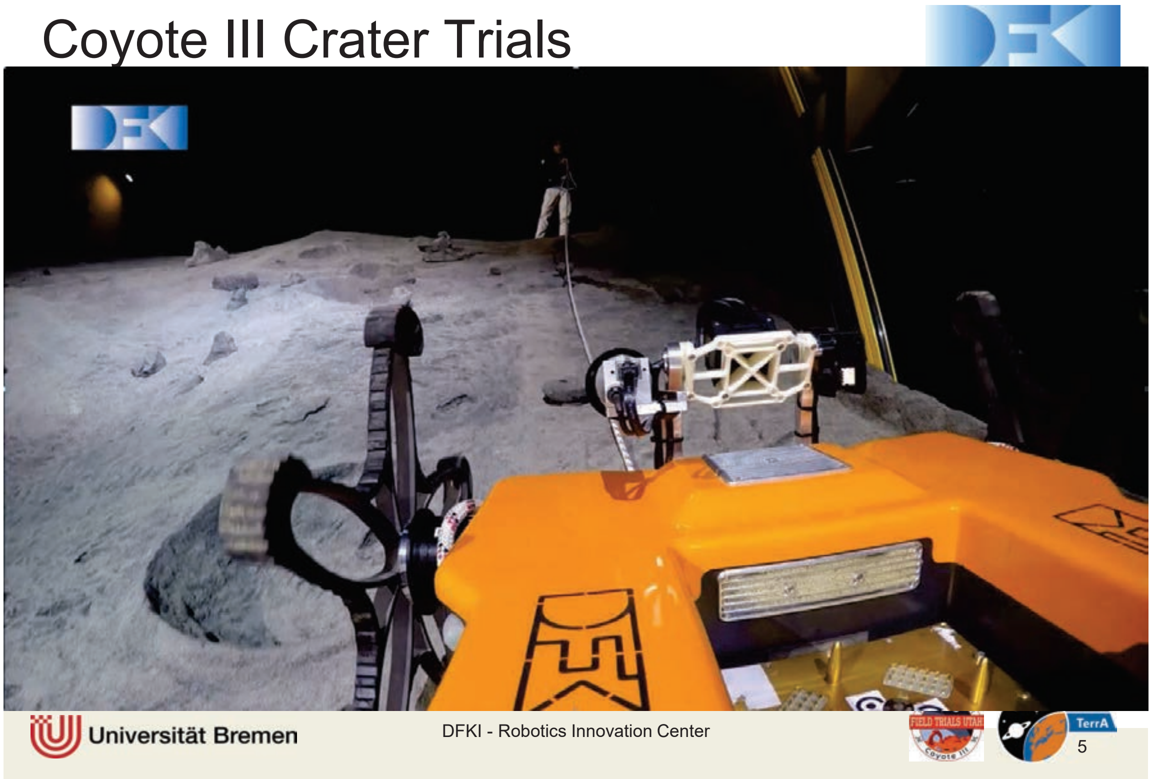
DFKI - Robotics Innovation Center
Trans
TerrA
4


Coyote III Crater Trials
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5


Coyote III with Manipulator
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6


Coyote III Point Turn
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TerrA
7


Coyote with new Foot Design
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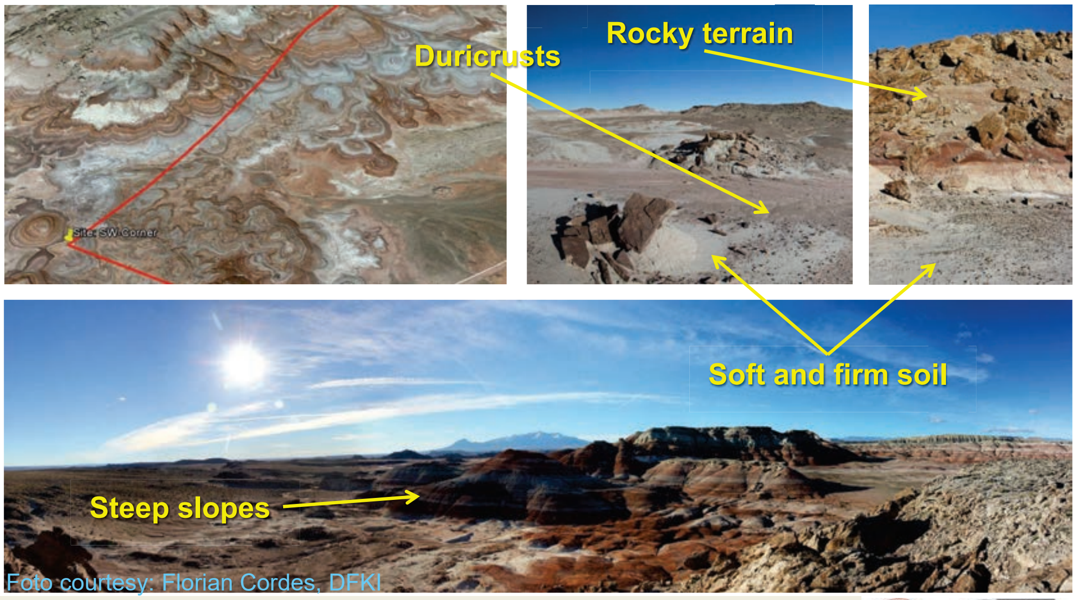
TerrA
8

Utah Test Site Investigation



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9

Utah Test Site - Soil Investigation

Video courtesy: Florian Cordes, DFKI

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DFKI - Robotics Innovation Center

10

Conclusion and Outlook

- There is (still) a lot of potential in terms of locomotion and mobility for the robots of the Asgurad-Family
- A more in depth analysis of the locomotion system and its control is needed for robust imporvements
- More insights will hopefully be gathered at the Utah Field Trials during tests like:
  - Slope driving test up/down
  - Slope driving test diagonally
  - Locomotion performance test
  - Drawbar pull test
  - Walking pattern test
  - Odometry test
  - Cliff exploration test
  - Night journey

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Coyote III Snow Run

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Thank You!
Roland Sonsalla
roland.sonsalla@dfki.de
22.09.2016
Insights into the Development and Evaluation of Coyote III

2.6 'Progress with SherpaTT – A Rover with Active Ground Adaption' (LM-P-01)

Florian Cordes [1]

(1) DFKI GmbH, Robotics Innovation Center, Robert-Hooke-Straße 1, 28359 Bremen, Germany

Contact: florian.cordes@dfki.de

Abstract

The poster gives an overview on the current progress with SherpaTT. A system overview is provided along with the description of a leg's workspace. The movement capabilities and locomotive advantages of an active suspension system are described. A short overview on the first outdoor locomotion tests is given. From these tests a comparison of force distribution on the wheels and the body's angular displacement is done, when driving without vs. with enabled ground adaption process.

Deutsches Forschungszentrum für Künstliche Intelligenz GmbH

Progress with SherpaTT

A Rover with Active Ground Adaption

System Overview

SherpaTT is a reconfigurable and versatile hybrid wheeled-leg robot. It features an active suspension system with four legs, each ending in a drivable and steerable wheel.
Three degrees of freedom (DoF) of each suspension unit are used for moving the leg end point (LEP) in the space around the robot. Two DoF are used for orienting and driving a wheel.

Photograph of SherpaTT equipped with flexible wheels and manipulation arm

Movement Possibilities due to Active Suspension System

Using the active suspension it is possible to:

- Move single LEPs to conform to the terrain
- Change the body's orientation by coordinated movement of all four LEPs
- Combine both possibilities to independently control the robot's posture while driving in rough terrain

The workspace of a LEP is a complex shape due to the two serially linked parallel structures in a leg. It has a maximum extension of about 770mm in height and 500mm in distance from the body. The volume of the movement range is spanned by rotating around the first joint of a leg (in total: 215°).

Photograph of SherpaTT with its legs in stow configuration

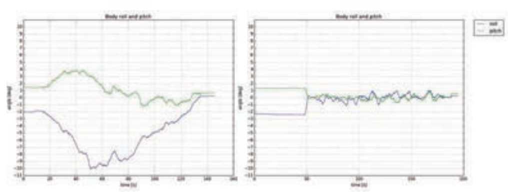
Locomotion Outdoor Tests

In preparation of the November 2016 field test campaign, several outdoor tests with SherpaTT were conducted during July and August 2016. Several shortcomings on hardware level and motion control were identified and improved. This included joint level control (i.e. usage of position sensor signals) and changing from single wheel controllers to a more integrated control using dependent offsets between the wheels. Among other advantages, drifting in adaption offsets and changes of commanded body height are now prevented.

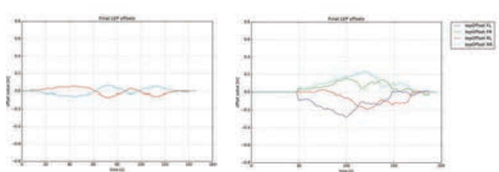
SherpaTT was able to climb a small hill with a slope between 15° and 30° as well as driving through sand pits with up to 400mm height difference between the wheels, all with keeping the body orientation constant at driving speeds of 100mm/s.

Photograph of SherpaTT while driving through a sand pitch, keeping the roll/pitch deviation of the body at a minimum

The plots shown below illustrate the difference between driving with and without active roll/pitch adaption (RPA) through the sand pitch shown in above image. The left plot shows the robot's body roll and pitch when only force-leveling (FLC) is active. Deviations up to -10° in roll and up to +4° in pitch occur.



Plots of roll (blue) and pitch (green) angles of body: Left without RPA, right with active RPA.



Plots of LEP-offsets. Left: for pure FLC (same Offset for pairs FL/RR and FR/RL). Right: FLC+RPA generate different offsets for all LEPs to keep the robot level with the ground

Universität Bremen

Gefördert durch: DLR

Kontakt:
DFKI Bremen & Universität Bremen
Robotics Innovation Center

Direktor: Prof. Dr. Frank Kirchner
E-Mail: robotik@dfki.de
Internet: www.dfki.de/robotik

3 ‘Navigation & Planning’

3.1 ‘AG Navigation & Planning Introduction’ (NP-T-01)

Leif Christensen[(1)]

(1) DFKI GmbH, Robotics Innovation Center, Robert-Hooke-Straße 1, 28359 Bremen, Germany

Contact: leif.christensen@dfki.de

Abstract

This talk gives a very brief introduction to the AG Navigation & Planning, it’s members, to past and future topics as well as the schedule for the project day.

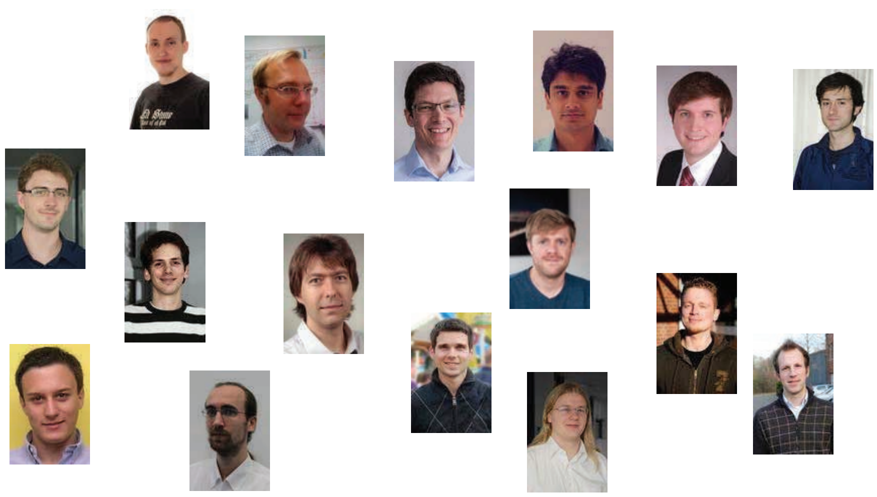
AG Navigation & Planning

Project Day
22.09.2016

DFKI Bremen & Universität Bremen
Robotics Innovation Center
Director: Prof. Dr. Frank Kirchner
www.dfki.de/robotics
robotics@dfki.de

Universität Bremen

AG Navigation & Planning



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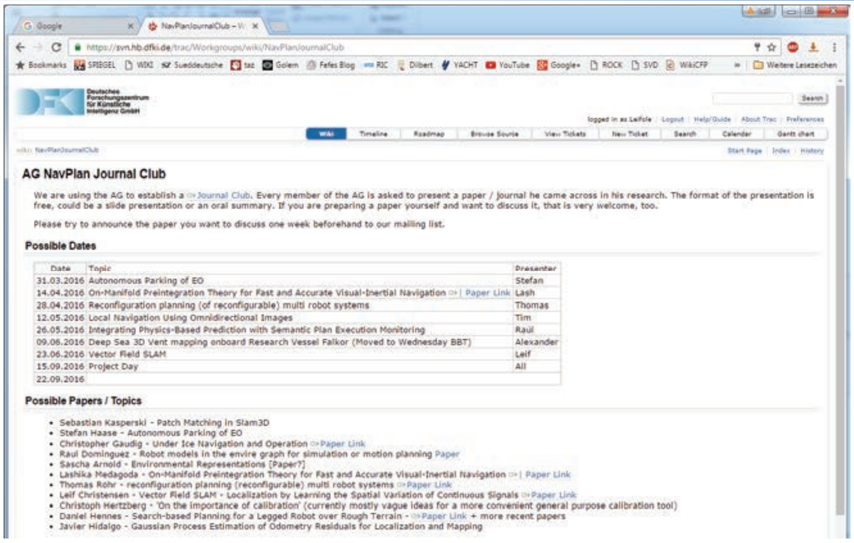
AG NavPlan Journal Club



https://svn.hb.dfki.de/trac/Workgroups/wiki/NavPlanJournalClub

AG NavPlan Journal Club

We are using the AG to establish a Journal Club. Every member of the AG is asked to present a paper / journal he came across in his research. The format of the presentation is free, could be a slide presentation or an oral summary. If you are preparing a paper yourself and want to discuss it, that is very welcome, too.

Please try to announce the paper you want to discuss one week beforehand to our mailing list.

Possible Dates

Date	Topic	Presenter
31.03.2016	Autonomous Parking of EO	Stefan
14.04.2016	On-Manifold Preintegration Theory for Fast and Accurate Visual-Inertial Navigation | Paper Link	Lash
28.04.2016	Reconfiguration planning (of reconfigurable) multi robot systems	Thomas
12.05.2016	Local Navigation Using Omnidirectional Images	Tim
26.05.2016	Integrating Physics-Based Prediction with Semantic Plan Execution Monitoring	Raúl
09.06.2016	Deep Sea 3D Vent mapping onboard Research Vessel Falkor (Moved to Wednesday BBT)	Alexander
23.06.2016	Vector Field SLAM	Leif
15.09.2016	Project Day	All
22.09.2016		

Possible Papers / Topics

- Sebastian Kasperski - Patch Matching in Slam3D
- Stefan Haase - Autonomous Parking of EO
- Christopher Gaudig - Under Ice Navigation and Operation Paper Link
- Raul Dominguez - Robot models in the envire graph for simulation or motion planning Paper
- Sascha Arnold - Environmental Representations [Paper?]
- Lashika Medagoda - On-Manifold Preintegration Theory for Fast and Accurate Visual-Inertial Navigation | Paper Link
- Thomas Rohr - reconfiguration planning (reconfigurable) multi robot systems Paper Link
- Leif Christensen - Vector Field SLAM - Localization by Learning the Spatial Variation of Continuous Signals Paper Link
- Christoph Hertzberg - 'On the importance of calibration' (currently mostly vague ideas for a more convenient general purpose calibration tool)
- Daniel Hennes - Search-based Planning for a Legged Robot over Rough Terrain - Paper Link + more recent papers
- Javier Hidalgo - Gaussian Process Estimation of Odometry Residuals for Localization and Mapping

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Agenda

AG Navigation & Planning

10:20 – 10:25	**Introduction Workgroup Navigation & Planning** (Leif Christensen)
10:25 – 10:40	**Camera Flatport Calibration** (Alexander Duda)
10:40 – 10:55	**Velodyne/Fisheye-Camera Cross Calibration** (Christoph Hertzberg)
10:55 – 11:05	**Dos and Don'ts of IMU / Magnetometer Placement on Robots** (Leif Christensen)
11:05 – 11:25	**EuropaExplorer: Project Review and Future Work** (Marc Hildebrandt)
11:25 - 11:30	Break
11:30 – 11:45	**3D Path Planning for an UGV** (Janosch Machowinski, Arne Böckmann)
11:45 – 12:00	**Removing Dynamic Objects from Map Representations** (Sebastian Kasperski)
12:00 – 12:15	**Space Rover Analog Test Field Trials on Vulcano / Viator Field Trials on FS Alkor** (Jakob Schwendner)
12:15 – 12:30	**URDF and SMURF robot models in Envire and Mars** (Raul Dominguez)
12:30 – 12:45	**Project FlatFish: Phase 1, Docking and planned work for Phase 2** (Christopher Gaudig, Sascha Arnold)
12:45 – 15:00	Lunch and Poster Session at the Foyer

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3.2 ‘Camera: Flat-Port Calibration’ (NP-T-02)

Alexander Duda[(1)]

(1) DFKI GmbH, Robotics Innovation Center, Robert-Hooke-Straße 1, 28359 Bremen, Germany

Contact: alexander.duda@dfki.de

Abstract

This talk gives an overview on the topic of camera flat port calibration. The often used pin hole camera model has its limitations when dealing with flat port underwater camera housings, which are often used because they are cheap and easy to manufacture in comparison with for example dome port or Rebikoff-Ivanoff based housings.

The talk will discuss a new flat port camera model, which allows for in-air calibration with promising results compared to in-water calibration using the conventional pin hole camera model.

Camera: Flat-Port Calibration

Alexander Duda

DFKI Bremen & Universität Bremen
Robotics Innovation Center
Director: Prof. Dr. Frank Kirchner
www.dfki.de/robotics
robotics@dfki.de

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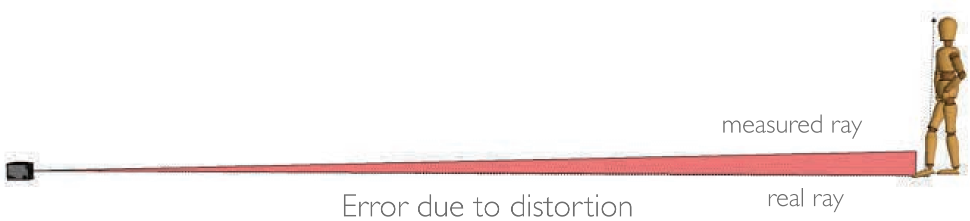
Why Calibration?

Objectives:

- accurate mapping between pixel and its 3D ray
- compensate non linear behavior of the camera optics



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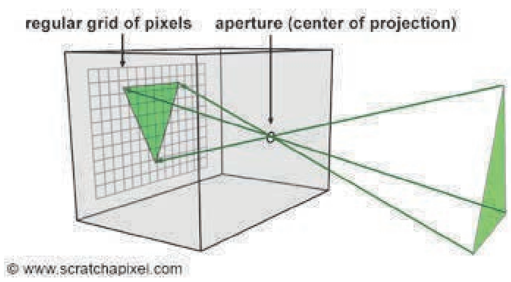
2

Pinhole Camera Model

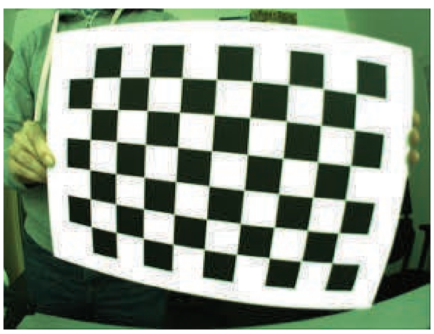


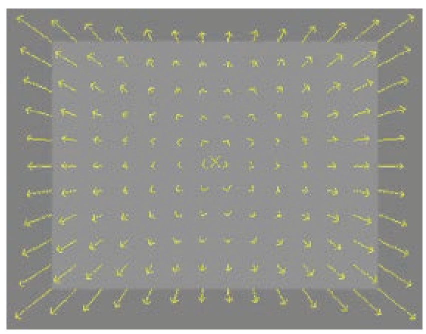
$$\begin{pmatrix} x \\ y \\ w \end{pmatrix} = P_{3\times 4} \begin{pmatrix} X \\ Y \\ Z \\ T \end{pmatrix}$$

$$P = KR[I \mid -\tilde{C}]$$

$$K = \begin{bmatrix} \alpha_x & & x_0 \\ & \alpha_y & y_0 \\ & & 1 \end{bmatrix}$$

Camera & Distortion


Distorted image


Inverse Distortion

Brown–Conrady Distortion Model

$$x_\mathrm{d} = x_\mathrm{u}(1 + K_1 r^2 + K_2 r^4 + \cdots) + (P_2(r^2 + 2x_\mathrm{u}^2) + 2P_1 x_\mathrm{u} y_\mathrm{u})(1 + P_3 r^2 + P_4 r^4 + \cdots)$$
$$y_\mathrm{d} = y_\mathrm{u}(1 + K_1 r^2 + K_2 r^4 + \cdots) + (P_1(r^2 + 2y_\mathrm{u}^2) + 2P_2 x_\mathrm{u} y_\mathrm{u})(1 + P_3 r^2 + P_4 r^4 + \cdots)$$

$(x_\mathrm{d},\ y_\mathrm{d})$ = distorted image point as projected on image plane using specified lens,
$(x_\mathrm{u},\ y_\mathrm{u})$ = undistorted image point as projected by an ideal pin-hole camera,
$(x_\mathrm{c},\ y_\mathrm{c})$ = distortion center (assumed to be the principal point),
$K_n = n^\mathrm{th}$ radial distortion coefficient,
$P_n = n^\mathrm{th}$ tangential distortion coefficient [note that Brown's original definition has P_1 and P_2 interchanged],
$r = \sqrt{(x_\mathrm{u} - x_\mathrm{c})^2 + (y_\mathrm{u} - y_\mathrm{c})^2}$, and

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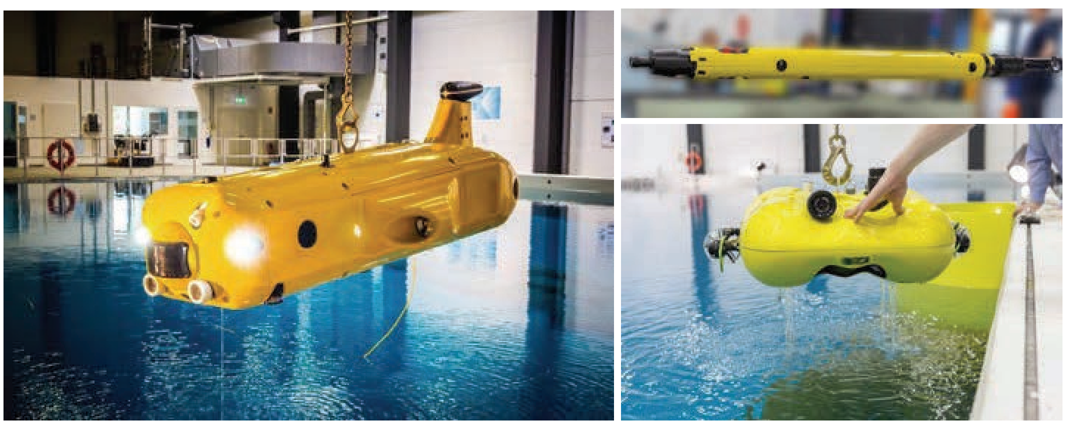
Distortion: Camera Housings



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Distortion: Camera Housings

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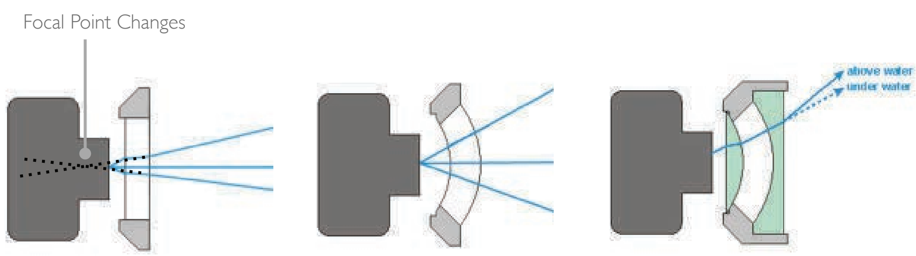
7

Camera Housings



Flat Port
- Washout colors
- Narrow field of view
- Objects appear bigger
- Cheap & simple to manufacture

Dome Port
- High precision is needed
- Focal point must be fixed
- Camera must focus a virtual image around 4r away.

Rebikoff-Ivanoff
- Works under and above water
- Not perfectly sharp
- Focus at real distance
- More depth of field

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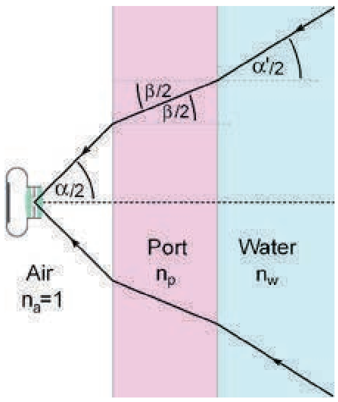
8

Light Refraction



Flat-Port Camera

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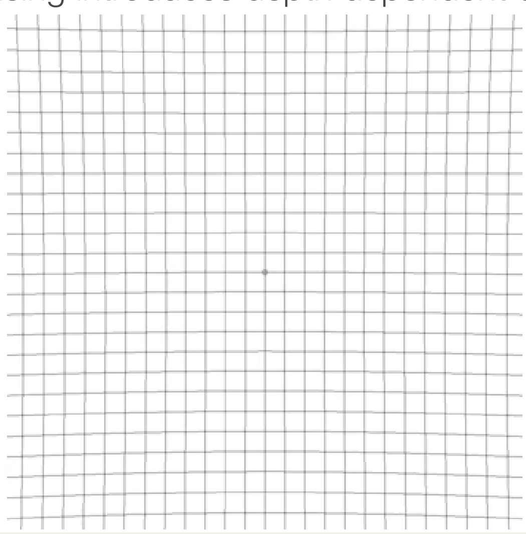
9

Flat-Port Distortion

Flat-Port housing introduces depth dependent distortion:



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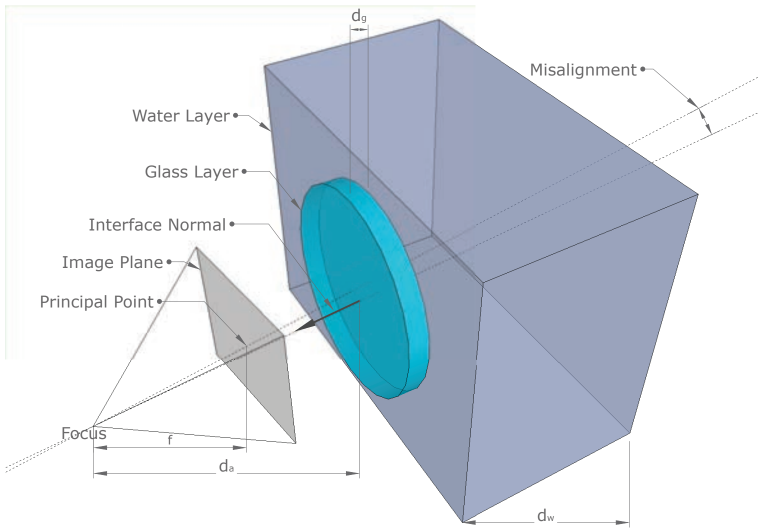
10

Flat Port Camera Model



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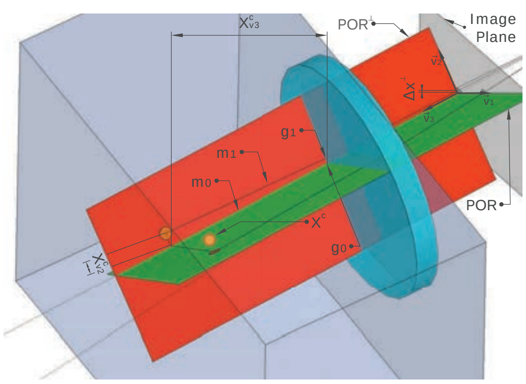
11

Flat Port Camera Model



$$\Delta x^{\perp} = \frac{X_{v2}}{d_a + \frac{X_{v3}}{\sqrt{X_{v3}^2+X_{v1}^2}}\left(X_{v3}\frac{n_a}{n_w} + d_g\frac{n_a}{n_g}\right)}$$

$$\Delta x^{\parallel} = \frac{(X_{v1} - X_{v3}m_0)\Delta}{g(x_0^{\parallel}+\Delta) - g_0 + X_{v3}(m(x_0^{\parallel}+\Delta, n_w) - m_0)}$$

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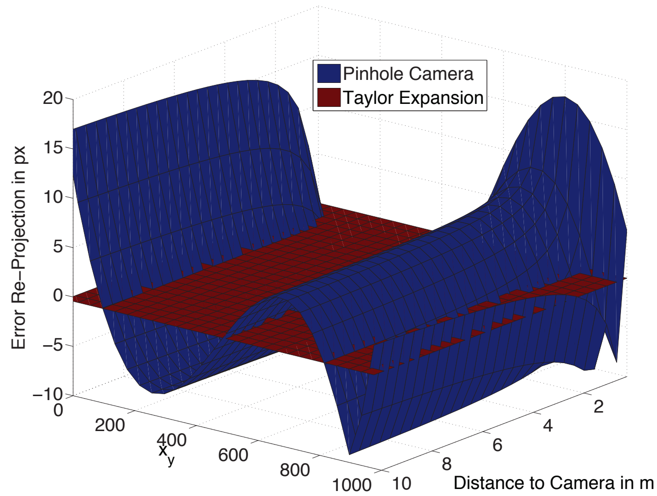
12

Flat-Port vs Pinhole Camera



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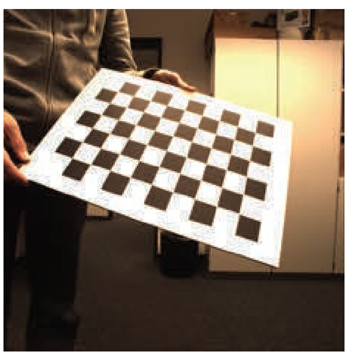
In air vs in water calibration



In air:

- sharp images
- good illumination
- chessboard pose can easily being changed

In water:

- blurred images
- bad illumination
- chessboard pose cannot easily being changed

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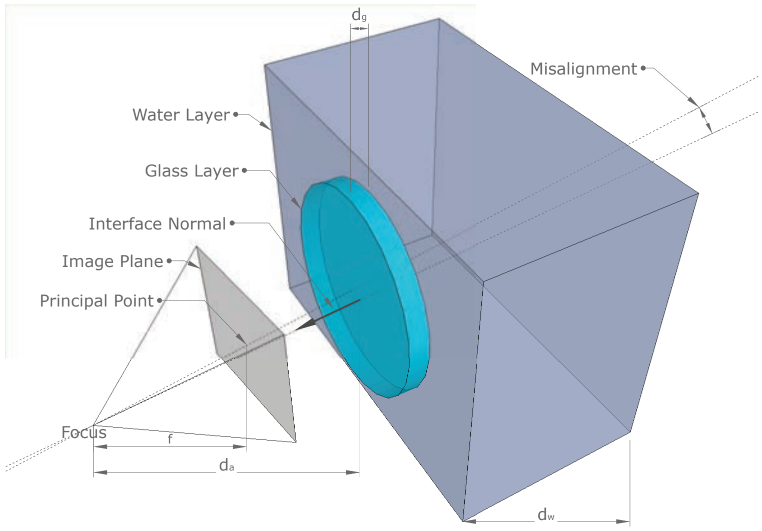
In air vs in water calibration



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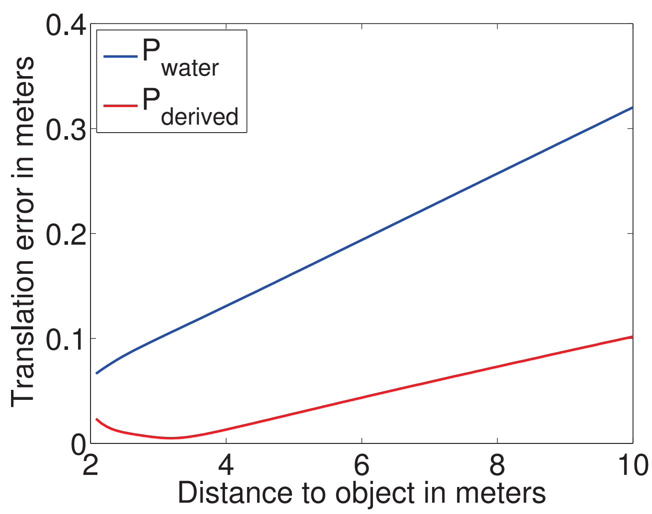
15

In air vs in water calibration



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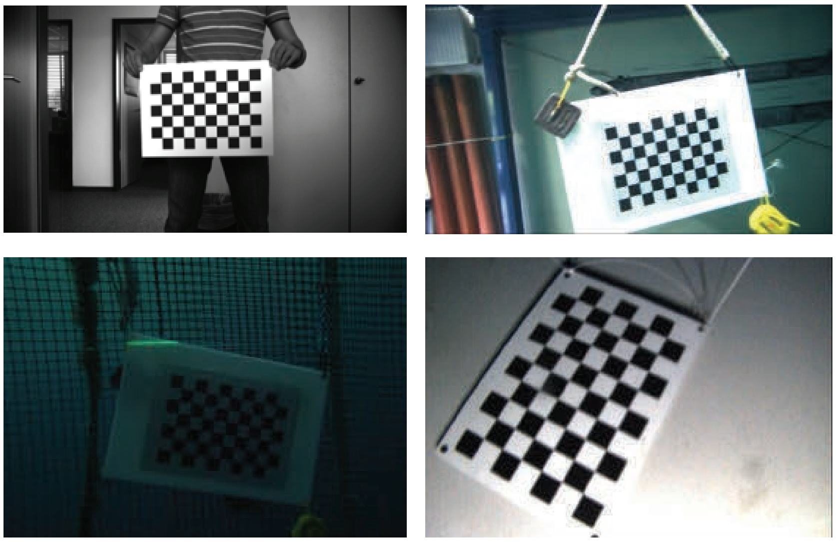
16

Calibration best practice



Examples of bad calibration images

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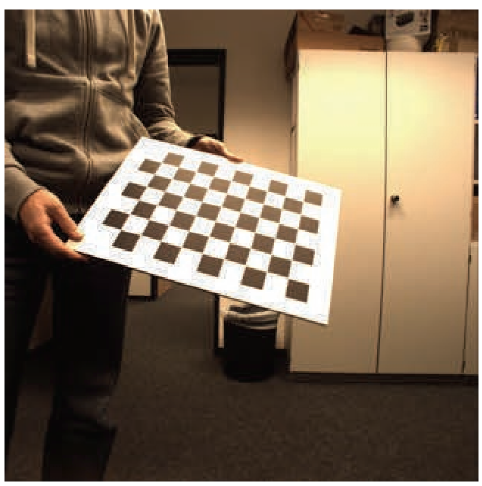
17

Calibration best practice



Example of a good calibration

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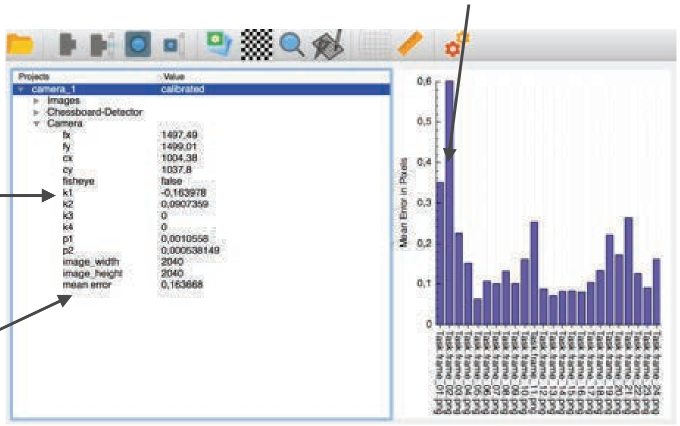
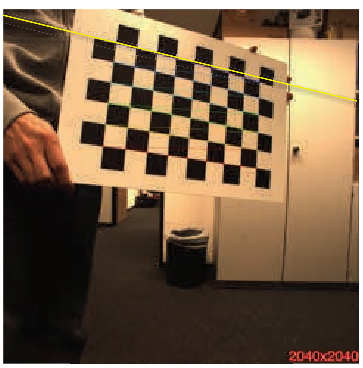
18

Calibration best practice



Example of a good calibration

Calibration best practice

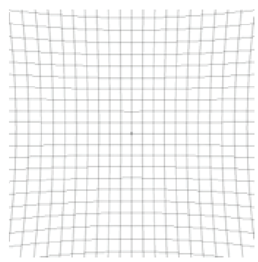


uncalibrated

calibrated

Conclusion

- Calibration is necessary to increase the accuracy between a 3D point/ray and its calculated projection onto the camera image.
- Underwater Flat Port cameras can be calibrated in air with an higher accuracy than in water due to better image quality.
- Not all images showing chessboards are suited for camera calibration.



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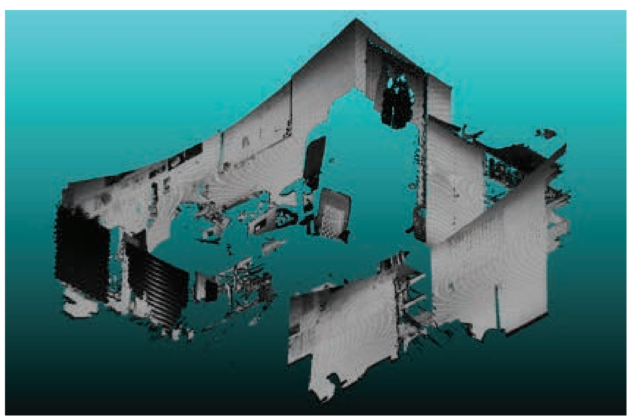
21

Thank you!



DFKI Bremen & Universität Bremen
Robotics Innovation Center
Director: Prof. Dr. Frank Kirchner
www.dfki.de/robotics
robotics@dfki.de

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[1] Wikipedia: The free encyclopedia. (2004, July 22). FL: Wikimedia Foundation, Inc. Retrieved August 10, 2004, from http://www.wikipedia.org

[2] Duda, A., Schwendner, J., & Gaudig, C. (2015). SRSL : Monocular Self-Referenced Line Structured Light. IEEE International Conference on Intelligent Robots and Systems (IROS).

[3] Institute, S. O. (2016). Schmidt Ocean Institute.

[4] Kwasnitschka, T., Jamieson, J., Köser, K., Marc, H., Gartman, A., Alexander, D., … Funganita, C. (2016). Virtual Vents. Retrieved from http://schmidtocean.org/cruise/virtual-vents-changing-face-hydrothermalism-revealed/

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[6] Agisoft PhotoScan @ www.agisoft.com. (n.d.). Retrieved from http://www.agisoft.com/

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3.3 ‘Velodyne/Fisheye-Camera Cross Calibration’ (NP-T-03)

Christoph Hertzberg[(1)]

(1) Universität Bremen, Arbeitsgruppe Robotik, Robert-Hooke-Straße 1, 28359 Bremen, Germany

Contact: `chtz@informatik.uni-bremen.de`

Abstract

This talk gives first insights into cross-calibration of a Velodyne LIDAR with two super-fisheye cameras. The remission values of the LIDAR allow to extract edge position of a checker board which allows to estimate its pose relative to the LIDAR. The same is possible with classical camera calibration, which in this talk is extended to super-fisheye cameras (i.e., cameras with an opening angle above 180 degrees) by proposing a new camera model.

Estimating all of the above simultaneously using non-linear least squares fitting allows to cross-calibrate the sensors positions and intrinsics.

Velodyne/Fisheye-Camera Cross Calibration

Christoph Hertzberg

DFKI Bremen & Universität Bremen
Robotics Innovation Center
Director: Prof. Dr. Frank Kirchner
www.dfki.de/robotics
robotics@dfki.de

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Summary

Velodyne Lidar
- Edge Extraction

Fisheye Camera
- Super Fisheye Lenses
- Open Issues

Cross Calibration
- How?

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Cross Calibration
September 22, 2016
2/8

Velodyne Lidar

Edge Extraction

- Each scanpoint returns distance and remission
- Large gradients in remission are likely edges
- Fit extracted edges to assumed position of chessboard

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Cross Calibration
September 22, 2016

3/8

Velodyne Lidar

Edge Extraction

- Each scanpoint returns distance and remission
- Large gradients in remission are likely edges
- Fit extracted edges to assumed position of chessboard

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Cross Calibration
September 22, 2016

3/8

Velodyne Lidar

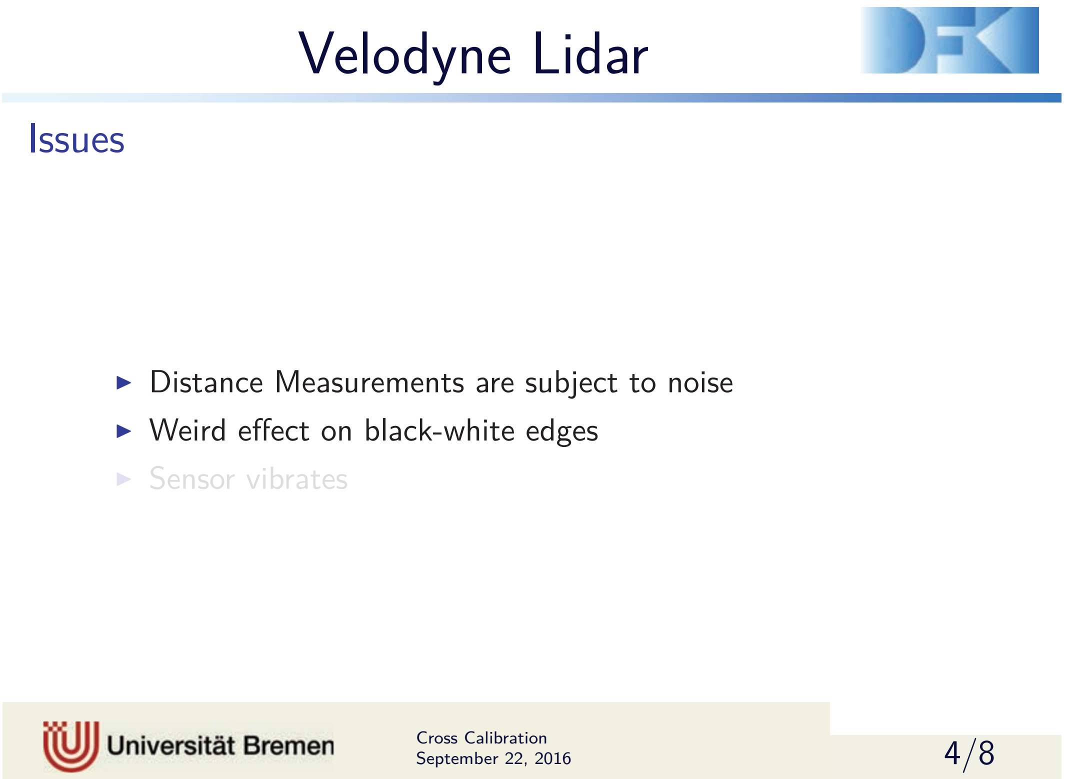
Edge Extraction

- Each scanpoint returns distance and remission
- Large gradients in remission are likely edges
- Fit extracted edges to assumed position of chessboard

Velodyne Lidar

Issues

- Distance Measurements are subject to noise
- Weird effect on black-white edges
- Sensor vibrates


Velodyne Lidar
Issues
► Distance Measurements are subject to noise
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► Sensor vibrates
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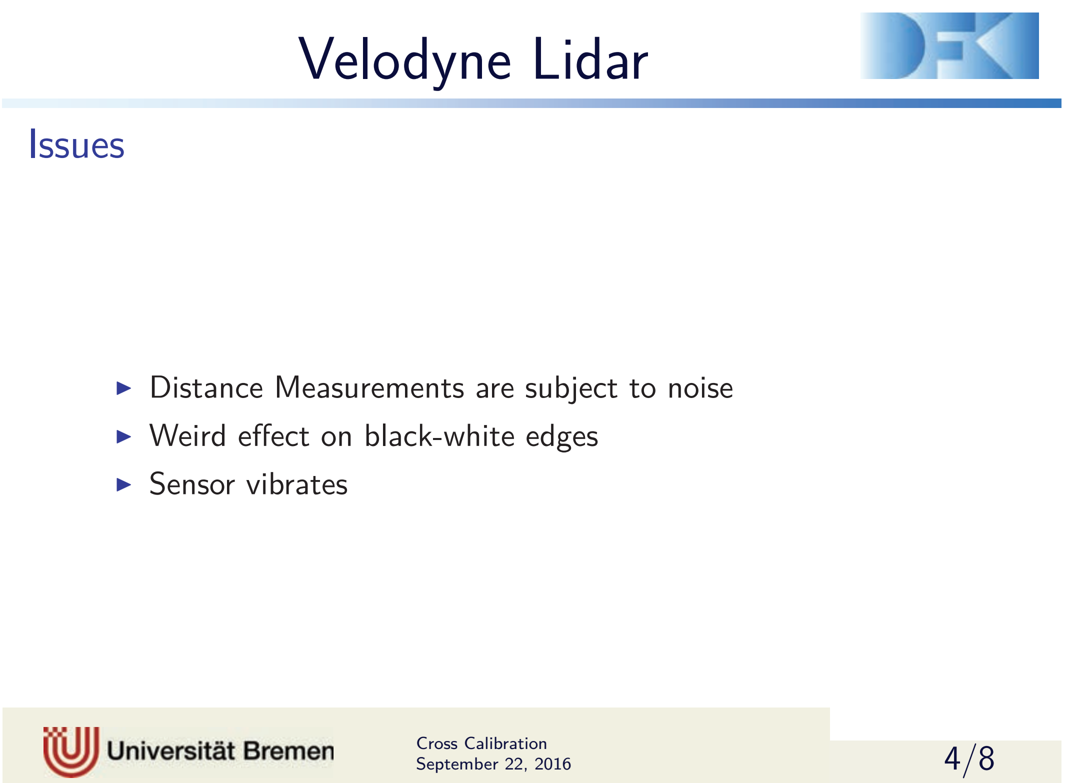
4/8


Velodyne Lidar
Issues
► Distance Measurements are subject to noise
► Weird effect on black-white edges
► Sensor vibrates
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Cross Calibration
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4/8

Fisheye Camera

Camera Model

- Problem: Standard pinhole model does not work with opening angles above 180 degrees $f([x,y,z]^\top) = \frac{1}{z}[x,y]$
- FishEyeModel: $f(x,y,z) = \text{atan2}(r,z)/r \cdot [x,y]$, with $r = \sqrt{x^2+y^2}$
- Pending Pull-Request to OpenCV

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Fisheye Camera

Camera Model

- Problem: Standard pinhole model does not work with opening angles above 180 degrees $f([x,y,z]^\top) = \frac{1}{z}[x,y]$
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Fisheye Camera

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- Pending Pull-Request to OpenCV

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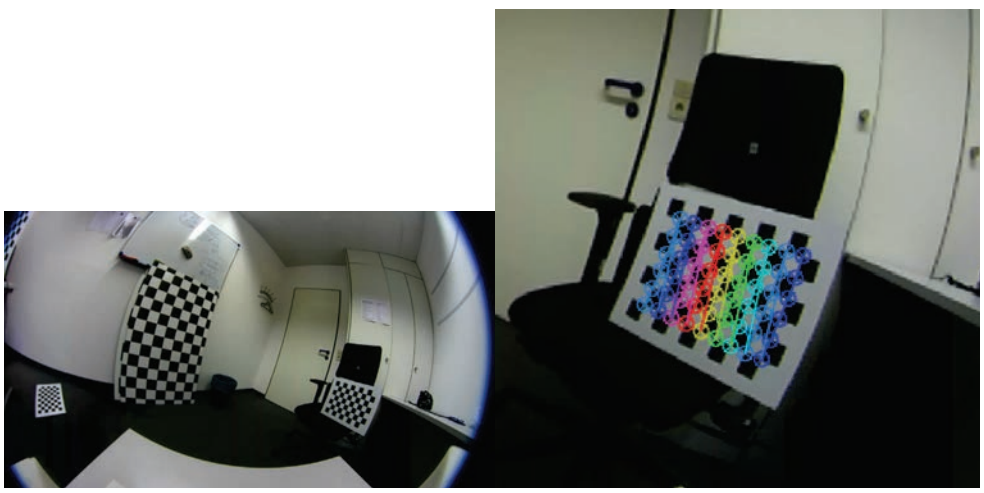
Fisheye Camera

Checkerboard Extraction



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Fisheye Camera

Open Issues

- Chromatic aberration
  - Different wavelengths are refracted differently
  - Effect is noticable near image borders
  - Could be compensated by calibrating channels separately

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Fisheye Camera

Open Issues

- Chromatic aberration
  - Different wavelengths are refracted differently
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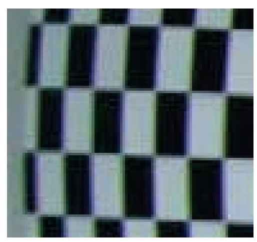

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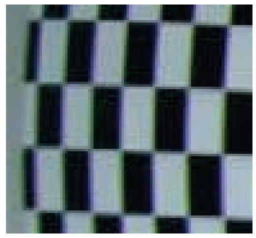
Fisheye Camera

Open Issues



- Chromatic aberration
  - Different wavelengths are refracted differently
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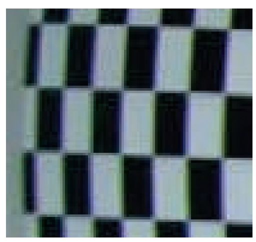
Fisheye Camera

Open Issues



- Chromatic aberration
  - Different wavelengths are refracted differently
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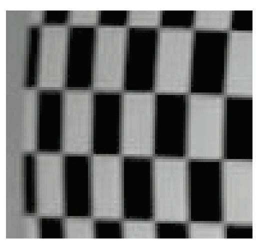

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Fisheye Camera

Open Issues

- Chromatic aberration
  - Different wavelengths are refracted differently
  - Effect is noticable near image borders
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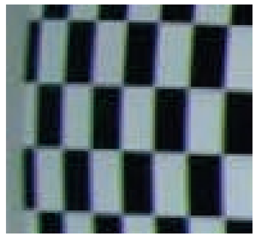

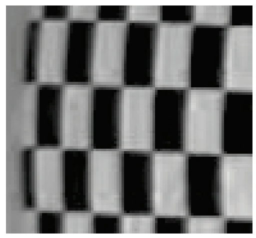

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Cross Calibration
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7/8

Cross Calibration

How to Cross Calibrate

- Unknown: Poses X_i and Calibration C
- Known: Measurement model $f(X, C)$
- Known: Actual measurements Z_i (subject to noise!)
- Solution: Least Squares Optimization of $\sum \|f(X_i, C) - Z_i\|^2$
- Start with initial guess and iteratively improve solution

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Cross Calibration
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Cross Calibration

How to Cross Calibrate

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Cross Calibration
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Cross Calibration

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Cross Calibration
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Cross Calibration

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Cross Calibration

How to Cross Calibrate

- Unknown: Poses X_i and Calibration C
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- Solution: Least Squares Optimization of $\sum \|f(X_i, C) - Z_i\|^2$
- Start with initial guess and iteratively improve solution

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3.4 ‘Dos and Don’ts of IMU / Magnetometer Placement on Robots’ (NP-T-01)

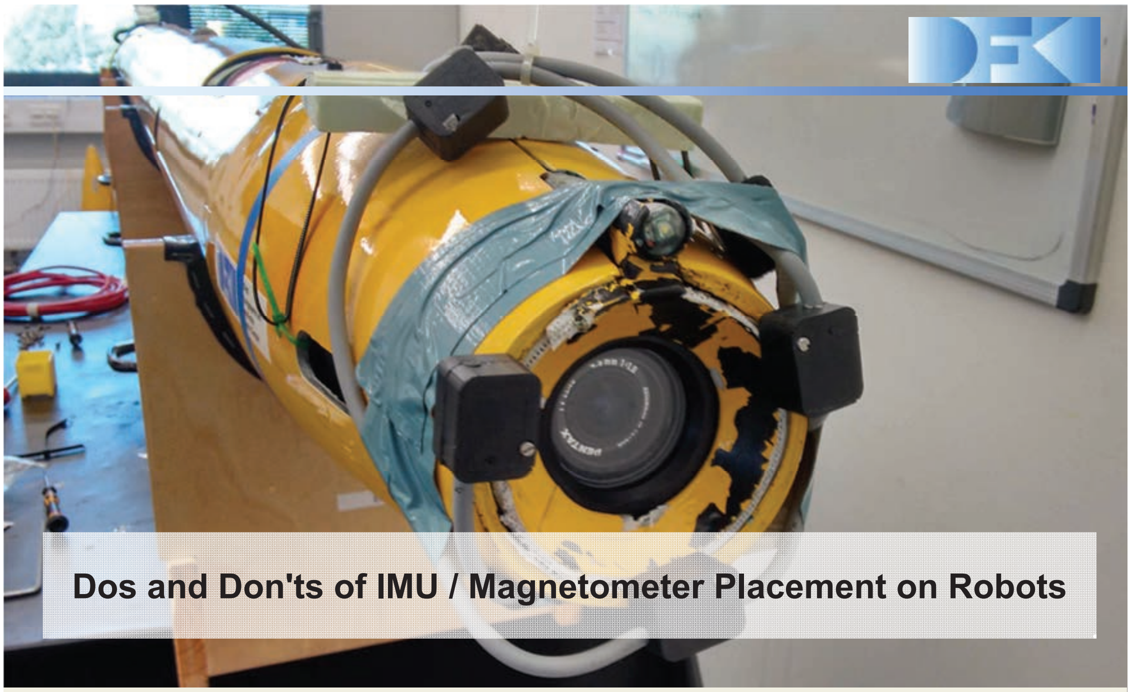
Leif Christensen[(1)]

(1) DFKI GmbH, Robotics Innovation Center, Robert-Hooke-Straße 1, 28359 Bremen, Germany

Contact: `leif.christensen@dfki.de`

Abstract

This talk gives an overview on the topic of placing Inertial Measurement Units integrating magnetometers on robots with restricted placement options. The talk will discuss the typical distortions we face when dealing with robotic systems and will try to give hints how to avoid these or lower their impact.



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Leif Christensen (DFKI Robotics Innovation Center)
AG Navigation & Planning Project Day Talk – 22.09.2016

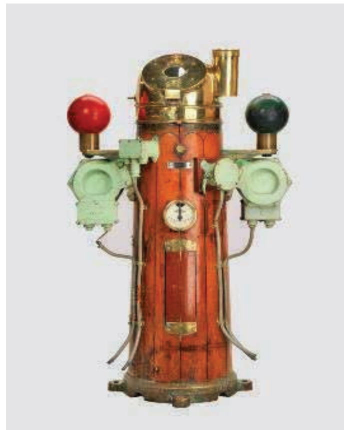
THE CHALLENGE (AKA THE PROBLEM)

Universität Bremen

Leif Christensen (DFKI Robotics Innovation Center)
AG Navigation & Planning Project Day Talk – 22.09.2016

Local Disturbances / Deviation

- „Robots have bodies“ -> unfortunately in this case, since we need to subtract deviation of local body frame from external field
- Local static disturbances
  - Permanent magnetism („Hard Iron“)
  - Induced magnetism („Soft Iron“)
  - Depending on permeability μ_r
- Local dynamic disturbances
  - Electromagnetism



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Leif Christensen (DFKI Robotics Innovation Center)
AG Navigation & Planning Project Day Talk – 22.09.2016

Susceptibility / Relative Permeability

- Magnetic Remanence
- Ferromagnetism
- Ferrimagnetism
- Paramagnetism
- Diamagnetism

Relative permeability and magnetic susceptibility [edit]

Relative permeability, sometimes denoted by the symbol μ_r, is the ratio of the permeability of a specific medium to the permeability of free space μ_0:

$$\mu_r = \frac{\mu}{\mu_0},$$

where $\mu_0 = 4\pi \times 10^{-7}$ N A^{-2}. In terms of relative permeability, the magnetic susceptibility is

$$\chi_m = \mu_r - 1.$$

The number χ_m is a dimensionless quantity, sometimes called *volumetric* or *bulk* susceptibility, to distinguish it from χ_p (*magnetic mass* or *specific* susceptibility) and χ_M (*molar* or *molar mass* susceptibility).

Magnetic susceptibility and permeability data for selected materials

Medium	Susceptibility χ_m (volumetric SI)	Permeability μ [H/m]	Relative permeability μ/μ_0
Metglas 2714A (annealed)		1.26×10^{0}	1 000 000[7]
Iron (99.95% pure Fe annealed in H)		2.5×10^{-1}	200 000[8]
NANOPERM®		1.0×10^{-1}	80 000[9]
Mu-metal		6.3×10^{-2}	50 000[11]
Mu-metal		2.5×10^{-2}	20 000[10]
Cobalt-Iron (high permeability strip material)		2.3×10^{-2}	18 000[12]
Permalloy	8000	1.0×10^{-2}	8000[10]
Iron (99.8% pure)		6.3×10^{-3}	5000[8]
Electrical steel		5.0×10^{-3}	4000[10]
Platinum		1.256970×10^{-6}	1.000 265
Aluminum	2.22×10^{-5}[18]	1.256665×10^{-6}	1.000 022
Wood		$1.25663760 \times 10^{-6}$	1.000 000 43[16]
Air		$1.25663753 \times 10^{-6}$	1.000 000 37 [17]
Teflon		1.2567×10^{-6}[10]	1.0000
Hydrogen	-2.2×10^{-9}[18]	1.2566371×10^{-6}	1.000 0000
Sapphire	-2.1×10^{-7}	1.2566368×10^{-6}	0.999 999 76
Copper	-6.4×10^{-6} or -9.2×10^{-6}[18]	1.256629×10^{-6}	0.999 994
Water	-8.0×10^{-6}	1.256627×10^{-6}	0.999 992
Bismuth	-1.66×10^{-4}	1.25643×10^{-6}	0.999 834
Ferritic stainless steel (annealed)		$1.26 \times 10^{-3} - 2.26 \times 10^{-3}$	1000–1800[13]
Martensitic stainless steel (annealed)		$9.42 \times 10^{-4} - 1.19 \times 10^{-3}$	750–950[13]
Ferrite (manganese zinc)		$>8.0 \times 10^{-4}$	640 (or more)
Nickel		$1.26 \times 10^{-4} - 7.54 \times 10^{-4}$	100[13] – 600
Carbon Steel		1.26×10^{-4}	100[13]
Martensitic stainless steel (hardened)		$5.0 \times 10^{-5} - 1.2 \times 10^{-4}$	40–95[13]
Ferrite (nickel zinc)		$2.0 \times 10^{-5} - 8.0 \times 10^{-4}$	16–640
Neodymium magnet		1.32×10^{-6}	1.05[15]
Austenitic stainless steel		$1.260 \times 10^{-6} - 8.8 \times 10^{-6}$	1.003–7 [13][14] [note 1]
Vacuum	0	$4\pi \times 10^{-7}$ (μ_0)	1, exactly[19]
Concrete (dry)			1[18]
Superconductors	−1	0	0

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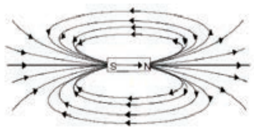
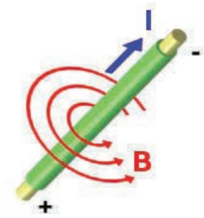
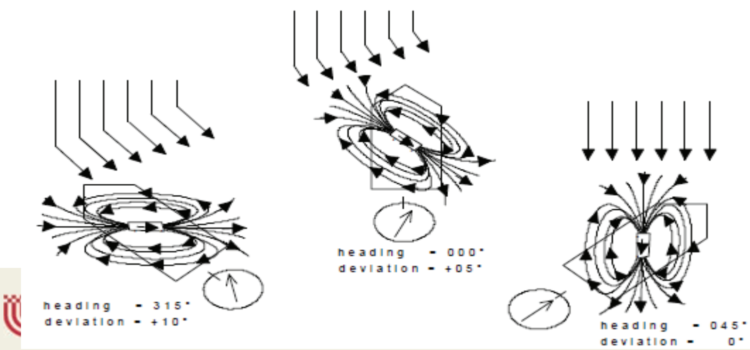
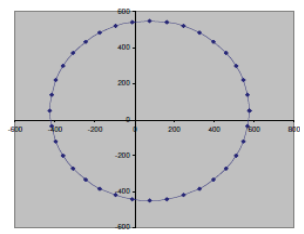
Hard Iron / Electromagnetic Effect

- Caused by magnetic material or electromagnetic field
- Permanent constant offset
- E.g. a magnet or current flowing through a wire



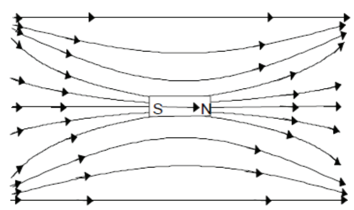


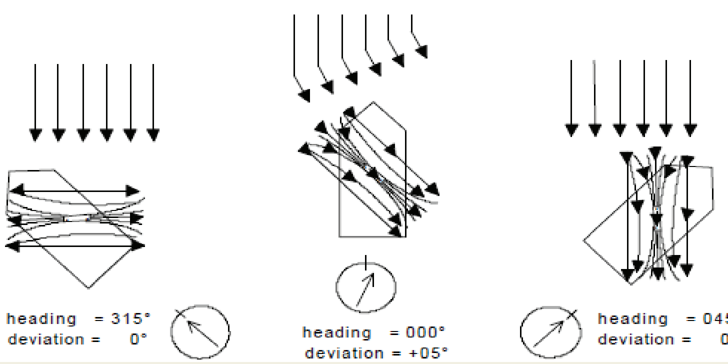


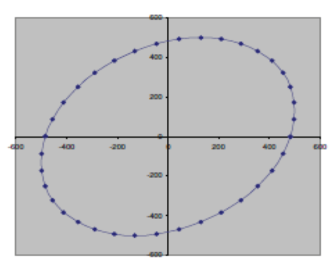


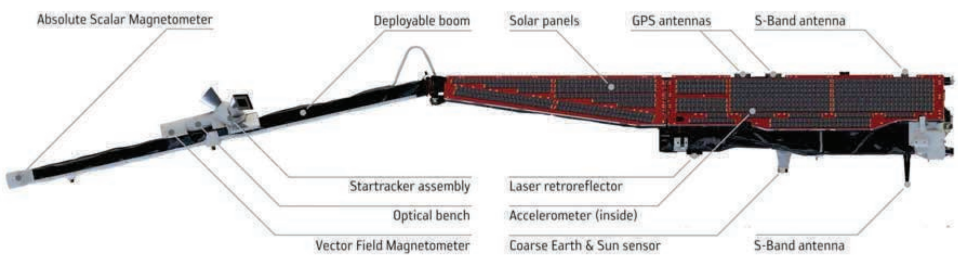
Soft Iron Effect

- Induced magnetism
- While external field is applied
- Path of lower impedance









IMU / MAGNETOMETER PLACEMENT

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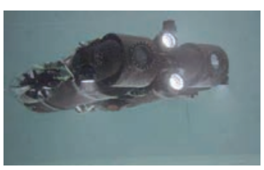
System Distortions - Dynamic



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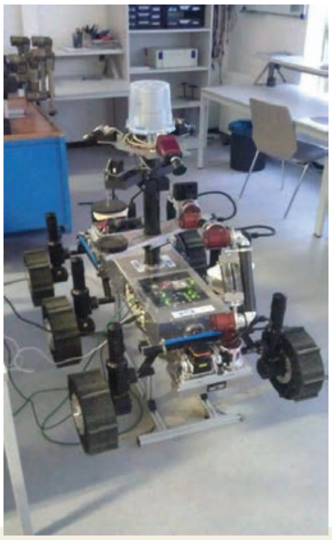
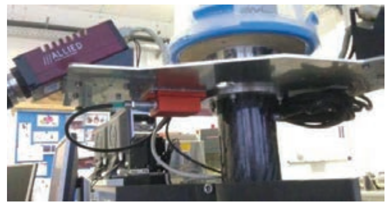
Dynamic Distortions - SpaceBot





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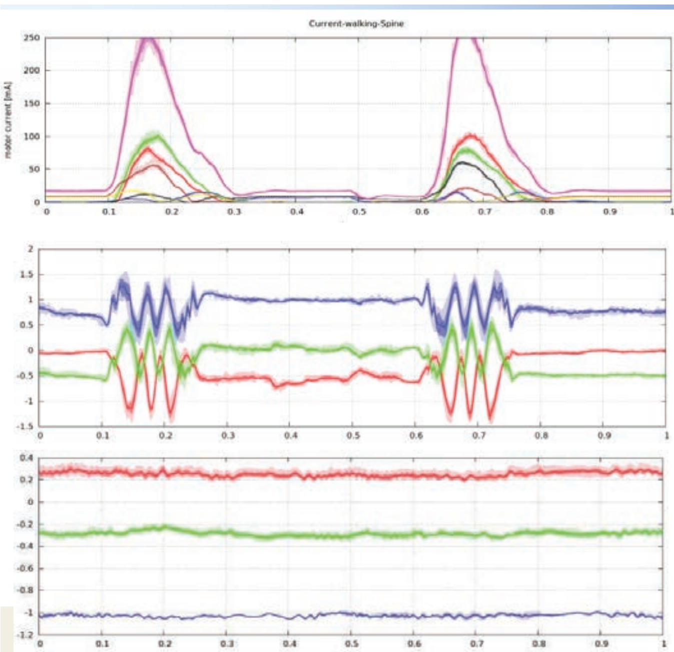
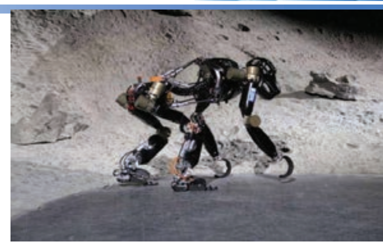
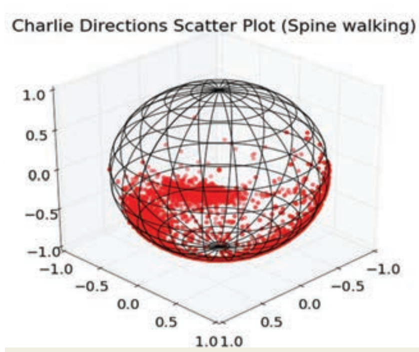
Dynamic Distortions - Charlie







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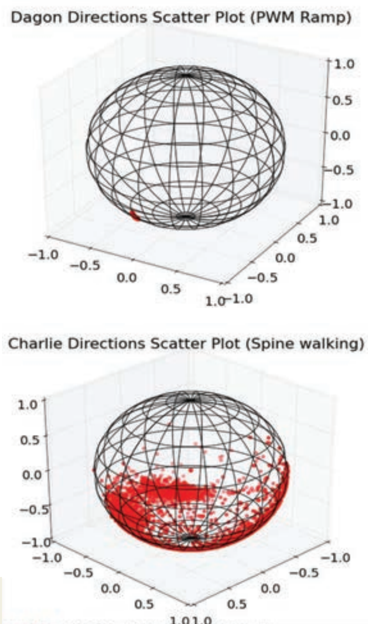
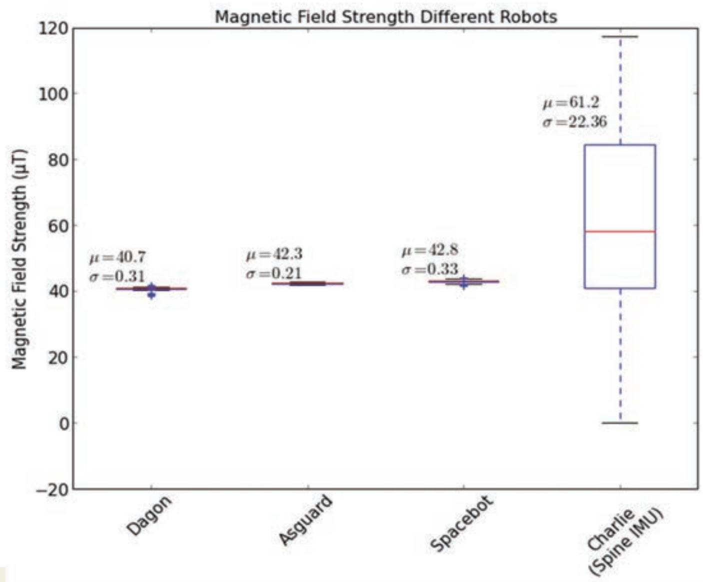
System Distortion - Dynamic





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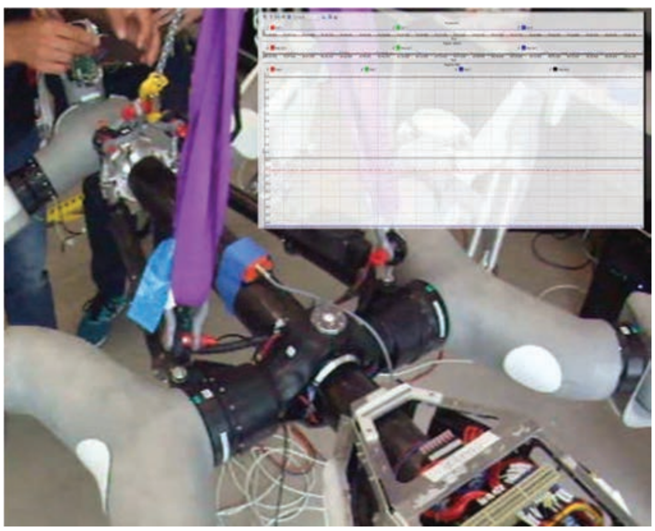
Mantis



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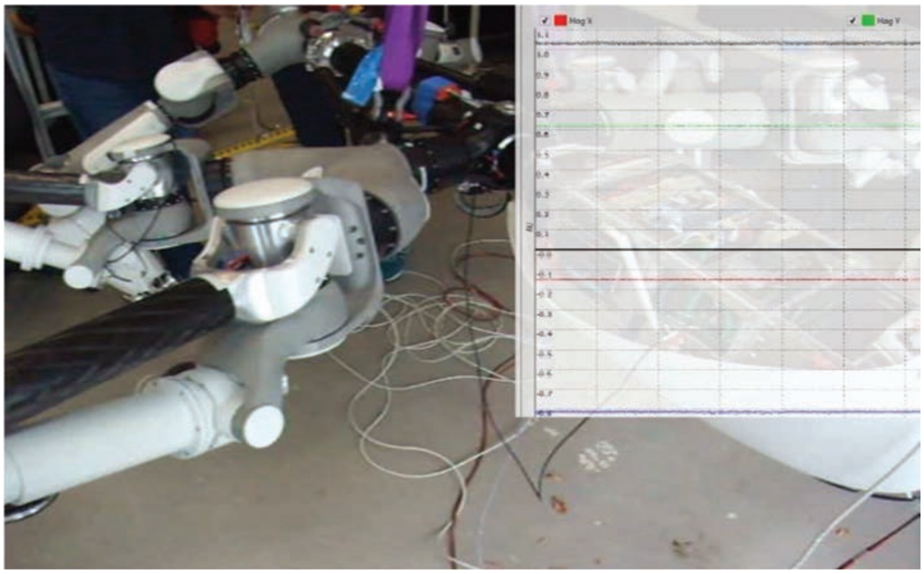
Mantis



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After proper placement:

CALIBRATION & COMPENSATION

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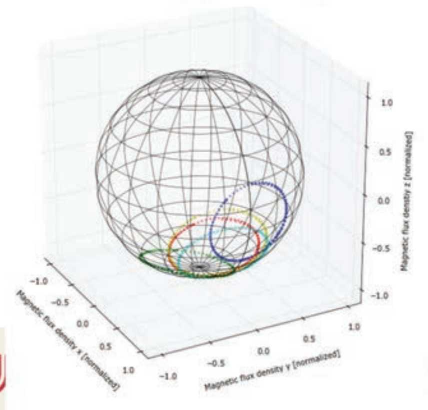
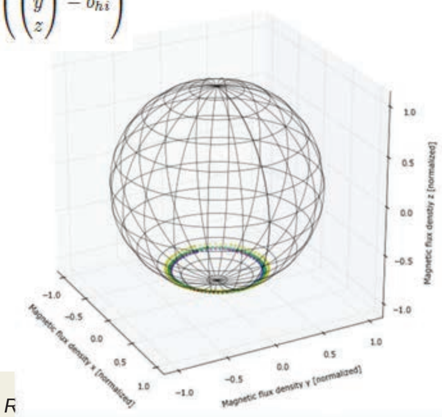
Compensation & Alignment

$$\mathbf{v}_{\mathrm{rot}} = \mathbf{v}\cos\theta + (\mathbf{k}\times\mathbf{v})\sin\theta + \mathbf{k}(\mathbf{k}\cdot\mathbf{v})(1-\cos\theta) \longrightarrow \mathbf{K} = \begin{bmatrix} 0 & -k_3 & k_2 \\ k_3 & 0 & -k_1 \\ -k_2 & k_1 & 0 \end{bmatrix}$$

$$\mathbf{M}_{\mathrm{align}} = \mathbf{I} + (\sin\theta)\mathbf{K} + (1-\cos\theta)\mathbf{K}^2$$

$$\begin{pmatrix}\hat{x}\\ \hat{y}\\ \hat{z}\end{pmatrix} = M_{align}\cdot\begin{pmatrix} sc_x & 0 & 0\\ 0 & sc_y & 0\\ 0 & 0 & sc_z\end{pmatrix}\cdot M_{si}\cdot\left(\begin{pmatrix}x\\ y\\ z\end{pmatrix} - b_{hi}\right)$$





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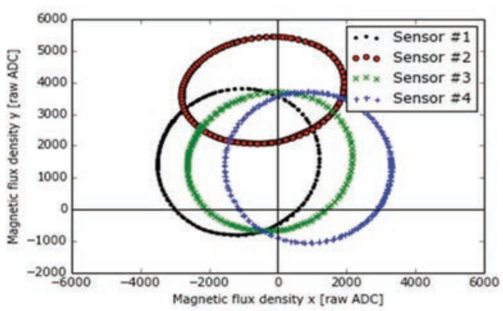
Why we should always calibrate

$$\begin{pmatrix}\hat{x}\\ \hat{y}\\ \hat{z}\end{pmatrix} = M_{align}\cdot\begin{pmatrix} sc_x & 0 & 0\\ 0 & sc_y & 0\\ 0 & 0 & sc_z\end{pmatrix}\cdot M_{si}\cdot\left(\begin{pmatrix}x\\ y\\ z\end{pmatrix} - b_{hi}\right)$$

$$b_{hi} = \begin{pmatrix} x_{hi} & y_{hi} & z_{hi}\end{pmatrix}^T$$



Magnetometer Readings (xy-plane) during 360° turn – Crawler Wally

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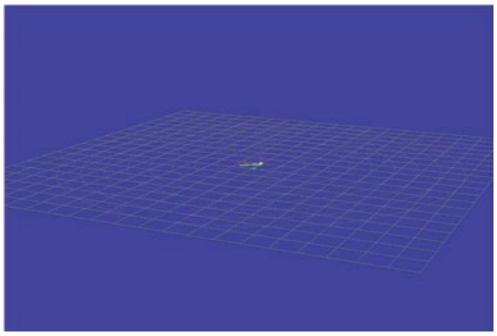
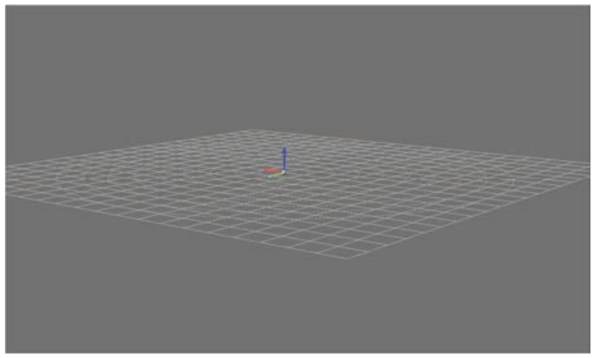
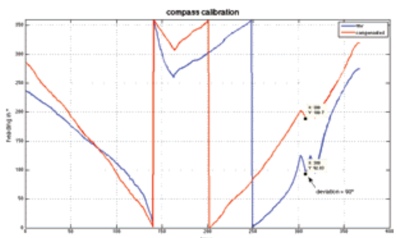
Wally Uncalibrated / Calibrated







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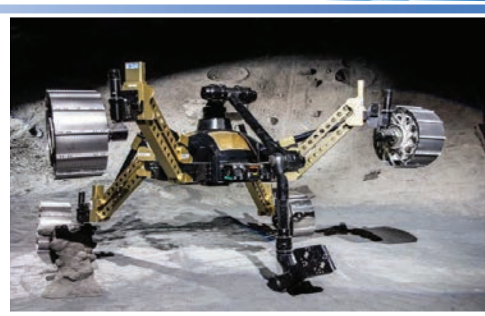
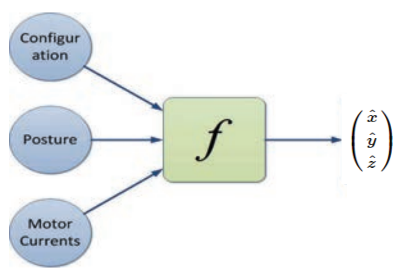
Dynamic Magnetic Distortion Model

- Dynamically changing
  - Different currents
  - Different postures
  - Different configurations
- Too complex to establish analytical model
- Known proprioceptive data
- ML – Support Vector Regression





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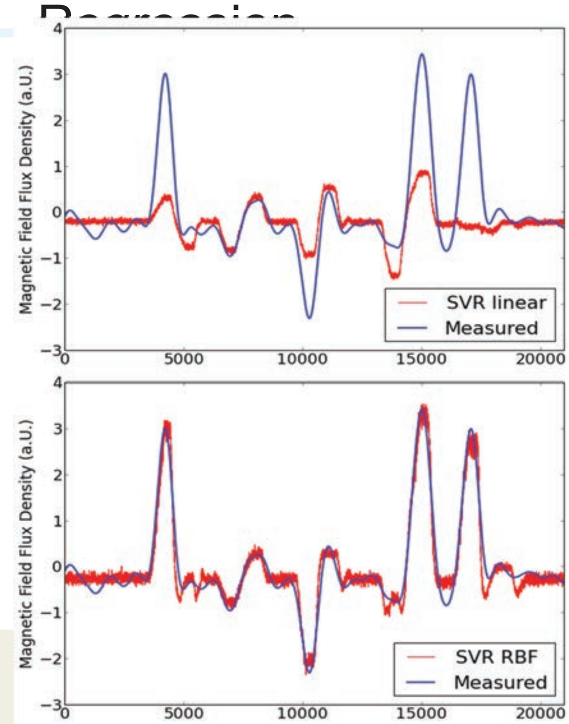
Distortion Model – Support Vector Regression



- Linear kernel
  - R^2-score: 0.29
- RBF kernel
  - R^2-score: 0.94
- Component-wise prediction
- Hyper-parameter tuning using grid_score)
  - R^2-score: 0.97

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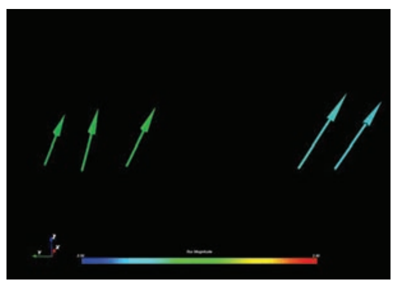
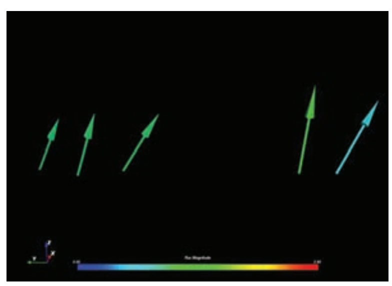
vMF Consensus Filter

- Online compensation
- Another approach: ML (SVR)
  - Needs realtime access to internal state data
- Here: Filter approach
- Local distortion assumption
- Probabilitstic consensus approach





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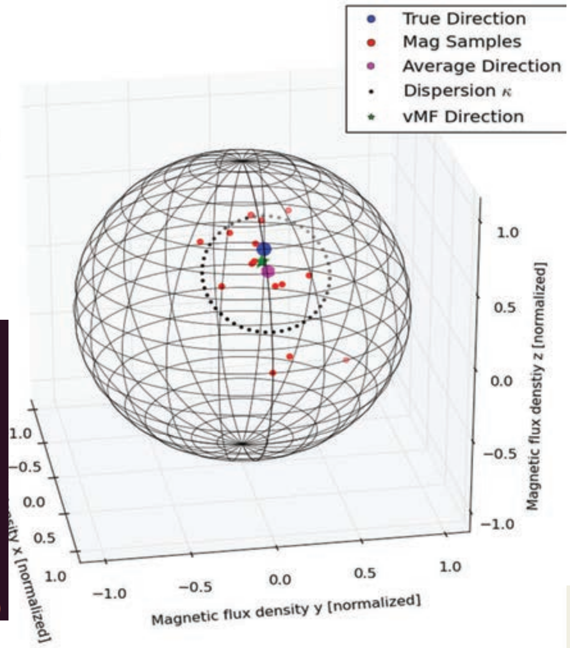
vMF Consensus Filter

function DYNAMIC_FILTER
  for $i \leftarrow 1$ **to** n **do**
    $x_i \leftarrow readout\_magnetometer(i)$
  end for
  $\mu_{st}, \sigma \leftarrow$ mean and std of strength (L2 norm)
  $\mu_{dir}, \kappa \leftarrow$ mean and concentration parameter of vMF distribution
  $w_i \leftarrow p(x_i|\mu_{st}, \sigma) p(x_i|\mu_{dir}, \kappa)$
  return normalized weighted sum of x
end function

```
In [45]: vmf.filter(a_with_outs,debug_output=True)
00: 0.78
01: 0.98
02: 1.29
03: 2.06
04: 0.59
05: 1.47
06: 0.56
07: 2.05
08: 2.06
09: 1.03
10: 2.02
11: 1.71
12: 0.14
13: 0.05
14: 0.29
Out[45]: array([ 0.76091214, -0.02186422,  0.64848644])
```



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„Do's & Don'ts" / Points to consider

- Placement / Material Choise
  - Keep away from ferromagnetic material
  - Keep away from moving parts
  - Keep away from material with $\mu_r > 1$
  - Keep away from main power supply
- Do validate on System
  - Consider environment
  - Check static and dynamic case
- Do calibrate
- Apply filters
  - Low pass for magnetic fields AC parts
  - Multi sensor consensus filtering (e
- Compensate
  - If knowledge about system state available
  - Establish learning function / LUT
  - Learning

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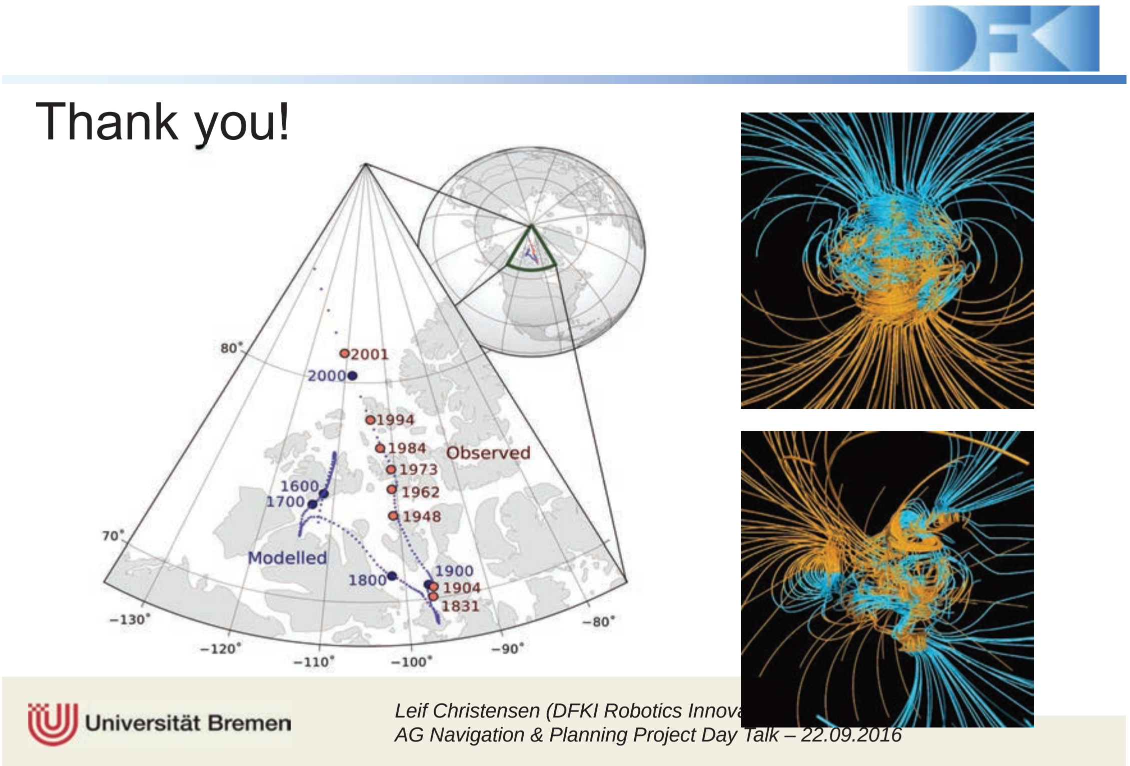
Thank you!
80°
70°
2001
2000
1994
1984
Observed
1973
1962
1948
1600
1700
Modelled
1800
1900
1904
1831
−130°
−120°
−110°
−100°
−90°
−80°
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3.5 'EuropaExplorer: Project Review and Future Work' (NP-T-05)

Marc Hildebrandt[(1)]

(1) DFKI GmbH, Robotics Innovation Center, Robert-Hooke-Straße 1, 28359 Bremen, Germany

Contact: marc.hildebrandt@dfki.de

Abstract

In this presentation the project Europa-Explorer is recapped. Having been recently finished with a very successful final demonstration of the complete team of IceShuttle, AUV Leng and Microgliders in the RIC's test basin the planning now has started for future work with these systems. These ideas and topics will be discussed.

EurEx

Europa-Explorer - Vorbereitung einer Mission zum Jupitermond Europa

Projekttag Nav-Plan
22.09.2016

DFKI Bremen & Universität Bremen
Robotics Innovation Center
Director: Prof. Dr. Frank Kirchner
www.dfki.de/robotics
robotics@dfki.de

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Projektziele

- Vorbereitung einer Mission zum Jupitermond Europa
  → **Missionskonzept**
- Machbarkeitsnachweis einer möglichen Mission in einem terrestrischen Szenario
- **Sichere Navigation** unter Eis
  - Langzeitautonomie
  - Autonomes Eisbohren mit Nutzlast
  - Aufbau einer Navigationsinfrastruktur unter der Eisdecke
- Aufbau eines funktionsfähigen **Demonstrationssystems** aus AUV und Eisbohrer

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2


Missionskonzept
DFKI - EuropaExplorer - DLR
EurEx
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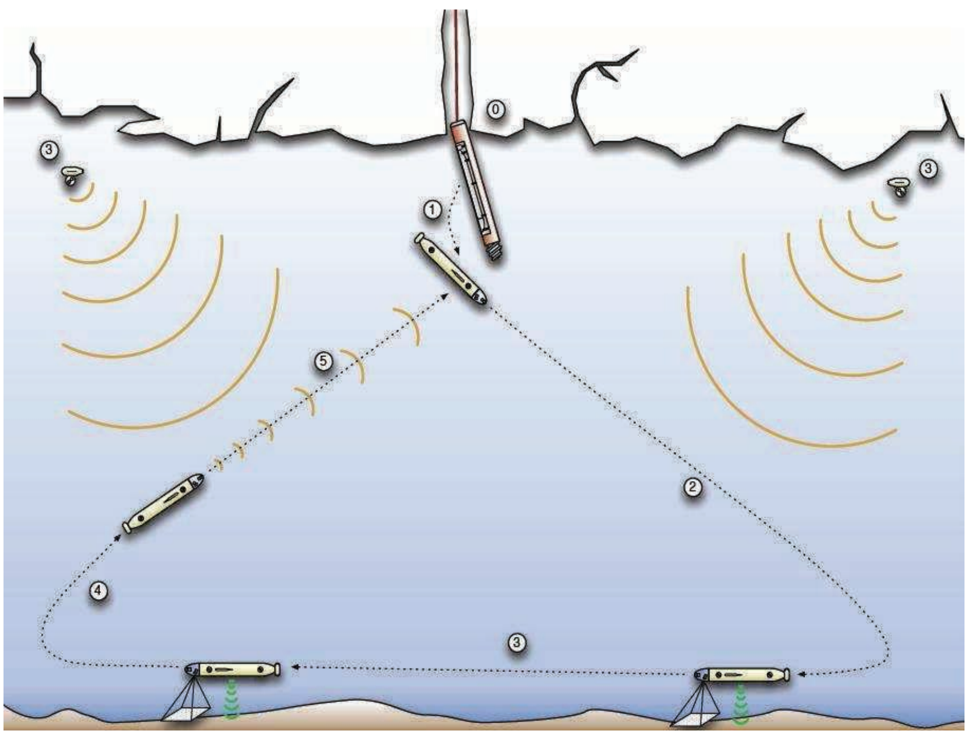
3


0
1
2
3
4
5

Europa-Explorer

Video

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5

AUV

(Autonomous Underwater Vehicle)

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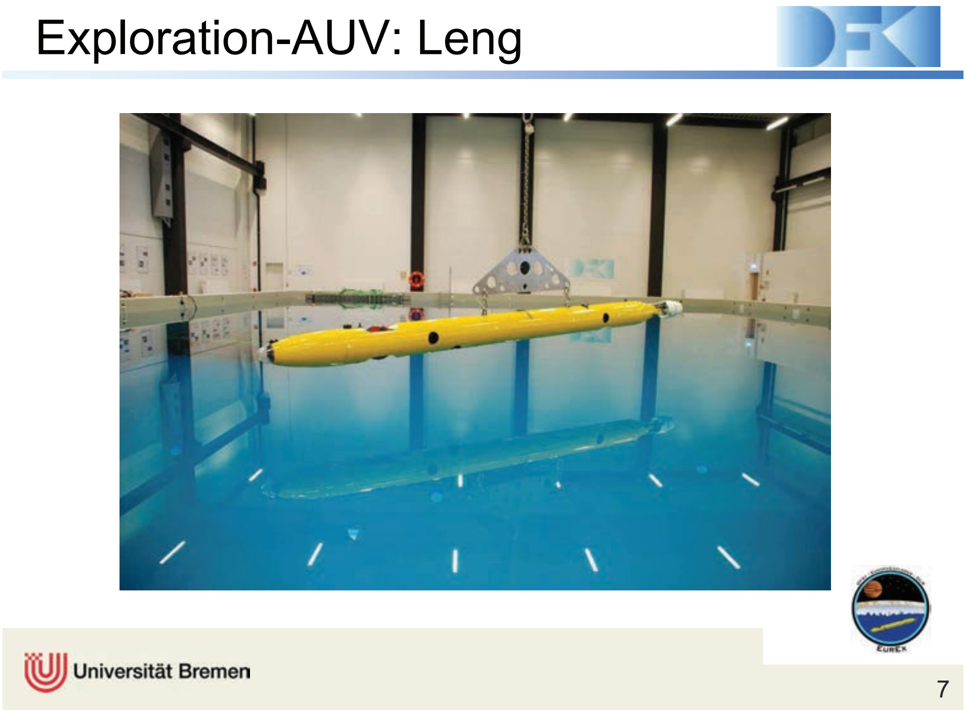
6


Exploration-AUV: Leng
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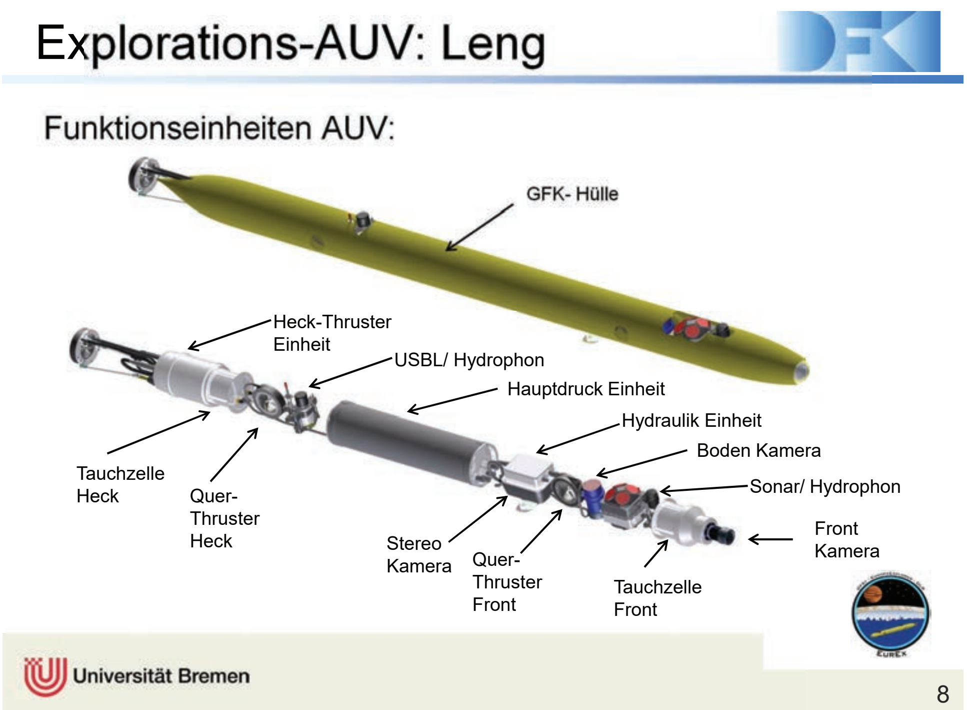
7


Explorations-AUV: Leng
Funktionseinheiten AUV:
GFK- Hülle
Heck-Thruster
Einheit
USBL/ Hydrophon
Hauptdruck Einheit
Hydraulik Einheit
Boden Kamera
Sonar/ Hydrophon
Front
Kamera
Tauchzelle
Heck
Quer-
Thruster
Heck
Stereo
Kamera
Quer-
Thruster
Front
Tauchzelle
Front
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8

IceShuttle

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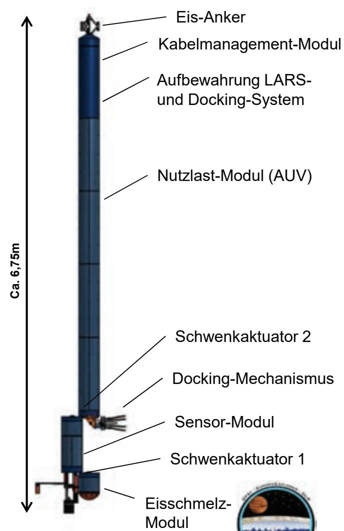
9

IceShuttle

- Anforderungen:
  - **Transport** des AUVs durch einen Eispanzer
  - Dauerhaftes Halten der finalen Position
  - **Ausbringen** und starten des AUVs
  - Bereitstellung zusätzliche **Navigations-Systeme** für das AUV (USBL, CTD, akustischer Pinger)
  - **Docking-Schnittstelle** AUV
  - Aufnehmen und **reintegrieren** des AUV ins Transport-Modul (Anforderung: terrestr. Szenario)
  - **Größenbeschränkung** (Abhängigkeit zwischen benötigter Schmelzleistung und Baugröße)
  - **Entfaltung (kompaktes System)**
- Hauptanforderungen:
  - *Integration eines hochautonomen AUVs in eine Eisschmelzsonde*
  - *Demonstration des vollen Missionsumfangs*



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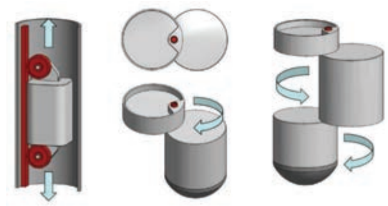
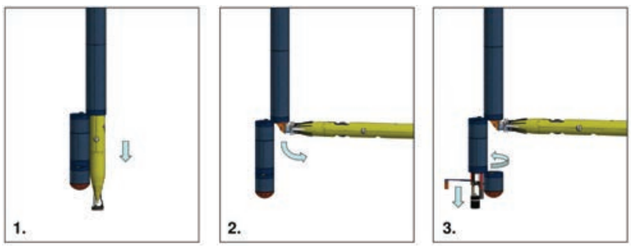
Entfalten & Ausbringen - Strategie

1. Aktives lineares verfahren "Aufzug"
2. Verschwenken um exzentrische Achse
3. Seriell hintereinander geschaltete Schwenkeinheiten
   → axial hintereinander gestaffelte Komponenten können ausgebracht werden





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Navigation

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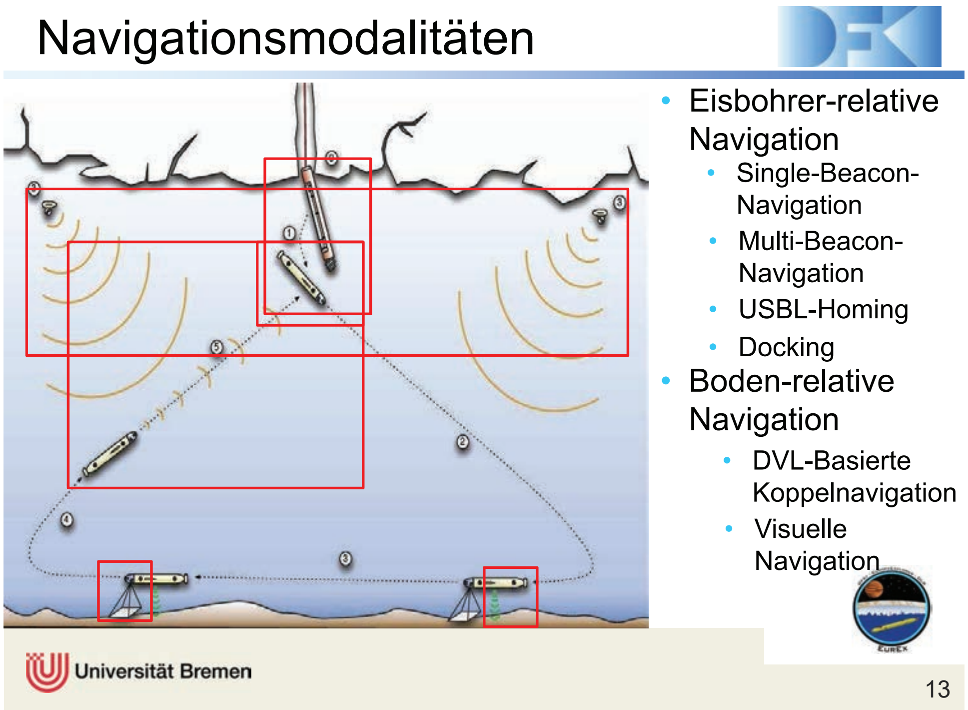
12


Navigationsmodalitäten
• Eisbohrer-relative Navigation
• Single-Beacon-Navigation
• Multi-Beacon-Navigation
• USBL-Homing
• Docking
• Boden-relative Navigation
• DVL-Basierte Koppelnavigation
• Visuelle Navigation
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DFKI - EuropaExplorer - DLR
Demoszenario
Überblick
EurEx
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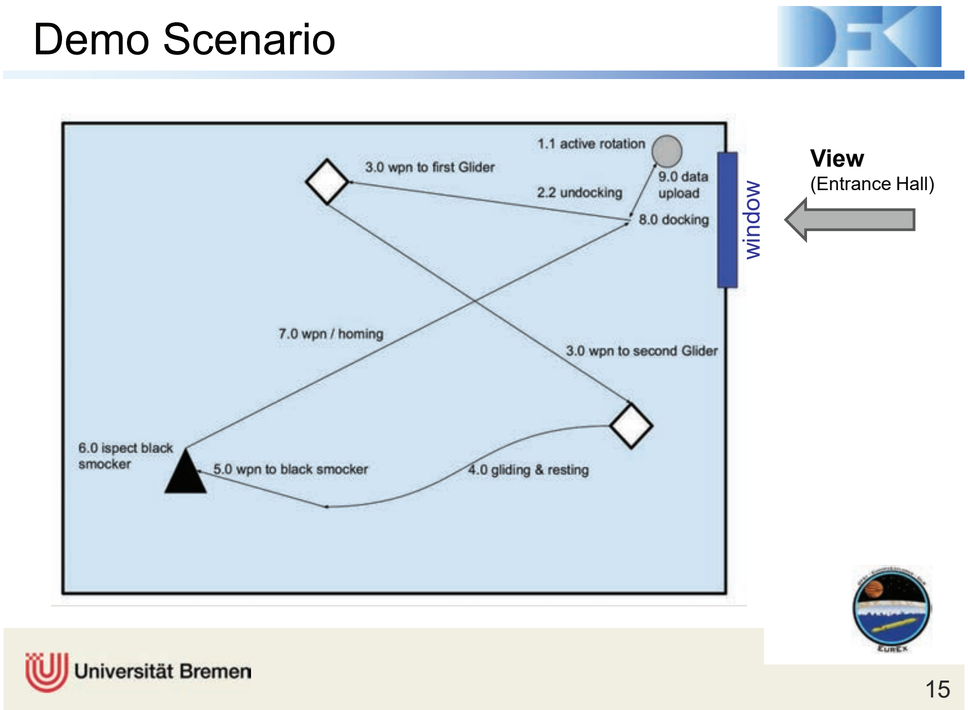
14


Demo Scenario
1.1 active rotation
3.0 wpn to first Glider
9.0 data upload
2.2 undocking
8.0 docking
window
View
(Entrance Hall)
7.0 wpn / homing
3.0 wpn to second Glider
6.0 ispect black smocker
5.0 wpn to black smocker
4.0 gliding & resting
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EurEx II
Überblick
EUREX
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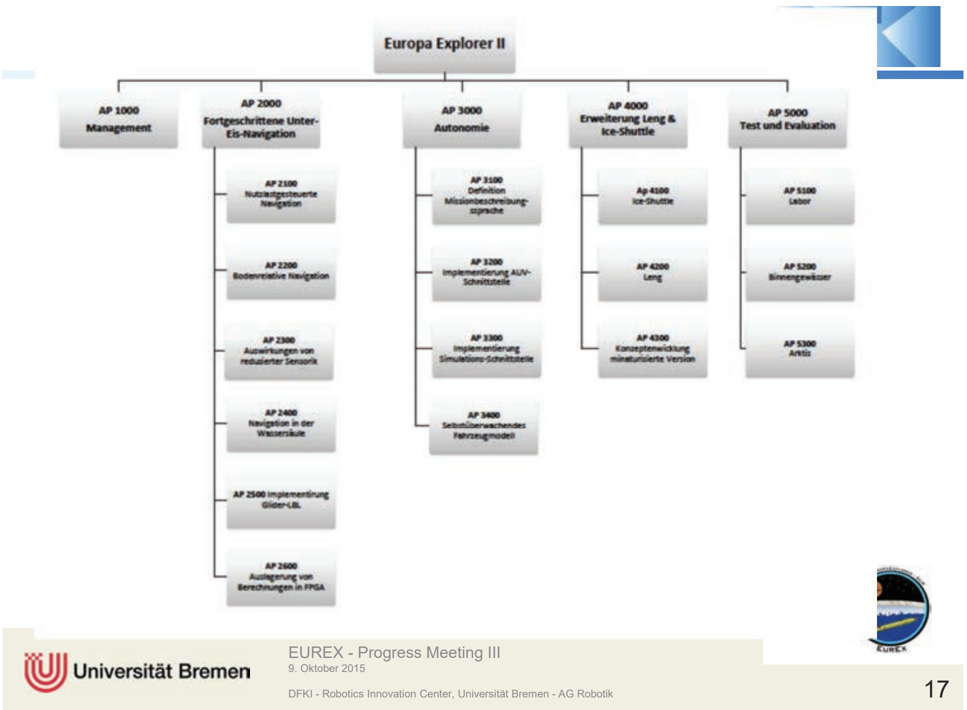
16


Europa Explorer II
AP 1000 Management
AP 2000 Fortgeschrittene Unter-Eis-Navigation
AP 2100 Nutzlastgesteuerte Navigation
AP 2200 Bodenrelative Navigation
AP 2300 Auswirkungen von reduzierter Sensorik
AP 2400 Navigation in der Wassersäule
AP 2500 Implementirung Glider-LBL
AP 2600 Auslagerung von Berechnungen in FPGA
AP 3000 Autonomie
AP 3100 Definition Missionbeschreibung-ssprache
AP 3200 Implementierung AUV-Schnittstelle
AP 3300 Implementierung Simulations-Schnittstelle
AP 3400 Selbstüberwachendes Fahrzeugmodell
AP 4000 Erweiterung Leng & Ice-Shuttle
Ap 4100 Ice-Shuttle
AP 4200 Leng
AP 4300 Konzeptenwicklung miniaturisierte Version
AP 5000 Test und Evaluation
AP 5100 Labor
AP 5200 Binnengewässer
AP 5300 Arktis
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robotics@dfki.de
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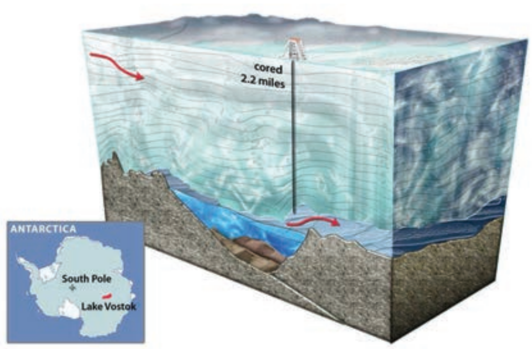
Future Ambitions

…the Arctic, Antarctica, subglacial lakes.



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DLR-Site Cologne, 19th April 2016
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19

Missions-Simulation AUV

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20

Missions-Simulation

Basis des Simulationsframeworks:

- MARS
  - Simulation:
    - Festkörperphysik
    - Thruster
    - Auftriebskraft
    - Sensorik
  - Visualisierung
- ROCK
  - Steuerung
    - Realer und simulierter Roboter
    - Kann Entscheidungen auf der Basis realer und simulierter Sensordaten treffen
  - ⇒ Die gleiche Steuerung in Simulation und Realität einsetzbar

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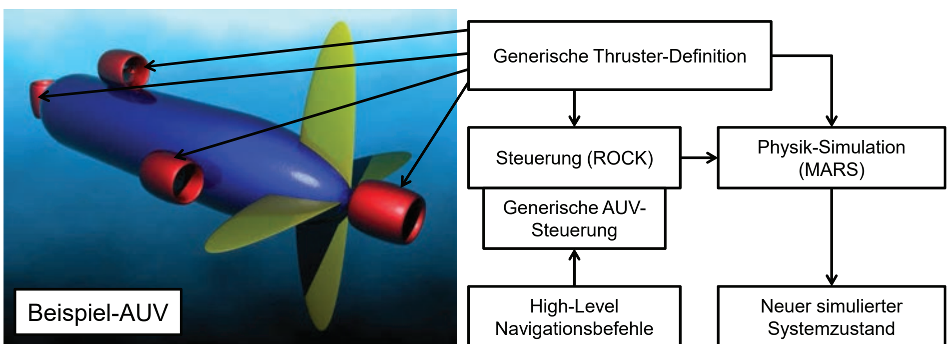
Missions-Simulation

Erweiterung des Simulationsframeworks:

- Unterstützung generischer Thruster-Konfigurationen
  - Definierbar für MARS und ROCK
  - Allgemein ansteuerbar durch High-Level Befehle
  - ⇒ Anpassbarkeit des Modells erhöht



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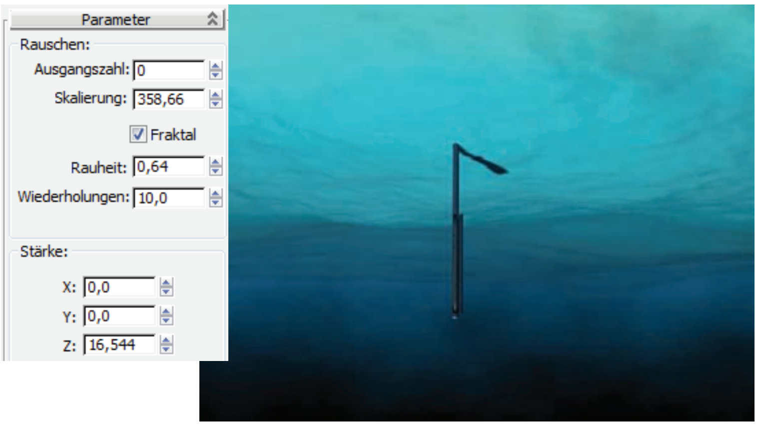
Missions-Simulation

Parametrierbares Modell der Eisdecke:

- Anpassbare Parameter wie maximale Höhenunterschiede und Rauheit der Oberfläche



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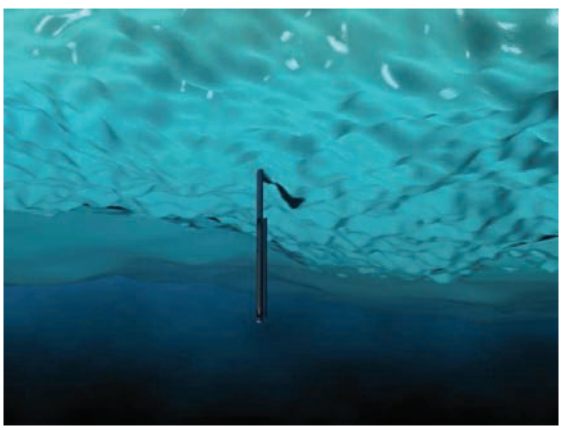
Missions-Simulation

Parametrierbares Modell der Eisdecke:

- Anpassbare Parameter wie maximale Höhenunterschiede und Rauheit der Oberfläche



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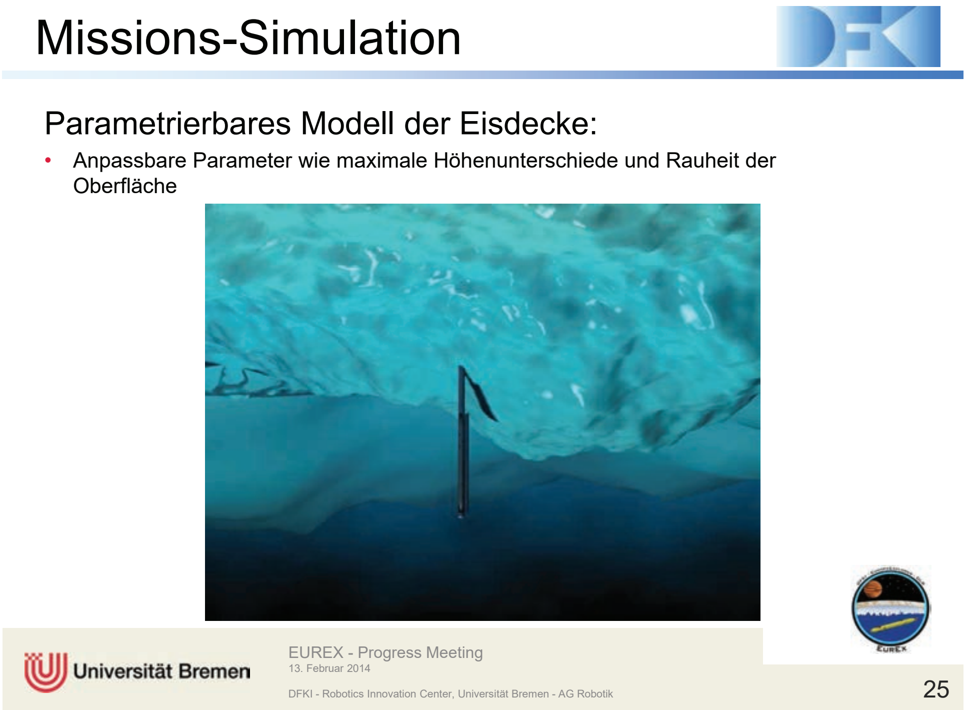
Missions-Simulation
Parametrierbares Modell der Eisdecke:
• Anpassbare Parameter wie maximale Höhenunterschiede und Rauheit der Oberfläche
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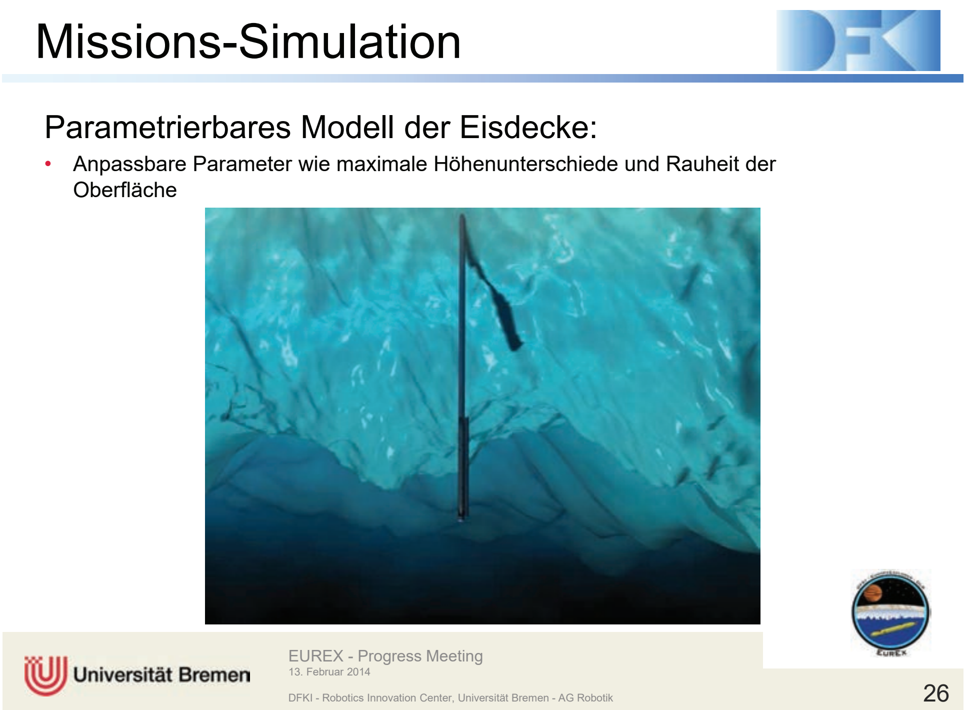
Missions-Simulation
Parametrierbares Modell der Eisdecke:
• Anpassbare Parameter wie maximale Höhenunterschiede und Rauheit der Oberfläche
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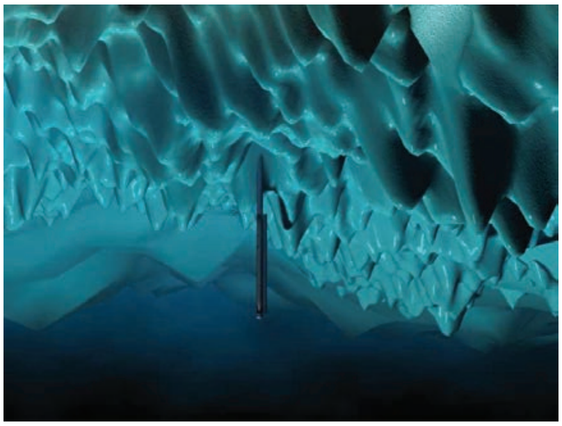
Missions-Simulation

Parametrierbares Modell der Eisdecke:

- Anpassbare Parameter wie maximale Höhenunterschiede und Rauheit der Oberfläche



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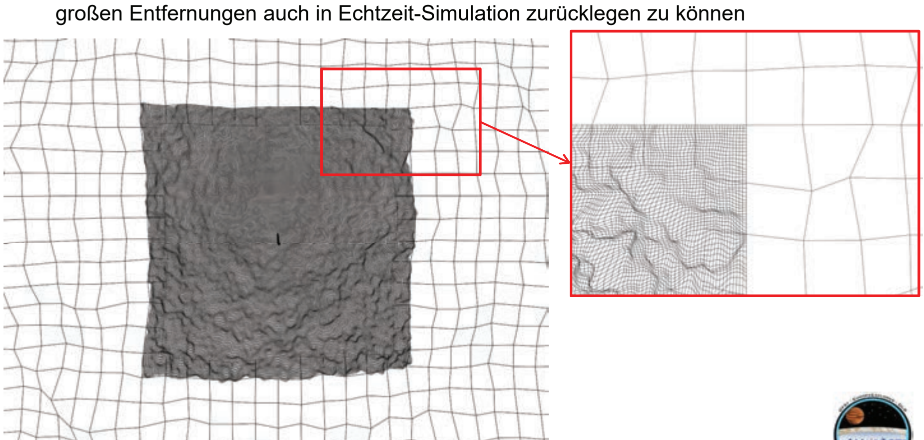
Missions-Simulation

Verschiedene Detailstufen der Eisdecke:

- Reduktion der Modellkomplexität in äußeren Bereichen, um die geplanten großen Entfernungen auch in Echtzeit-Simulation zurücklegen zu können



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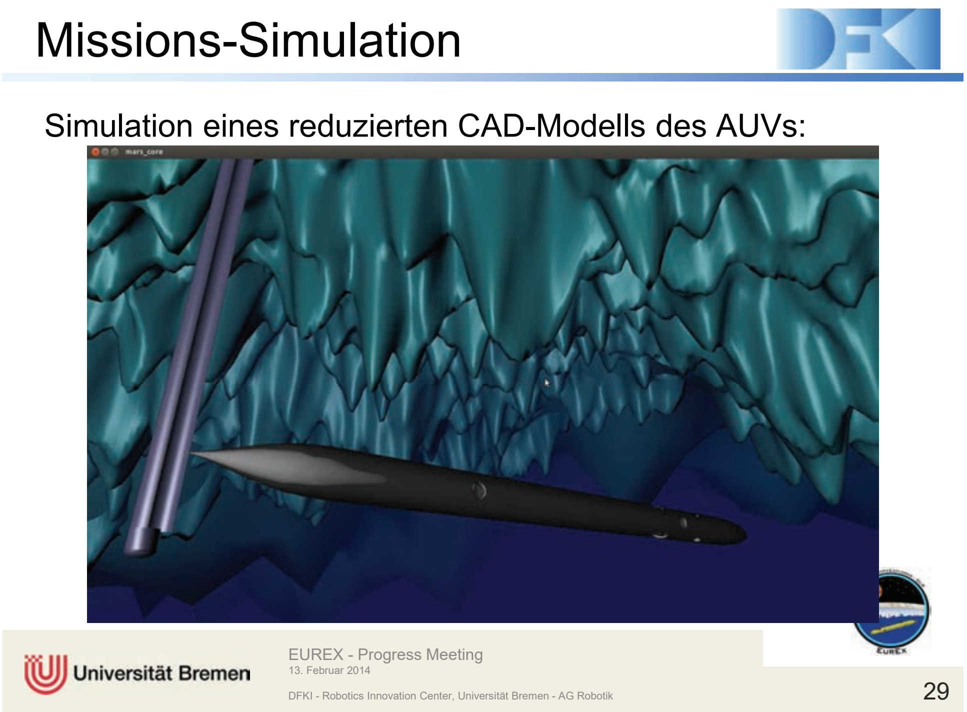
Missions-Simulation
Simulation eines reduzierten CAD-Modells des AUVs:
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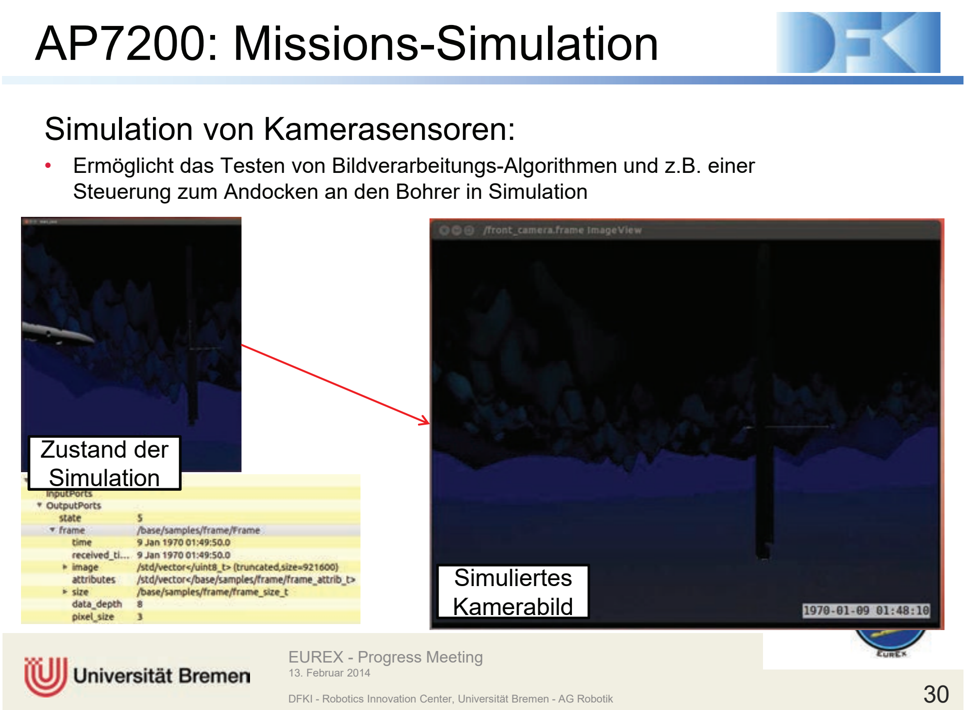
AP7200: Missions-Simulation
Simulation von Kamerasensoren:
Ermöglicht das Testen von Bildverarbeitungs-Algorithmen und z.B. einer Steuerung zum Andocken an den Bohrer in Simulation
Zustand der Simulation
InputPorts
OutputPorts
state 5
frame /base/samples/frame/Frame
time 9 Jan 1970 01:49:50.0
received_ti... 9 Jan 1970 01:49:50.0
image /std/vector</uint8_t> (truncated,size=921600)
attributes /std/vector</base/samples/frame/frame_attrib_t>
size /base/samples/frame/frame_size_t
data_depth 8
pixel_size 3
/front_camera.frame ImageView
Simuliertes Kamerabild
1970-01-09 01:48:10
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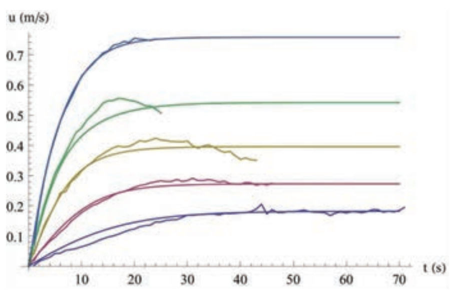
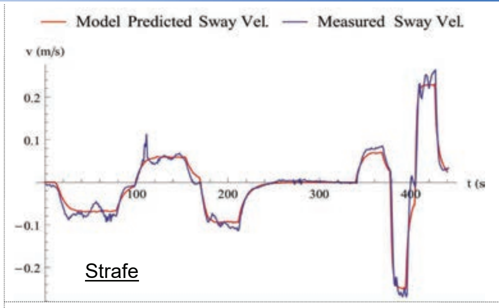
Motion Modeling

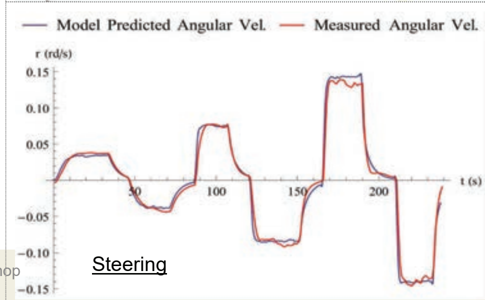
- Experimental results



Surge (forward)



Strafe



Steering

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Verwertung

- Missionsbeschreibungssprache könnte mögliches Softwareprodukt werden
- Selbstüberwachendes Fahrzeugmodell bisher noch nie eingesetzt (wegen Komplexität). Potentielles Patent
- Navigation in der Wassersäule zusammen mit bodenrelativer Navigation von großem Interesse für breite Anwenderschaft (Wissenschaft, Industrie), potentielles Softwareprodukt)
- Micro-Glider-LBL sehr attraktives Produkt für unzugängliche/zeitlich kritische AUV-Operationen
- Demonstration der Funktionsfähigkeit einzelner Komponenten/Artefakte in Realumgebungen „Proven Technology"

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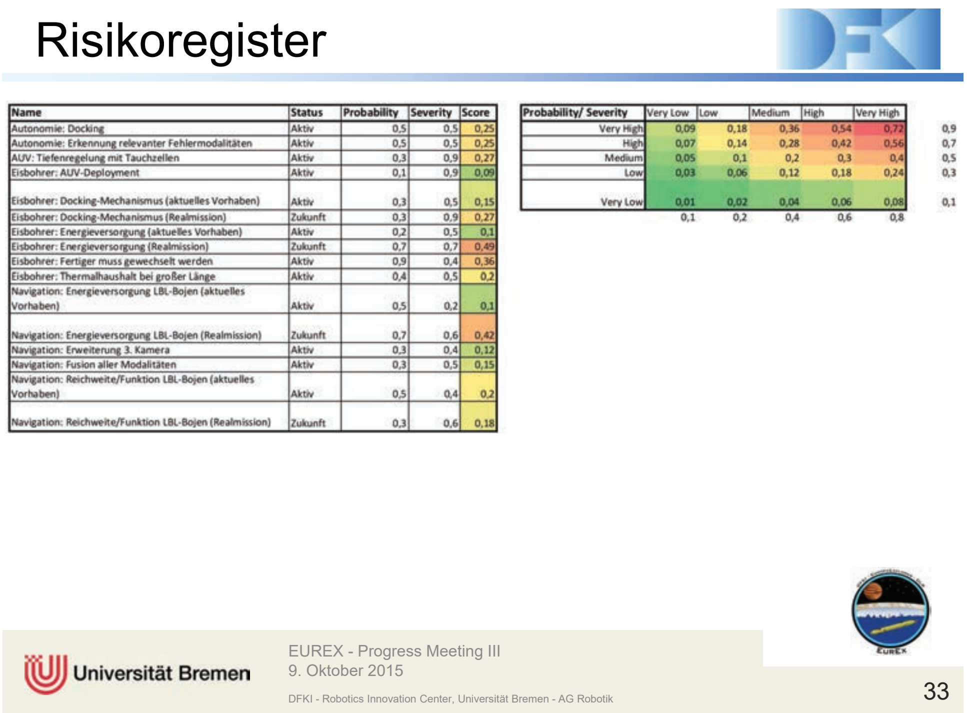
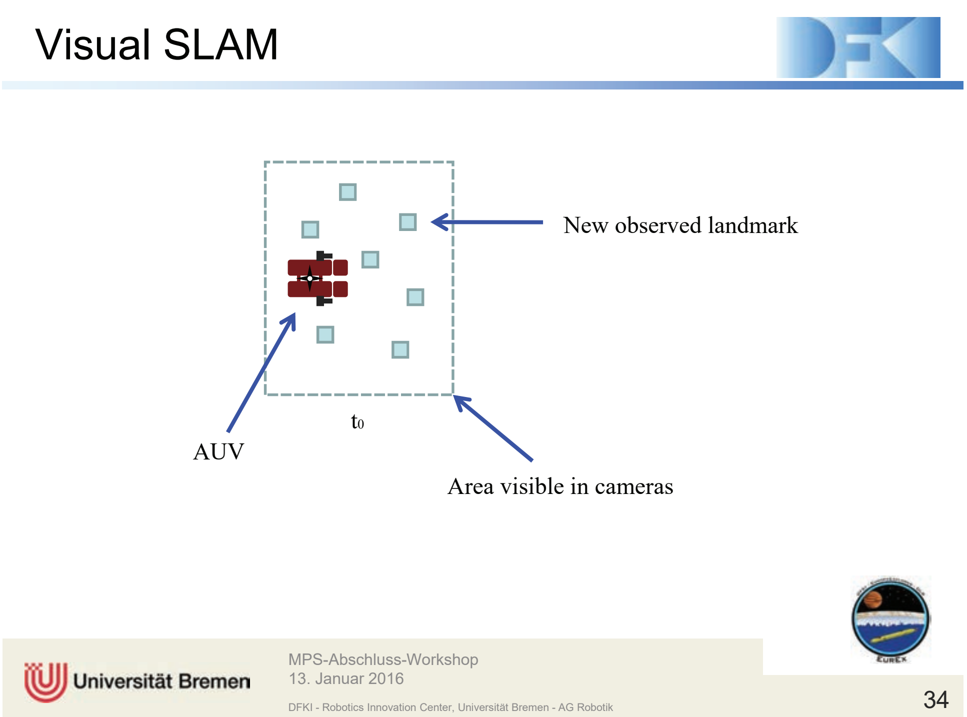
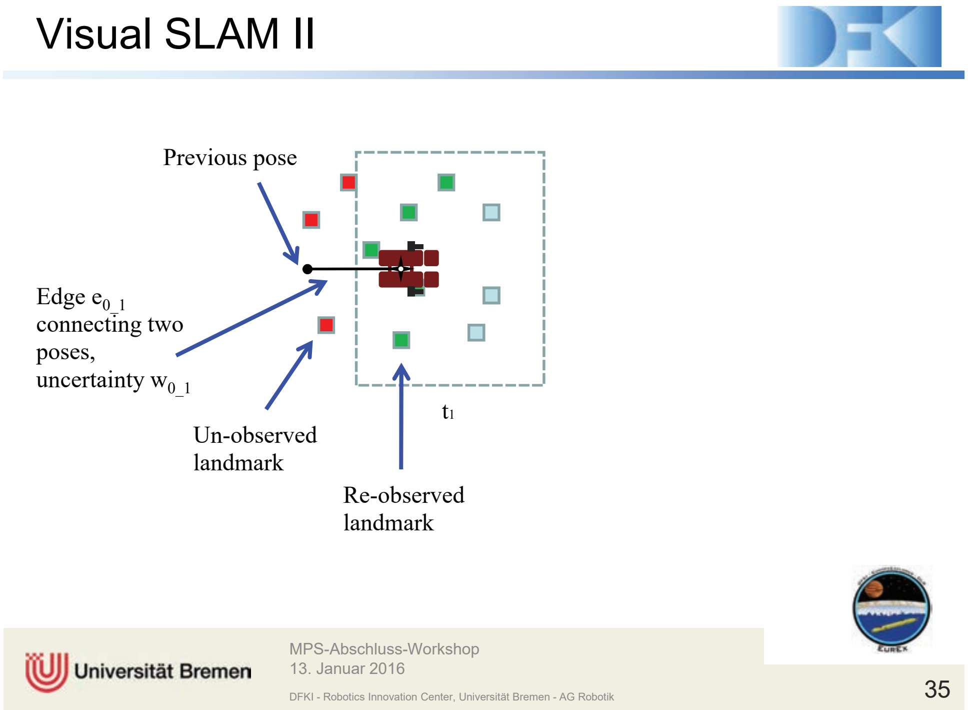


Name	Status	Probability	Severity	Score
Autonomie: Docking	Aktiv	0,5	0,5	0,25
Autonomie: Erkennung relevanter Fehlermodalitäten	Aktiv	0,5	0,5	0,25
AUV: Tiefenregelung mit Tauchzellen	Aktiv	0,3	0,9	0,27
Eisbohrer: AUV-Deployment	Aktiv	0,1	0,9	0,09
Eisbohrer: Docking-Mechanismus (aktuelles Vorhaben)	Aktiv	0,3	0,5	0,15
Eisbohrer: Docking-Mechanismus (Realmission)	Zukunft	0,3	0,9	0,27
Eisbohrer: Energieversorgung (aktuelles Vorhaben)	Aktiv	0,2	0,5	0,1
Eisbohrer: Energieversorgung (Realmission)	Zukunft	0,7	0,7	0,49
Eisbohrer: Fertiger muss gewechselt werden	Aktiv	0,9	0,4	0,36
Eisbohrer: Thermalhaushalt bei großer Länge	Aktiv	0,4	0,5	0,2
Navigation: Energieversorgung LBL-Bojen (aktuelles Vorhaben)	Aktiv	0,5	0,2	0,1
Navigation: Energieversorgung LBL-Bojen (Realmission)	Zukunft	0,7	0,6	0,42
Navigation: Erweiterung 3. Kamera	Aktiv	0,3	0,4	0,12
Navigation: Fusion aller Modalitäten	Aktiv	0,3	0,5	0,15
Navigation: Reichweite/Funktion LBL-Bojen (aktuelles Vorhaben)	Aktiv	0,5	0,4	0,2
Navigation: Reichweite/Funktion LBL-Bojen (Realmission)	Zukunft	0,3	0,6	0,18

Probability/ Severity	Very Low	Low	Medium	High	Very High	
Very High	0,09	0,18	0,36	0,54	0,72	0,9
High	0,07	0,14	0,28	0,42	0,56	0,7
Medium	0,05	0,1	0,2	0,3	0,4	0,5
Low	0,03	0,06	0,12	0,18	0,24	0,3
Very Low	0,01	0,02	0,04	0,06	0,08	0,1
	0,1	0,2	0,4	0,6	0,8	




Visual SLAM II
Previous pose
Edge e0_1 connecting two poses, uncertainty w0_1
Un-observed landmark
Re-observed landmark
t1
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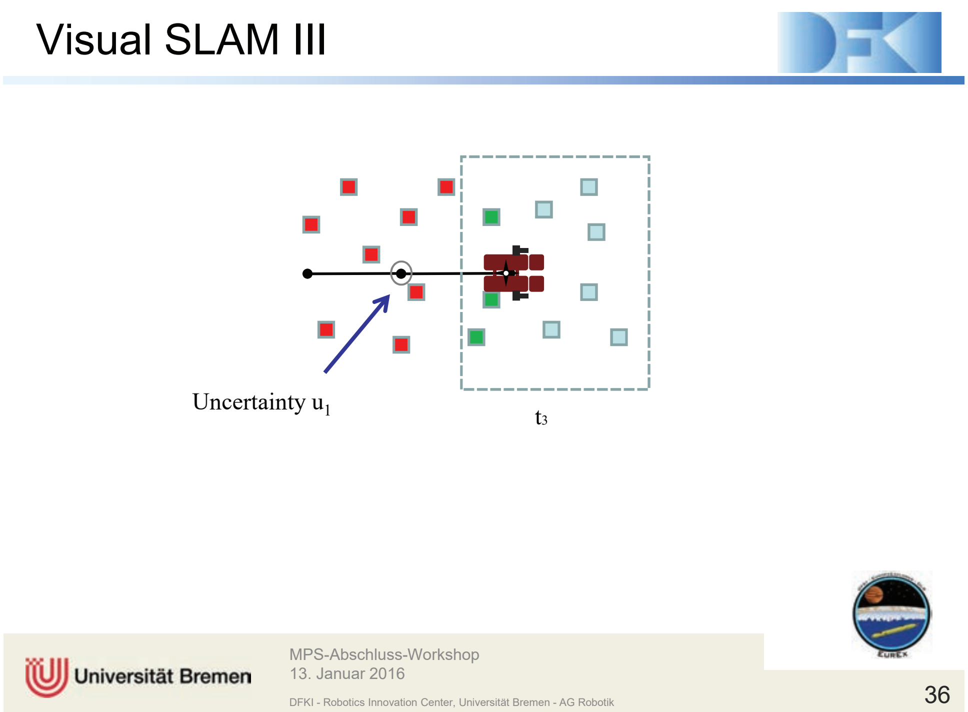
Visual SLAM III
Uncertainty u1
t3
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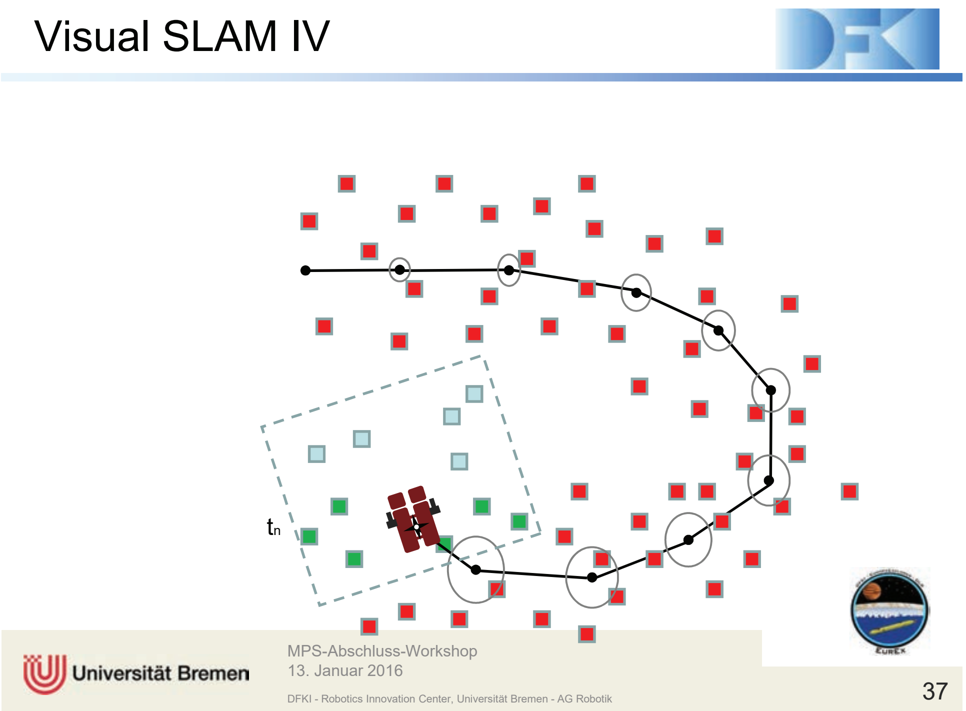
Visual SLAM IV
t_n
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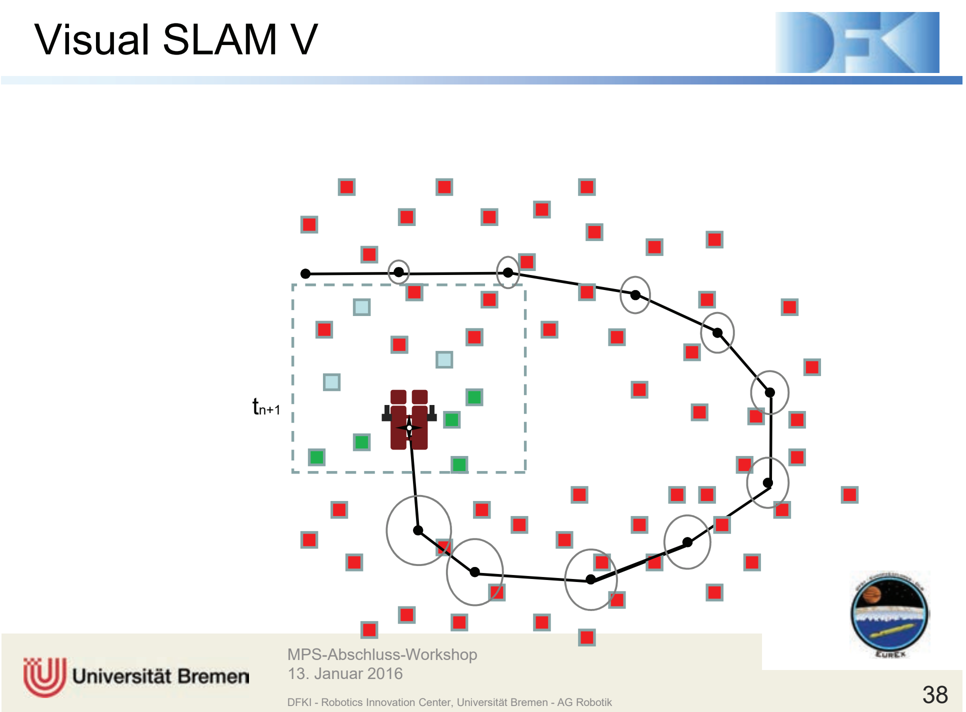
Visual SLAM V
t_{n+1}
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Microglider

(Multi-Beacon Navigation)

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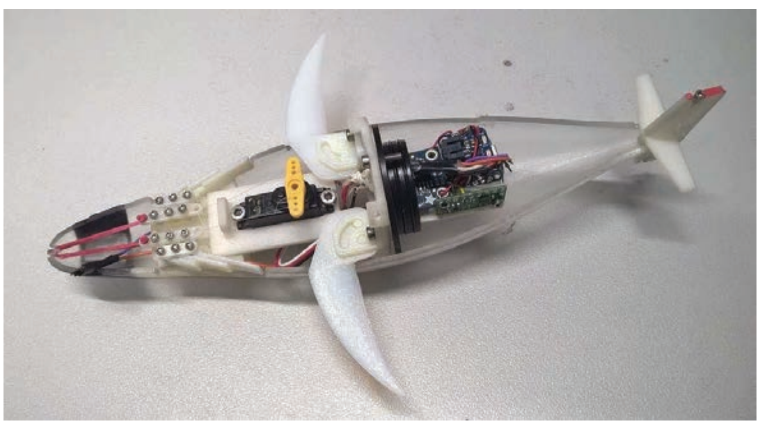
EurEx-Microglider



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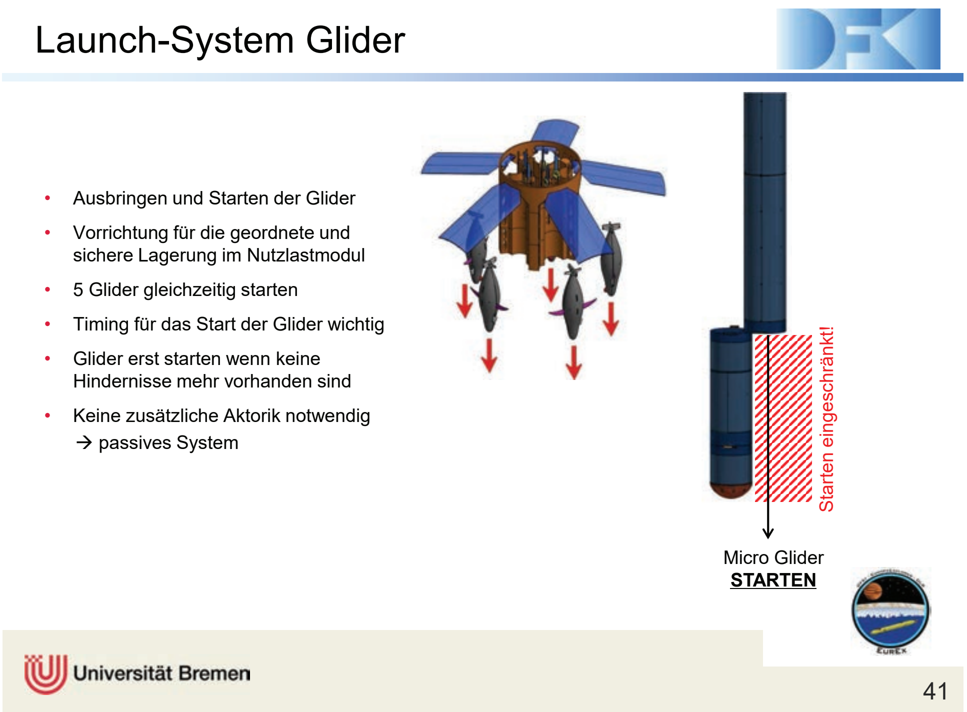
Launch-System Glider
Ausbringen und Starten der Glider
Vorrichtung für die geordnete und sichere Lagerung im Nutzlastmodul
5 Glider gleichzeitig starten
Timing für das Start der Glider wichtig
Glider erst starten wenn keine Hindernisse mehr vorhanden sind
Keine zusätzliche Aktorik notwendig → passives System
Starten eingeschränkt!
Micro Glider
STARTEN
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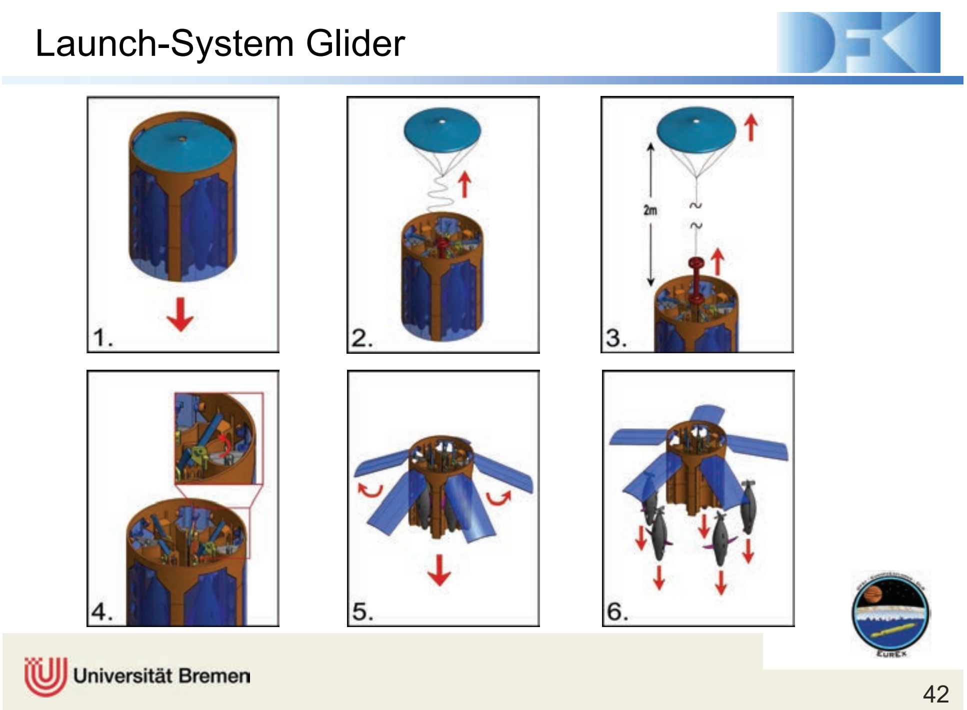
Launch-System Glider
1.
2.
2m
3.
4.
5.
6.
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3.6 '3D Path Planning for an UGV' (NP-T-06)

Janosch Machowinski, Arne Boeckmann[(1)]

(1) DFKI GmbH, Robotics Innovation Center, Robert-Hooke-Straße 1, 28359 Bremen, Germany

Contact: janosch.machowinski@dfki.de, arne.boeckmann@dfki.de

Abstract

This talk gives an overview of the new 3D path planner, that has been developed in the context of project Entern. The planner utilizes a newly developed 3D traversability map to search for the shortest sequence of motion primitives that move a robot between two points on the map. The search is done using the ARA* algorithm.

3D Path Planning for UGVs

Arne Böckmann, Janosch Machowinski

DFKI Bremen & Universität Bremen
Robotics Innovation Center
Director: Prof. Dr. Frank Kirchner
www.dfki.de/robotics
robotics@dfki.de

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Überblick

3D Traversability Map
- Generating a 3D Traversability Map from a MLS map

Search-Based Planning
- Spline Based Motion Primitives
- Custom SBPL Environment (X, Y, Z, θ)

Results

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3D Traversability Map

3D Traversability Map

- A gridmap with a predefined resolution
- Every gridcell contains a sorted list of TraversabilityNodes
- The height of a node is continous
- Access in X/Y is O(1)
- TraversabilityNode access is O(1) + O(log(n)), where n is the number of nodes in the X/Y cell

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3D Traversability Map

TraversabilityNode

- Has a height
- Has connections to all nodes, that might be reachable from this node
- Has a type / state (Obstacle, Traversable, Not Expanded)

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3D Traversability Map

Summary 3D Traversability Map

- 3D graph structure
- Saved in gridmap for fast access
- partly discrete (X/Y position)

3D Traversability Map

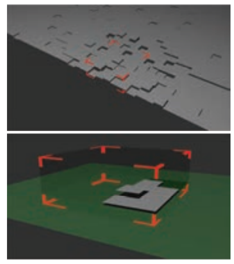
Generation of the Map

- Input :
  - Start point P in 3D
  - Robot parameters
  - MLS map
- Generate node from start point
- Expand all nodes, until no candidate node is left

3D Traversability Map

Generation of a Node

- Input : Point P
- Select all points in the mls, that are :
  - Within half of the robot width around p
  - Within the 'step height' of the robot
- If not enough points are found
  - → Obstacle (hole)



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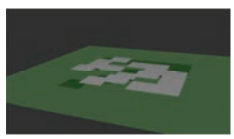
3D Traversability Map

Generation of a Node (2)

- Fit a plane using RANSAC



- Check if slope of plane if to high for robot
  - → Obstacle (to steep)
- Correct height of patch to intersection of unit Z vector with plane
- Check if there are obstacles blocking the node :
  - Ceilings within height of robot
  - Objects that stick out of the ground

- If fine, connect neighbors

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3D Traversability Map

Connection of neighbors

- Search in the 8 neighbors cells of the grid
- If a node with a reachable height is found
  - Connect node to current node
  - Update distance to start recursive
- If not
  - Create a candidate node
  - Connect candidate node to current node

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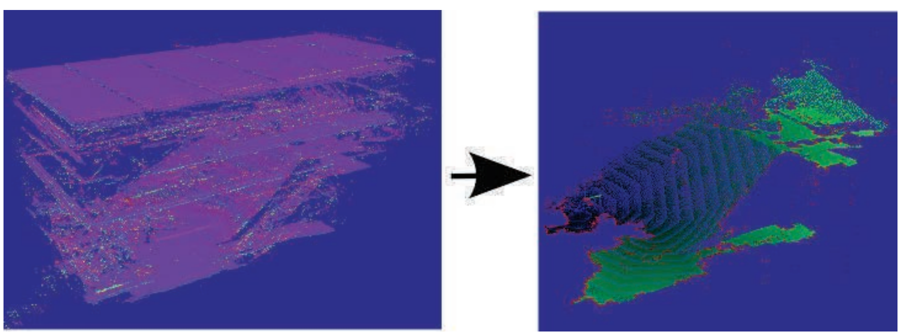
3D Traversability Map

Result



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Search-Based Planning

Introduction

- Uses classic graph search methods (A*, D*, ARA*, etc.)
- Discretized search space (e.g. using a grid)
- Two problems:
  1. Discretize
  2. Search

Search-Based Planning

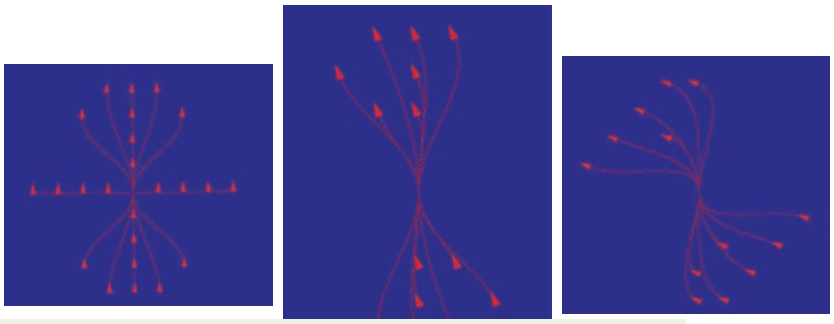
libsbpl

- Use sbpl library from sbpl.net
- Provides interfaces to common graph search algorithms
- Need to provide mapping to graph
- Implement additional domain dependent stuff (collision checking, etc.)

Search-Based Planning

Spline Based Motion Primitives

- Discretize motions using b-splines
- Each motion consists of:
  - Discrete start location (x, y, θ)
  - Discrete end location (x, y, θ)
  - Continuous b-spline from start to end



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Search-Based Planning

SBPL Environment (X, Y, Z, θ)

- Combines our data representation with the SBPL library
- Main functions needed :
  - GetStartHeuristic
  - GetGoalHeuristic
  - GetSuccs

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Search-Based Planning

GetSuccs

- Returns for a given state all valid success states
  - Fetches the corresponding TraversabilityNode for the given state id
  - Tries to generate a successor for every predefined motion primitive

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Search-Based Planning

Generation of successors

- For every motion primitive there is a precomputed discrete version
- Starting from the current node
- Walk through the discrete precomputed motion primitives
  - Find a connected TraversabilityNode in the given neighbors cell
  - Check if it is traversable
  - Perform a collision check with a bounding box model of the robot
  - Adjust path cost by slope

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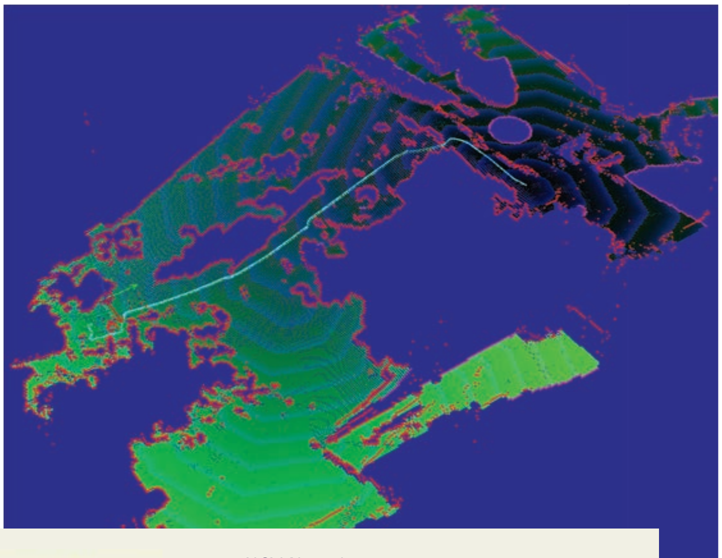
Results

Crater Max. 40° Slope



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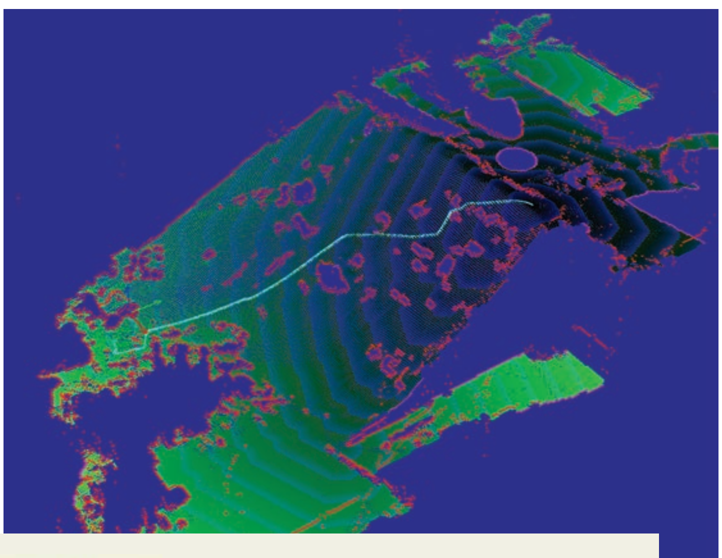
Results

Crater Max. 50° Slope



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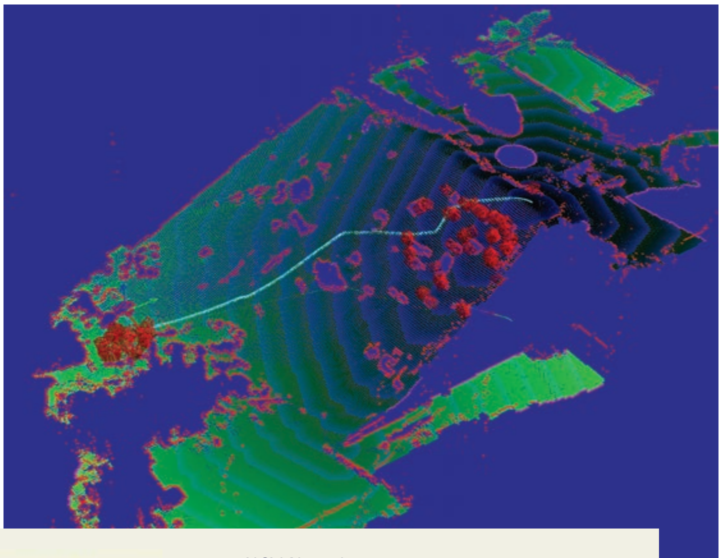
18/21

Results

Crater Max. 50° Slope Obstacles



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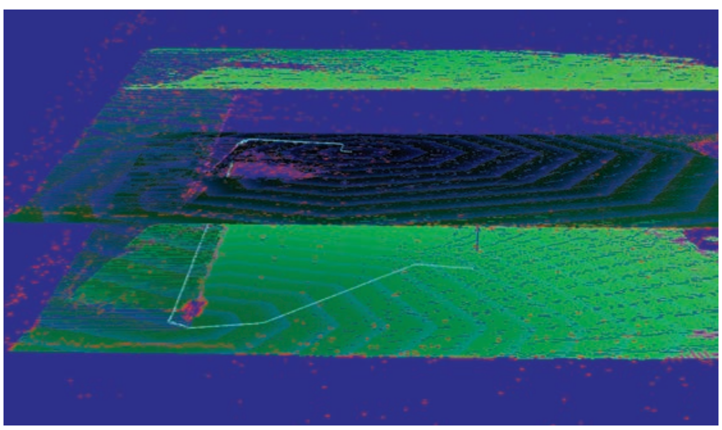
Results

Car Park



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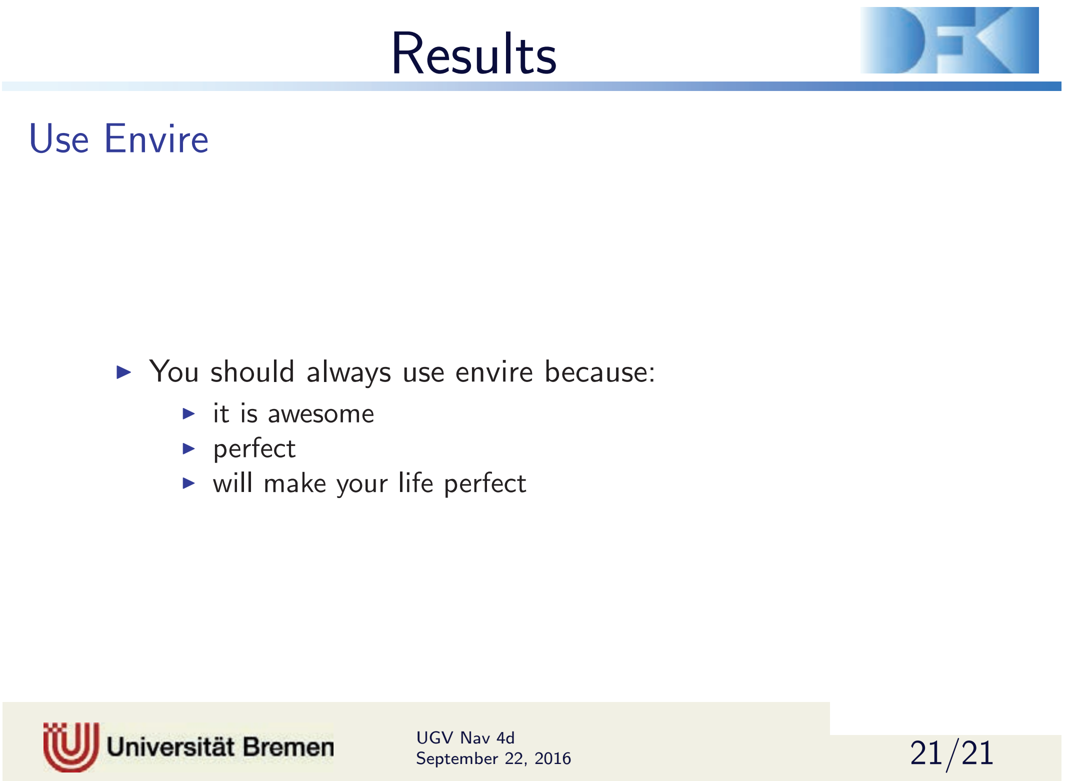
Results
Use Envire
You should always use envire because:
it is awesome
perfect
will make your life perfect
Universität Bremen
UGV Nav 4d
September 22, 2016
21/21

3.7 'Removing Dynamic Objects from Map Representations' (NP-T-07)

Sebastian Kasperski[(1)]

(1) DFKI GmbH, Robotics Innovation Center, Robert-Hooke-Straße 1, 28359 Bremen, Germany

Contact: sebastian.kasperski@dfki.de

Abstract

Robots navigating in real environments are confronted with a variety of dynamic objects. The talk focuses on the problem of removing objects from a build map that are no longer present at their original position. A solution is presented for the removal of dynamic objects based on the OctoMap representation. Objects that are not longer present are detected via raytracing and the respective points are removed from all measurements. The method is demonstrated on a sample data set captured with the Sherpa-TT robot.

Removing Dynamic Objects from Map Representations

Combining graph based SLAM
with Octo-Map 3D grid representation

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Introduction

- Most common issues with navigation:
  - Someone stands next to the robot, when it is turned on
  - Someone walks by during a test run
  - False positives (reflections) clutter the map
- Every time, an obstacle is added to the map
  - At some point, the map becomes unusable
- Path planning fails and everything has to be restarted
- Objects that are no longer present, have to be removed from the map representation

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Map types for range sensors

- Grid based maps used at DFKI
  - Traversability-Map (2D)
  - Multi-Layer-Surface-Map (2.5D)
  - Octo-Map (3D)
- Graph based mapping libraries at DFKI
  - graph_slam
  - slam3d
  - envire
  - envire 2.0 (currently in development)
- For navigation and planning, grid maps are build on demand from all scans in the pose graph

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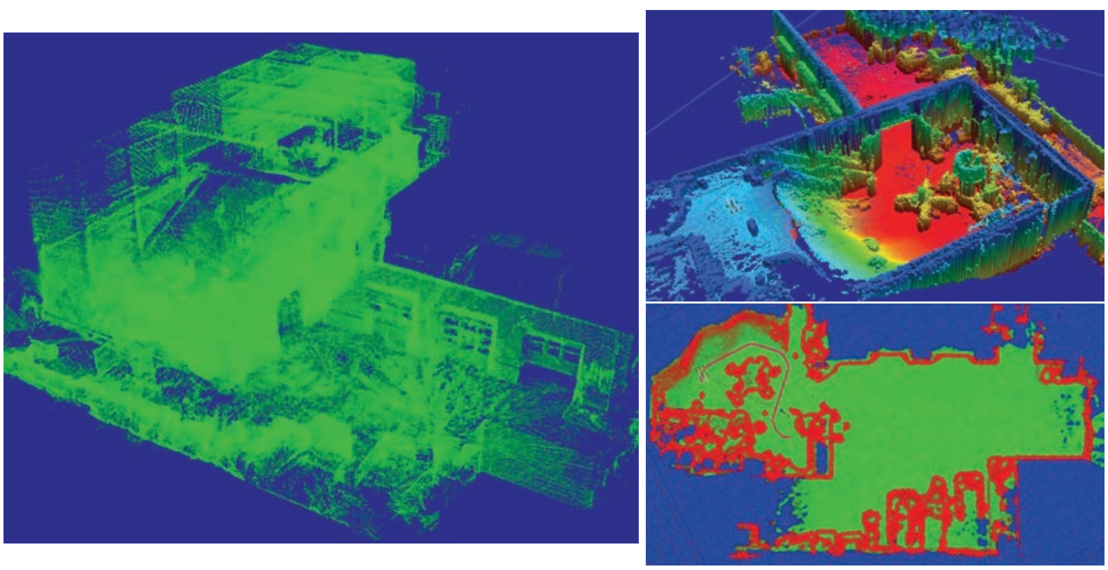
Building maps from scans



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Types of objects

- Static objects
  - Remain static for the whole operation time
  - E.g.: walls (floor plan), buildings, trees, …
- Low dynamic objects
  - Stay static for some time, but occasionally change their location
  - Motion cannot be sensed directly
  - E.g.: furniture, parked cars, …
- High dynamic objects
  - Move fast and at any time
  - Motion can be sensed directly
  - E.g.: people, driving cars, other robots, …

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Problems with graph based SLAM

- Low update rate (addition of scans)
  - (High) dynamic objects should be handled separately.
  - Detection and tracking of moving objects.
- Map should only contain static objects.
  - Filtering of high dynamic objects may fail.
  - Low dynamic objects will appear static at first.
- Objects that have disappeared should be removed from the map
  - Changes in the environment have to be detected
  - Integration of negative information
  - Representation of free space

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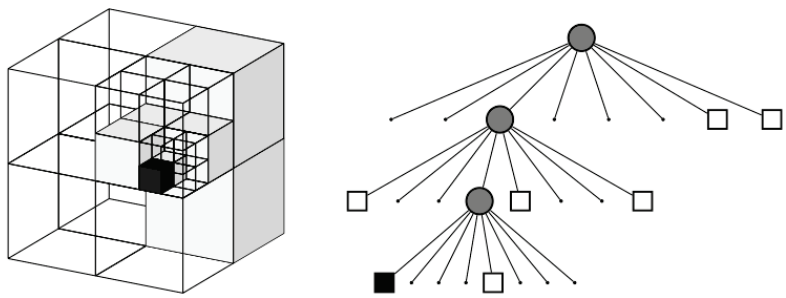
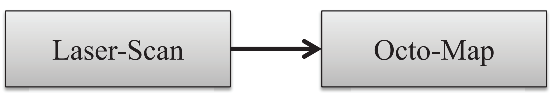
Representing 3D-Grids as Octrees

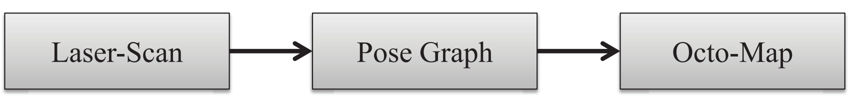
- Recursively divides cubic space into 8 sub-cubes
- Memory efficient way to store voxel grid maps
- Can be used as if it was a regular 3-dimensional array
- Every node stores an occupancy probability
- Negative information is added with raytracing



Octo-SLAM vs. Graph-SLAM



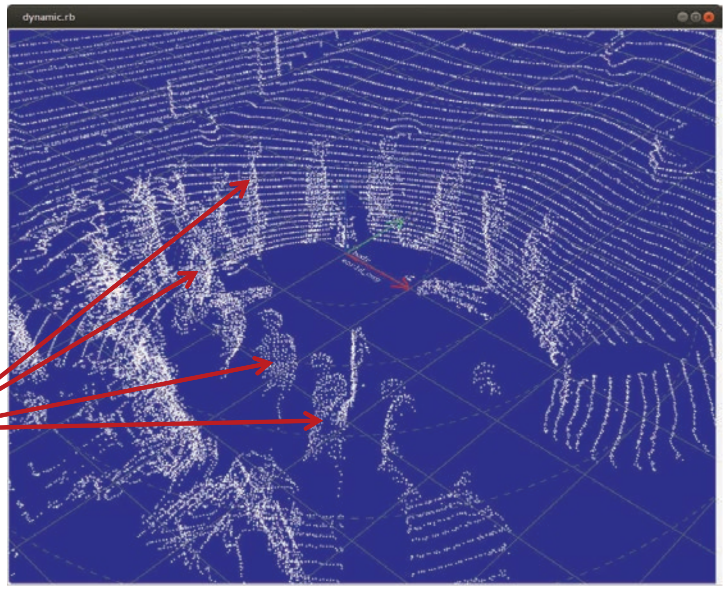
- Constant (more or less) map size
- Constant update time
- Best suited for smaller, high dynamic environments with global localization (GPS or static a-priori-map)



- Allows handling of loop closures (global optimization)
- Best suited for large, mostly static environments without global localization

Common use case

Pointcloud from
20 velodyne scans



person walking
around the robot

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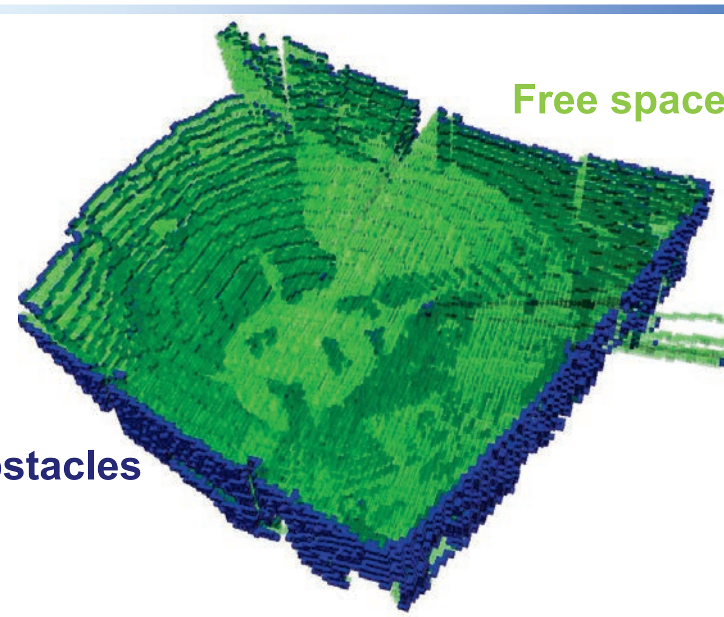
Free space tracking by raytracing



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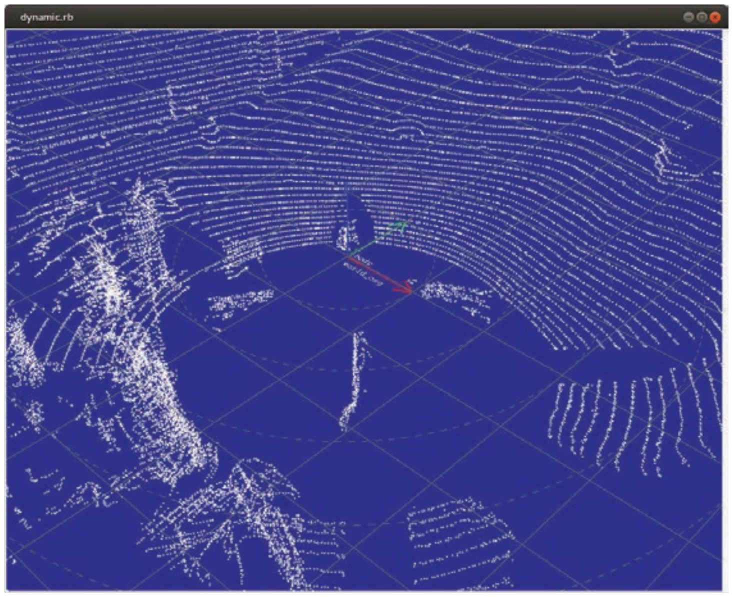
Remove dynamic objects

- Removed all points within free space from scans
- Flexible structure of the pose graph is retained



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Conclusions

- Pro:
  - Spatial flexibility of the pose graph (handle loop closures)
  - Representation of free space
  - Integration of negative information
  - Enables long-term applications in slowly changing environments
  - Map is not corrupted anymore by someone walking by
- Con:
  - Both representations in memory
  - Full map generation after optimization is computational expensive
  - Not suitable for high dynamic environments

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3.8 'URDF and SMURF Robot Models in EnviRe and Mars' (NP-T-09)

Raúl Domínguez[(1)]

(1) DFKI GmbH, Robotics Innovation Center, Robert-Hooke-Straße 1, 28359 Bremen, Germany

Contact: raul.dominguez@dfki.de

Abstract

The talk summarizes the steps given in the context of the project Entern to improve the integration of the simulation software Mars and the environment representation software Envire. An introduction to the two software tools and how they integrate with each other is provided. After the introduction, it is presented how the robot models are loaded in Mars through EnviRe.

URDF and SMURF Robot Models In Envire and Mars

Raúl Domínguez

DFKI Bremen & Universität Bremen
Robotics Innovation Center
Director: Prof. Dr. Frank Kirchner
www.dfki.de/robotics
robotics@dfki.de

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Table of Contents

Universität Bremen September 21, 2016 2/16

Introduction

Table of Contents

Universität Bremen September 21, 2016 3/16

Introduction

What Envire is

- Base library for environment representation
- Consists of
  - Spatio-temporal graph
  - Tools for storage of any C++ object
  - Graph manipulation
  - Information retrieval
  - Event-Based supervision
- Serialization and communication through Rock ports supported
- Rock independent

Motivation: Communication and representation homogenization

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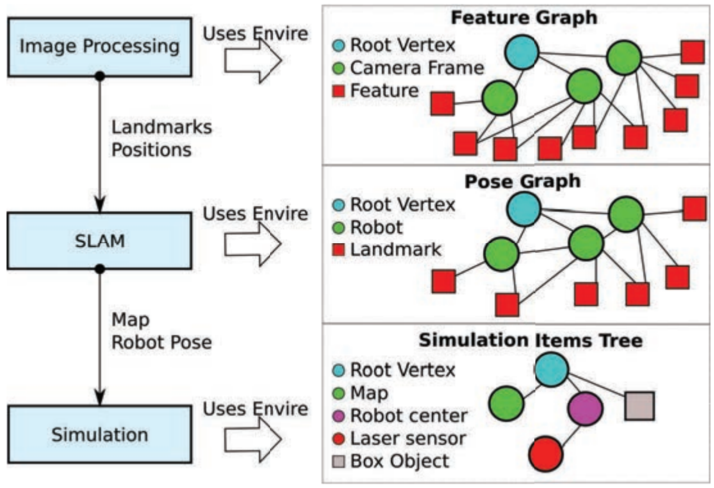
Introduction

What Envire is



Introduction

What Mars is

- A robotics simulator
- Consist of
  - A physics simulator (Open Dynamics Engine)
  - A robotics simulation tools around core (e.g. sensors and motors)
  - Scenarios support tools
- Integrated in Rock and independent of it

Introduction

What EnviReMars is

- Mars clone but...
- A Envire graph is the core representational structure of the simulation software
- Graph gets updated based on the physics simulation
- Physics simulations are generated based on the contents (nodes) and transformations (edges) of the graph
- Plugin based architecture

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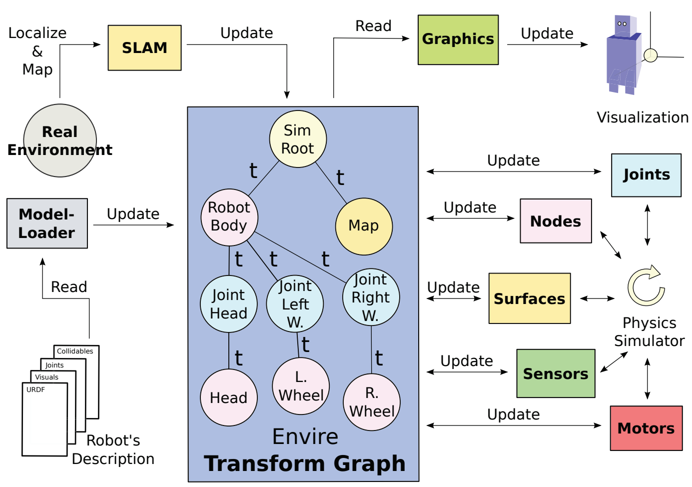
Introduction

What EnviReMars is



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Robot Models in Envire

Table of Contents

Universität Bremen September 21, 2016 9/16

Robot Models in Envire

Envire Graph Loader

- URDF: Universal Robot Description Format
- SMURF: Supplementable, Mostly Universal Robot Format

Tools to upload to an Envire graph structure:

- Envire URDF Graph Loader
- Envire SMURF Graph Loader
- Common templated parent class available

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Robot Models in EnvireMars

Table of Contents

Universität Bremen September 21, 2016 11/16

Robot Models in EnvireMars

SMURF Robot Models in EnvireMars

- Additional properties of the objects are provided to the simulator using the SMURF files
- Simulated objects references are stored in the graph
- Spatial region based access is eased
- Tested for Asguard IV and Crex
- Most sensors need adaptation

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Next Goals

Table of Contents

Next Goals

Next Goals

- Support for all Asguard and Crex sensors
- Integration with the navigation and planning stack
- Headless simulation
- Graphics-independent simulation loop
- Testing and bug-fixing
- EnvireMars refactorization
  - Completely remove the NodeManager
  - Unify GUIs Envire/Mars/Rock
  - Merge with Mars?

Conclusion

Table of Contents

Universität Bremen September 21, 2016 15/16

Conclusion

Conclusions, Discussion and ...Thanks!

- Common structure to store and manage spatio-temporal data products
- EnvireMars is robotics simulator based on an Envire graph
- Supports URDF and SMURF robot models load

Discussion

- Alright, Envire is awesome but how can I really benefit from it?
- Is the Envire robot representation only suited for simulation and navigation?

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3.9 'Project FlatFish: Phase 1, Navigation, Docking and planned work for Phase 2' (NP-T-10)

Christopher Gaudig, Sascha Arnold[(1)]

(1) DFKI GmbH, Robotics Innovation Center, Robert-Hooke-Straße 1, 28359 Bremen, Germany

Contact: christopher.gaudig@dfki.de, sascha.arnold@dfki.de

Abstract

This talk gives an overview on the hardware and software components that have been developed during phase one of the FlatFish project. A more detailed summary is given on the navigation components using the task of docking as an example. It is explained how the components of the control chain, the pose provider and the velocity provider are used to support this task. Concluding with an outlook on the planned work in phase two.

Project FlatFish:
Phase 1, Docking and planned work for Phase 2

Christopher Gaudig
Sascha Arnold

DFKI Bremen & Universität Bremen
Robotics Innovation Center
Director: Prof. Dr. Frank Kirchner
www.dfki.de/robotics
robotics@dfki.de

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Overview

FlatFish Phase 1

- Hardware (AUVs, Docking Station, SSIV Mock-Up)
- Basic control software (Control Chain, Filters and Safety)
- Autonomous Docking
- Testing

Phase 2: Planned work

- New docking hardware (Salvador & Bremen)
- Optical data transfer
- Realistic testing mission

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FlatFish Phase 1

Two identical AUVs built

- To allow for parallel software development and testing in Salvador (Brazil) and Bremen.
- Propulsion: Six hubless ring thrusters (60N each)
- Instrumentation: 4 cameras, 2 laser line projectors, 2 obstacle sonars, navigation sonar, inspection sonar, DVL, fiber-optic gyro IMU, surface-GPS, USBL

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FlatFish Phase 1

Two identical AUVs built

- Energy: 5.8kWh Li-Ion battery, extendable up to 11kWh
- Communications: Acoustic modem (up to 1km and 30kbps), surface WiFi (2.4GHz) and XBee (868MHz)
- Emergency System: Comms Tower w/ backup battery, GPS receiver and Iridium satellite modem (sends location via eMail)

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FlatFish Phase 1

Docking Station demonstrator

- FlatFish is designed to be subsea-resident (weeks up to months)
- Docking Station demonstrator provides hydraulic locking and positioning fine enough (few mm) to allow for wireless data transfer and power connector plugging

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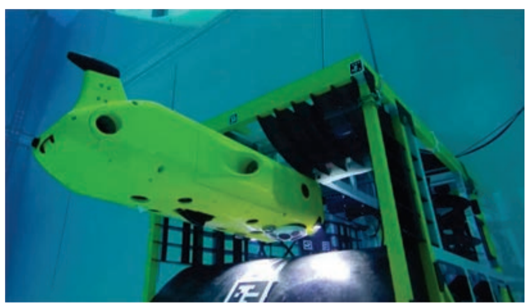
FlatFish Phase 1

Docking Station demonstrator

- Hydraulic actuation uses fresh water as the hydraulic medium (to prevent oil spilling into the DFKI basin)



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FlatFish Phase 1

SSIV mock-up

- SubSea Isolation Valve, very common Oil & Gas structure that hydraulically (or manually) disconnects seafloor pipeline from surface-connecting riser (e.g. during maintenance)

FlatFish Phase 1

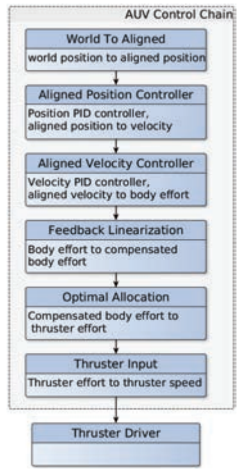
SSIV mock-up

- Mock-Up made out of plastic instead of steel, valve parts at 100% scale, outer frame at 70% scale
- Several defects can be simulated: Missing nuts and bolts, missing or half-depleted sacrificial anode (cathodic protection), gas leak (air bubbles), disconnected subcomponent grounding wire, broken joint of manual override

FlatFish Phase 1

Control chain

- Cascaded control chain
- The 6D input can be split up and applied at different levels of the chain
- E.g. possible inspection task with fixed depth:
  - z, pitch and roll in world frame
  - x and yaw in aligned (relative) frame
  - y in aligned velocity frame



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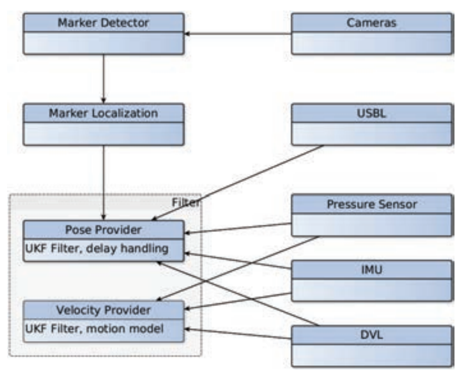
9/21

FlatFish Phase 1

Pose Provider

- UKF filter combining DVL, IMU, Pressure sensor, USBL and visual markers
- Can handle delayed inputs, e.g. from the USBL



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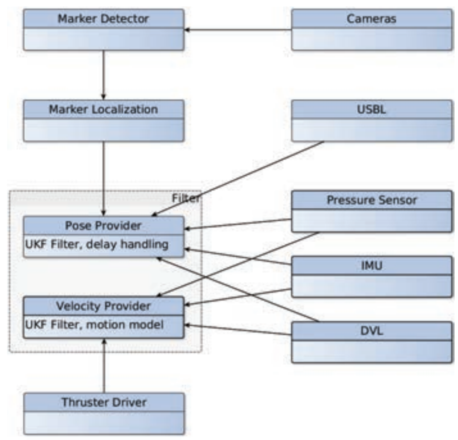
10/21

FlatFish Phase 1

Velocity Provider

- UKF filter combining DVL, IMU and thruster-based motion model inputs
- Can provide the current velocity with little delays and in high frequency



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11/21

FlatFish Phase 1

Basic control software

- Waypoint following
- Remote control via WiFi when surfaced
- Safety mechanisms
  - Simple emergency surfacing via acoustic modem command
  - Error modeling in Roby state machines (E.g. mission timeouts, battery voltage, water ingress)

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October 11, 2016
12/21

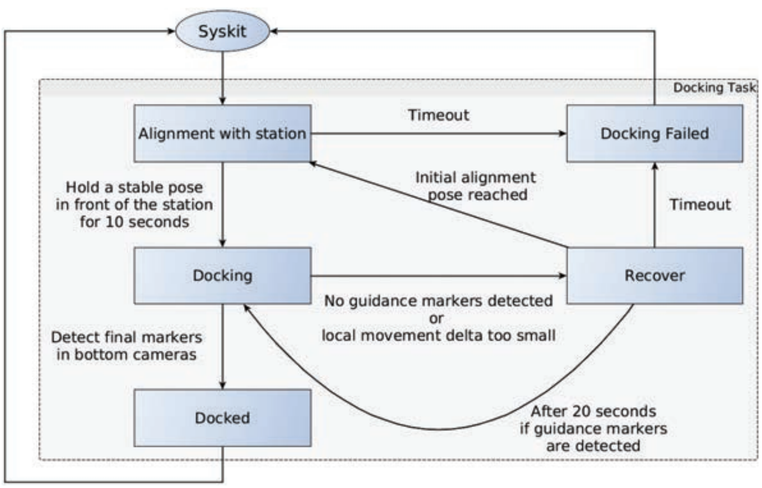
FlatFish Phase 1

Docking challenges and approaches

- USBL and DVL not useable inside the docking station
  - Use visual markers (AprilTags) to support the pose estimation
- Pose control in very narrow space with possible contacts
  - Soft PID controllers, apply x and y commands as pure accelerations, compensate for local air pressure
- Being stuck during the docking process or no visible markers
  - Recovery strategies

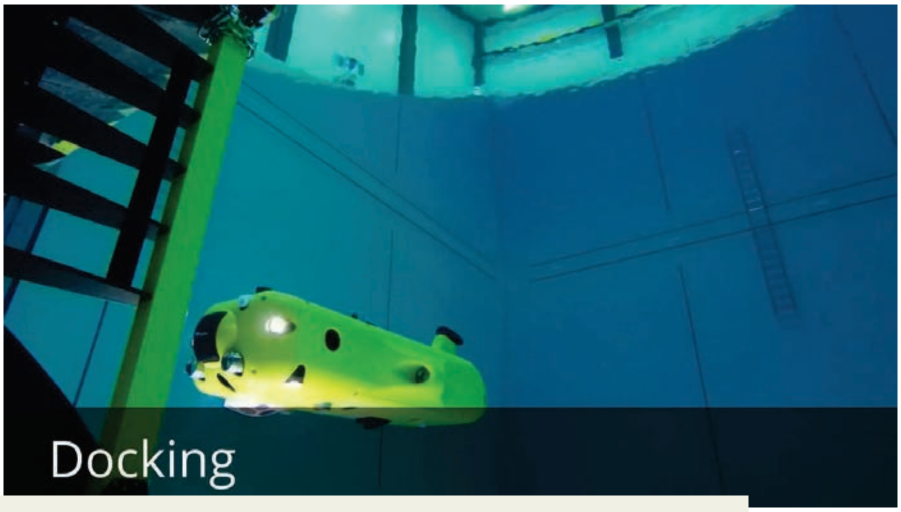
FlatFish Phase 1

Docking state machine



FlatFish Phase 1

Docking video



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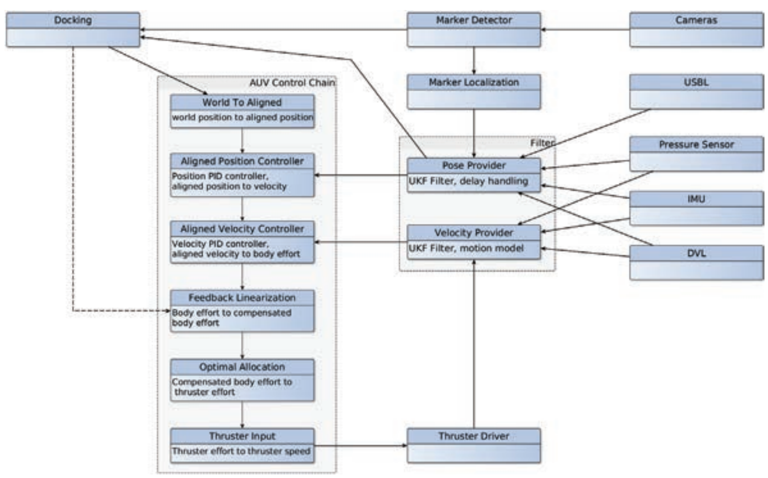
15/21

FlatFish Phase 1

Docking task in component network



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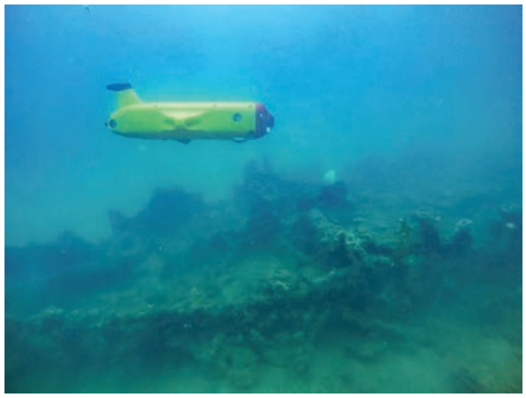
FlatFish Phase 1

Testing

- Frequent basin testing at DFKI
- Lake tests at Unisee (Stadtwaldsee)
- Near-shore testing in the Atlantic, close to Salvador (Brazil)



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Phase 2: Planned work

New docking hardware (Salvador & Bremen)

- Two identical setups
- Provide USBL/modem, passive visual markers, active visual markers, passive acoustic markers, optical data transfer system
- Basin testing in Bremen and near-shore testing in Salvador

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Phase 2: Planned work

Optical data transfer

- Teledyne-Sonardyne BlueComm or SIDUS OceanLink
- Uses blue LEDs
- High bandwidth (up to 100 MBit/s) compared to acoustics
- Longer range (meters) compared to WiFi (2-3cm)

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Phase 2: Planned work

Realistic testing mission

- Hover at docking point to download mission data via optical link
- Find pipeline and track it
- Inspect object at end of pipeline (using cameras, lasers, sonars)
- Backtrack and find docking point using USBL, passive acoustic markers as well as active and passive visual markers
- Establish acoustic and then optical link to upload the inspection results
- Hover at docking point to await follow-up mission download

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Thanks for your attention!
Questions?

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21/21

3.10 'Spatio-temporal planning for a reconfigurable multi-robot system' (NP-P-01)

Thomas M Roehr[(1)]

(1) DFKI GmbH, Robotics Innovation Center, Robert-Hooke-Straße 1, 28359 Bremen, Germany

Contact: `thomas.roehr@dfki.de`

Abstract

This poster describes a planning approach which relies on an ontology to model the functionalities individual physical agents offer within a multi-robot system, while an implicit domain representation is given. An inference layer on top of a knowledge-based system allows to account for superadditive effects from physically combining two or more robots. We present a formulation of the domain-specific planning problem and outline our spatio-temporal planning approach. This approach combines the use of constraint-based satisfaction techniques with linear optimization to solve a multicommodity min-cost flow problem to deal with the transportation of immobile robotic systems.

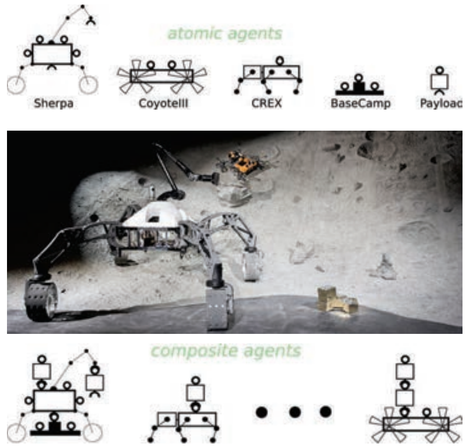
Deutsches Forschungszentrum für Künstliche Intelligenz GmbH

Spatio-Temporal Planning for a Reconfigurable Multi-Robot System

Thomas M. Roehr and Frank Kirchner

A reconfigurable multi-robot system

In this paper we introduce a spatio-temporal planning and scheduling approach for collaborative multi-robot systems. In particular, we are targeting an application to physically reconfigurable systems.



Organization model

An inference layer on top of a knowledge-based system called the organization model allows to account for (superadditive) effects from physically combining two or more robots:

- infer atomic agent functionalities based on available resources
- infer composite agent functionalities including superaddition
- *min* resource cardinality to identify functional saturation
- *max* resource cardinality to compute safety metrics

$$
\begin{aligned}
&Functionality && \sqsubseteq Resource \sqsubseteq \top \\
&MoveTo && \sqsubseteq Functionality \\
&ImgProvider && \sqsubseteq Functionality \\
&MoveTo && \equiv\ \geq 1.has.Locomotion \sqcap \geq 1.has.Localization \\
& && \quad \sqcap \geq 1.has.Mapping \sqcap \geq 1.has.Power \\
&ImgProvider && \equiv\ \geq 1.has.Camera \sqcap \geq 1.has.Power \\
&LocImgProvider && \equiv\ \geq 1.has.ImgProvider \sqcap \geq 1.has.MoveTo \\
&ARobot && \equiv\ Agent \sqcap \leq 1.has.Locomotion \sqcap \leq 1.has.Localization \\
& && \quad \sqcap \leq 1.has.Mapping \sqcap \leq 4.has.Camera \\
& && \quad \sqcap \leq 1.has.Power
\end{aligned}
$$

Functional saturation

Limit combinatorial explosion and differentiate between required resource or excess resource contributing to a safety margin for agent type $\hat{a}$, functionality f, concept (resource) c:

$$support(\hat{a}, c, f) = \frac{card_{max}(c, \hat{a})}{card_{min}(c, f)}$$

$$FSB(\hat{a}, f) = \max_{c \in C} \frac{1}{support(\hat{a}, c, f)}$$

- lower bound on agent instances to achieve a functionality
- upper bound for agents contributing to a functionality

Planning approach

Regard the sub-problem of transportation of immobile robotic systems as multicommodity min-cost flow problem; use a combination of constraint-based satisfaction techniques and linear optimization to solve the overall planning problem:

1. a **robotic mission**: is a tuple $\mathcal{M} = (A_a, STR, \mathcal{X})$, where $A_a = \{a_0, \ldots, a_n\}$ is the set of available atomic agents, STR is a set of spatio-temporally qualified expressions (*steqs*) and $\mathcal{X}$ is a set of (temporal) constraints, e.g.,

$$
\begin{aligned}
steq1 &= (\{\}, \{(Sherpa, 3), (CREX, 2), (CoyoteIII, 3), (Payload, 25), (BaseCamp, 5)\}@(lander, [t0, t1]) \\
steq2 &= (\{\}, \{(Payload, 3\})@(lander, [t4, t10]) \\
steq3 &= (\{LocImgProvider, EmiPowerProvider\}, \{(Payload, 3)\})@(b1, [t2, t3]) \\
steq4 &= (\{\}, \{(Payload, 1)\})@(b1, [t3, t14]) \\
steq5 &= (\{\}, \{(BaseCamp, 1)\})@(b1, [t4, t7]) \\
steq6 &= (\{LogisticHub, LocImgProvider, EmiPowerProvider\}, \{(Payload, 3)\})@(b2, [t2, t3]) \\
steq7 &= (\{LocImgProvider, EmiPowerProvider\}, \{(Payload, 6)\})@(b4, [t6, t7]) \\
steq8 &= (\{\}, \{(Payload, 3\})@(b4, [t8, t9]) \\
steq9 &= (\{\}, \{(BaseCamp, 3)\})@(b4, [t11, t14]) \\
steq10 &= (\{\}, \{(Payload, 1)\})@(b6, [t10, t14]) \\
\mathcal{X} &= \{\{t0 < t1\}, \{t1 < t2\}, \{t2 < t3\}, \ldots, \{t13 < t14\}\}
\end{aligned}
$$

2. **temporal constraint network**: compute qualitative temporal constraint network without gaps from mission specification
3. **model assignment**: identify feasible atomic and composite agent types that can fulfil a requirement
4. **role assignment**: identify concurrent activities and feasible agent instance (role) assignments; limited by the number of available agents
5. **logistic network**: compute transshipment problem using agent transport capacities
6. **flow violations**: resolve transport flow violations or backtrack

Planning results

A solution for the example above computed in 57.56 ± 9.8 s (averaged over 10 runs); the linear problem to solve the transshipment problem has the 9100 rows, 4320 columns and 21536 non-zeros:

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Contact:
DFKI Bremen & University of Bremen
Robotics Innovation Center

Director: Prof. Dr. Frank Kirchner
E-mail: robotics@dfki.de
Website: www.dfki.de/robotics

3.11 ‘Water-Current and IMU Aided AUV Localization in Deep Mid-Water’ (NP-P-02)

Lashika Medagoda [(1)]

(1) DFKI GmbH, Robotics Innovation Center, Robert-Hooke-Straße 1, 28359 Bremen, Germany

Contact: lashika.medagoda@dfki.de

Abstract

Survey class Autonomous Underwater Vehicles (AUVs) typically rely on Doppler Velocity Logs (DVL) for precise navigation near the seafloor. In cases where the distance to the seafloor is greater than the DVL bottom lock range, localizing between the surface where GPS is available and the seafloor presents a localization problem, since both GPS and DVL are unavailable in the mid-water column. Previous work proposed a solution to navigation in the mid-water column that exploits the stability of the vertical water current profile in space over the minutes scale. With repeated measurements of these currents with the Acoustic Doppler Current Profiler (ADCP) mode of the DVL during vertical descent, along with sensor fusion of other low cost sensors, position error growth is constrained to near the initial velocity uncertainty of the vehicle at the sea surface during the dive. Following DVL bottom lock, due to correlations in the joint vehicle and water current velocity estimation, the entire velocity history is further constrained. In this paper, we explore a 25 hour long straight-line mission at 5000m depth undertaken by the *Sentry* AUV, where an IMU prediction model is compared to a constant velocity model in this framework.

Water-Current and IMU Aided AUV Localization in Deep Mid-Water

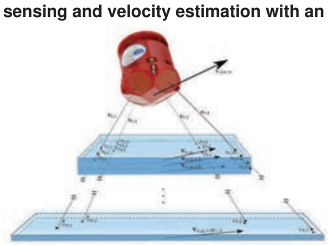
Lashika Medagoda[1] and James Kinsey[2]

[1]German Research Center for Artificial Intelligence (DFKI) [2]Woods Hole Oceanographic Institution

Introduction

- Survey class Autonomous Underwater Vehicles (AUVs) typically rely on Doppler Velocity Logs (DVL) for precise navigation near the seafloor.
- In cases where the distance to the seafloor is greater than the DVL bottom lock range, localizing between the surface where GPS is available and the seafloor presents a localization problem, since both GPS and DVL are unavailable in the mid-water column.
- Water currents are assumed slowly changing over the hours scale, with a spatial structure. With repeated measurements of these currents with the Acoustic Doppler Current Profiler (ADCP) mode of the DVL during vertical descent, along with sensor fusion of other sensors, position error growth is constrained during the mission.
- Following DVL bottom lock, due to correlations in the joint vehicle and water current velocity estimation, the entire velocity history is further constrained.
- In this work, the ADCP-aided filter is applied to a 25 hour 5000m deep straight line mission, with the environmental effects considered.
- The addition of IMU acceleration outputs from a navigation grade IMU for the prediction model as an alternative to the constant velocity model are implemented and analyzed.
- The re-acquisition of DVL bottom-lock at the end of the mission, simulating the vehicle lowering altitude to within range of the seafloor, is also investigated.

ADCP-aided sensing and velocity estimation with an AUV



The ADCP sensor possesses 4 beams in a Janus configuration, 30 degrees from the vertical. This allows fore, aft, port and starboard direction sensing capability.

IMU accelerations

The IMU sensor data from the iXSEA PHINS II has post-processing applied, as the raw measurements without added noise are not available due to export control. The unit supplies north-referenced attitude utilizing the gravity vector and gyrocompassing. The unit also supplies gravity-compensated acceleration outputs, in our case at 10 Hz. In order to use the acceleration output for our prediction model, the following model is applied:

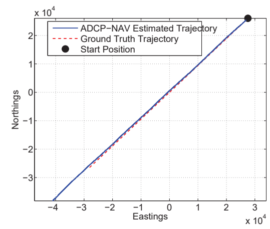
$$\mathbf{a}_{PHINS} = \mathbf{a}_{true} + \mathbf{b}_a + \nu_a \quad (1)$$

where $\mathbf{a}_{true}$ is the true acceleration of the vehicle, $\mathbf{b}_a$ is the accelerometer bias, and ν_a is zero-mean Gaussian noise.

Results

- Sentry AUV on long distance magnetic survey missions, obtaining magnetic measurements in the Western Pacific Ocean in December 2014 at operating depths of approximately 5000m.
- The experiment uses the DVL and USBL for initialization at the start of the mission, and then data-denies both for 25 hours. After 25 hours, DVL measurements are again processed by the filter to simulate DVL bottom-lock re-acquisition at low altitude.
- The processing times for each mission ∼7 hours on an Intel i7-4771 CPU @ 3.50GHz, implying potential real-time application.
- One challenging feature of this dataset is the magnitude of the noise in the ADCP measurements, as observed by analyzing the error velocity output, which range from 1-3 m/s (2σ). The deep water contains very few scatterers, thus making the return signal weak.

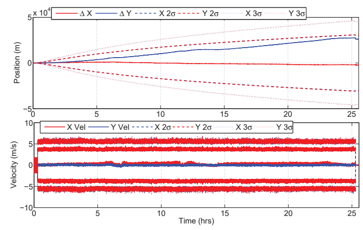
Sentry298/299 - Trajectory



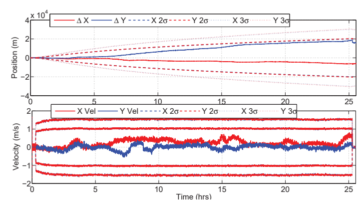
The estimation result is compared to the ground truth from USBL for Sentry 299.

Sentry298/299 - Errors

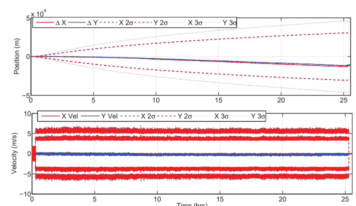
For each of the figure pairs below, the top plot shows the position residuals and 2 and 3 σ uncertainty bounds while the lower plot shows the velocity estimate residuals and uncertainty bounds.



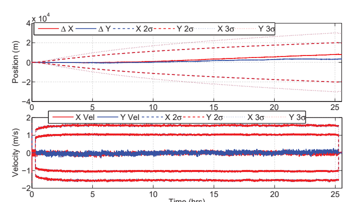
Sentry dive 298 with a constant velocity based prediction model. 27.5 km error after 25 hours with no DVL, with a 1.5 km correction with DVL bottom-lock.



Sentry dive 298 with an IMU based prediction model. 19.7 km error after 25 hours with no DVL, with a 2.7km km correction with DVL bottom-lock.



Sentry dive 299 with a constant velocity based prediction model. 17.3 km error after 25 hours with no DVL, with a 1.5 km correction with DVL bottom-lock.



Sentry dive 299 with an IMU based prediction model. 8.8 km error after 25 hours with no DVL, with a 37 m correction with DVL bottom-lock.

http://robotik.dfki-bremen.de/ lashika.medagoda@dfki.de, jkinsey@whoi.edu

3.12 'Water Current Estimation with an Autonomous Underwater Vehicle' (NP-P-03)

Lashika Medagoda [(1)]

(1) DFKI GmbH, Robotics Innovation Center, Robert-Hooke-Straße 1, 28359 Bremen, Germany

Contact: lashika.medagoda@dfki.de

Abstract

Water current velocities are a crucial component of understanding oceanographic processes and underwater robots, such as autonomous underwater vehicles (AUVs), provide a mobile platform for obtaining these observations. Additionally, a real-time estimate of the water-current velocity environment will aid the control and planning of the AUV, and localizing within a predicted water-current vector field is an area of continuing research. Estimating water current velocities requires both measurements of the water velocity, often obtained with an Acoustic Doppler Current Profiler (ADCP), as well as estimates of the vehicle velocity. Presently, vehicle velocities are supplied on the sea surface with velocity from GPS, or near the seafloor where Doppler Velocity Log (DVL) in bottom-lock is available; however, this capability is unavailable in the mid-water column where DVL bottom-lock and GPS are unavailable. Here we present a method which efficiently calculates vehicle velocities using consecutive ADCP measurements in the mid-water using an extended Kalman filter (EKF). The correlation of the spatially changing water current states, along with mass transport and shear constraints on the water current field, is formulated using least square constraints. Results from the Sentry AUV from a mid-water surveying mission at Deepwater Horizon and a small-scale hydrothermal vent flux estimation mission suggest real-time feasibility. Data-denial of DVL is undertaken to simulate mid-water missions to compare with ground truth DVL velocities. Results show quantifiable uncertainties in the water current velocities, along with similar performance, for the DVL and no-DVL case in the mid-water. A mission in a test tank is also completed, to show best case water current estimation for small flows.

Water Current Estimation with an Autonomous Underwater Vehicle

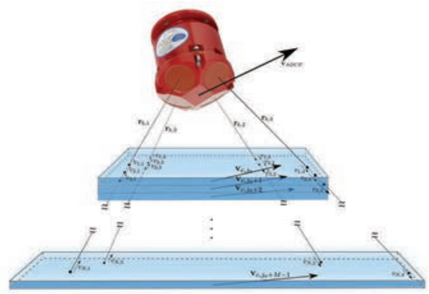
Lashika Medagoda[1], James Kinsey[2] and Sascha Arnold[1]

[1]German Research Center for Artificial Intelligence (DFKI) [2]Woods Hole Oceanographic Institution

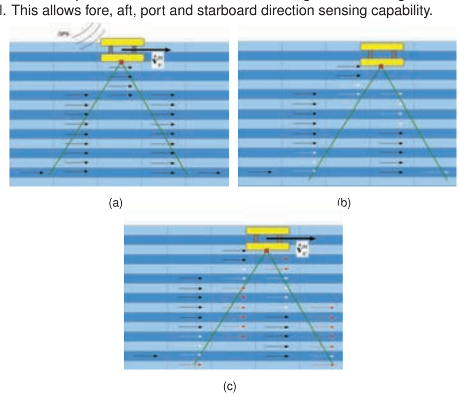
Introduction

- Underwater robots, such as autonomous underwater vehicles (AUVs), provide a mobile platform for obtaining water current velocities.
- This information could be used in real-time during an autonomous mission.
  - Water current informed path planning, so that vehicle control is optimized for energy or time.
  - Real-time adaptive sampling of the water current velocity field. e.g., by following the flow upstream or downstream in real-time, along with appropriate chemical sensing, the vehicle could search for a chemical source, or survey the extent of a chemical plume while accounting for the water transport.
- Estimating water current velocities requires both measurements of the water velocity, often obtained with an Acoustic Doppler Current Profiler (ADCP), as well as estimates of the vehicle velocity.
- Here we present a method which efficiently calculates water current velocities using consecutive ADCP measurements in the mid-water using an extended Kalman filter (EKF).
- The correlation of the spatially changing water current states, along with mass transport and shear constraints on the water current field, is formulated using least square constraints.
- Results from the Flatfish AUV in a test tank environment and the Sentry AUV from a mid-water surveying mission at Deepwater Horizon suggest real-time feasibility
- Similar performance is shown for the DVL and no-DVL case in the mid-water.

ADCP-aided sensing and velocity estimation with an AUV



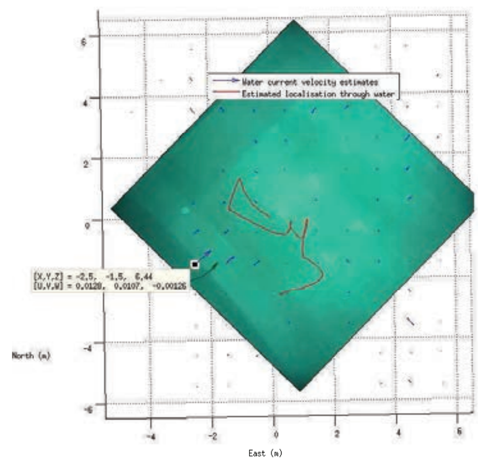
The ADCP sensor possesses 4 beams in a Janus configuration, 30 degrees from the vertical. This allows fore, aft, port and starboard direction sensing capability.



ADCP aiding method sequence in the mid-water (a) Initial GPS position and velocity are known, and water velocities with black arrows can be deduced. (b) The AUV moves, and repeatedly observes the same current bins, shown as white arrows.(c) The AUV velocity in the world frame can be deduced, along with new current bins shown in red.

Flatfish - DFKI test tank experiment

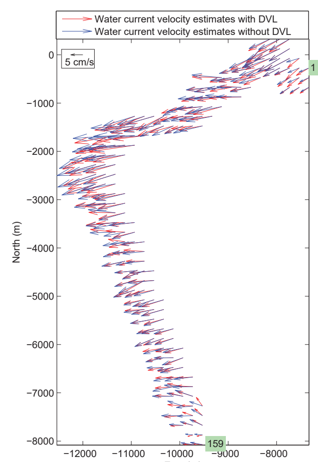
We validated this method using data obtained with the Flatfish AUV from the German Center for Artificial Intelligence (DFKI) developed for subsea inspection. This experiment seeks to estimate the water current flow from a submerged hose in a saltwater test tank located at the DFKI Robotics Innovation Center in Bremen. The vehicle collects DVL and ADCP measurements over a period of 600 seconds.



The hose is seen in the bottom left of the figure. The water current signal appears from that region. The reported accuracies by the filter were about 6 mm/s (2σ) for the water currents where the water current signal of approximately 1.5 cm/s. The water current estimates were calculated in MATLAB, with a processing time of 527 seconds, thus showing potential real-time application.

Sentry - Deep Water Horizon Oil Spill tracking

This mission completes a horizontal surveying mission undertaken by Sentry while tracking a hydrocarbon plume at $\sim$1100m depth During a 10000 second section of the mission with full DVL bottom-lock, a higher altitude mid-water is simulated by data-denying the DVL.



Water current velocity estimates with and without DVL with differences for the North and East velocity estimates within 2 cm/s. The processing time for the 10000 second mission in MATLAB on an Intel i7-4770K CPU at 3.50GHz was 3672 and 3016 seconds with and without DVL respectively, indicating real-time feasibility.

http://robotik.dfki-bremen.de/ lashika.medagoda@dfki.de, jkinsey@whoi.edu, sascha.arnold@dfki.de

German Research Center for Artificial Intelligence (DFKI) GmbH

DFKI Bremen
Robert-Hooke-Straße 1
28359 Bremen
Germany
Phone: +49 421 178 45-0
Fax: +49 421 178 45 4150

DFKI Saarbrücken
Stuhlsatzenhausweg 3
Campus D3 2
66123 Saarbrücken
Germany
Phone: +49 681 875 75 0
Fax: +49 681 857 75 5341

DFKI Kaiserslautern
Trippstadter Straße 122
67608 Kaiserslautern
Germany
Phone: +49 631 205 75 0
Fax: +49 631 205 75 5030

DFKI Projektbüro Berlin
Alt-Moabit 91c
10559 Berlin
Germany
Phone: +49 30 238 95 1800

E-mail:
reports@dfki.de

Further information:
http://www.dfki.de