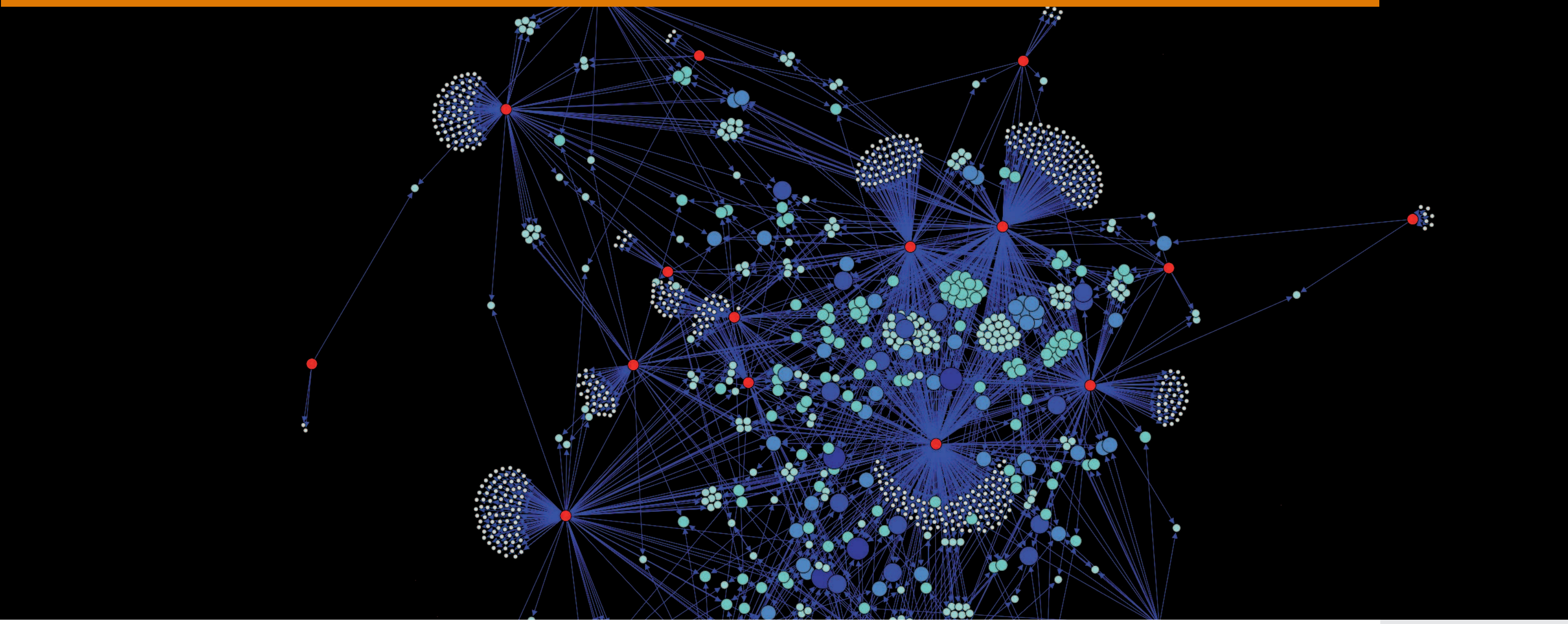
German Research Center for Artificial Intelligence

Document D-15-03



Proceedings of the RIC Project Day

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

Frank Kirchner (Editor)

Leif Christensen, Florian Cordes (Associate Editors)

09/2015

Document D-15-03

German Research Center for Artificial Intelligence (DFKI) GmbH

Bibliographic information published by the German National Library

The German National Library lists this publication in the German National Biography; detailed bibliographic data are available in the internet at http://dnb.ddb.de.

Issue D-15-03 (2015)
ISSN 0946-0098

German Research Center for Artificial Intelligence
Deutsches Forschungszentrum für Künstliche Intelligenz

DFKI GmbH

Founded in 1988, DFKI today is one of the largest nonprofit contract research institutes in the field of innovative software technology based on Artificial Intelligence (AI) methods. DFKI is focusing on the complete cycle of innovation – from world-class basic research and technology development through leading-edge demonstrators and prototypes to product functions and commercialization.

Based in Kaiserslautern, Saarbrücken and Bremen, the German Research Center for Artificial Intelligence ranks among the important 'Centers of Excellence' worldwide. An important element of DFKI's mission is to move innovations as quickly as possible from the lab into the marketplace. Only by maintaining research projects at the forefront of science DFKI has the strength to meet its technology transfer goals.

The key directors of DFKI are Prof. Wolfgang Wahlster (CEO) and Dr. Walter Olthoff (CFO). DFKI's research departments are directed by internationally recognized research scientists:

- Knowledge Management (Prof. A. Dengel)
- Cyber-Physical Systems (Prof. R. Drechsler)
- Robotics Innovation Center (Prof. F. Kirchner)
- Innovative Retail Laboratory (Prof. A. Krüger)
- Institute for Information Systems (Prof. P. Loos)
- Embedded Intelligence (Prof. P. Lukowicz)
- Agents and Simulated Reality (Prof. P. Slusallek)
- Augmented Vision (Prof. D. Stricker)
- Language Technology (Prof. H. Uszkoreit)
- Intelligent User Interfaces (Prof. W. Wahlster)
- Innovative Factory Systems (Prof. D. Zühlke)

In this series, DFKI publishes research reports, technical memos, documents (eg. workshop proceedings), and final project reports. The aim is to make new results, ideas, and software available as quickly as possible.

Prof. Wolfgang Wahlster
Director

Proceedings of the RIC Project Day

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

Frank Kirchner (Editor)

Leif Christensen, Florian Cordes (Associate Editors)

09/2015

Dokument D-15-03 des

Deutschen Forschungszentrums für Künstliche Intelligenz (DFKI)

Abstract

This document is the current edition of an ongoing series of proceedings to document the workgroups' topics, discussions and efforts at the Robotics Innovation Center of DFKI GmbH. The content of each of these editions represents presentations (talks and posters) of a project day which is organized by two workgroups, respectively.

Workgroups are formed by peers that are dedicated to a specifc topic, so that they provide a platform for cross-project communication and knowledge transfer. In 2008 the workgroups started to present their results and past years work in an open presentation format called brown-bag talk, being a year after moved to more specialized so-called project days. Every year, since 2009, each workgroup presents results and past years work this project day. This format was extended to talk and poster presentations accompanied by the corresponding proceedings as a DFKI Document in 2015.

Zusammenfassung

Dieses Dokument enthält die aktuelle Ausgabe einer laufenden Tagungsband-Serie, welche die Themen, Diskussionen und Bemühungen der Arbeitsgruppen am Robotics Innovation Center der DFKI GmbH dokumentiert. Inhalt einer jeden Ausgabe sind die Vorträge und Poster eines Projekttags, der von jeweils zwei Arbeitsgruppen organisiert wird.

Arbeitsgruppen haben einen Leiter und widmen sich einem bestimmten Themengebiet, in dem sie eine Plattform für Kommunikation und Wissenstransfer über die Projekte hinaus darstellen. Im Jahr 2008 begannen die Arbeitsgruppen ihre Ergebnisse und Arbeiten in einem offenen Vortragsformat (dem sog. Brown-Bag Talk) vorzustellen, welches dann ein Jahr später in eigene Projekttage mündete. Seit 2014 ist dieses Format des Projekttags nochmal zu Vorträgen und Poster-Sitzungen erweitert worden, die seitdem in dem entsprechenden Tagungsband im Format eines DFKI Documents festgehalten werden.

Contents

1 Editorial

This is the third edition of 2015 to document the efforts of the DFKI-RIC thematic workgroups. 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 start 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 further colleagues of the institute. Nowadays, the project day is organized as a one-day workshop with oral presentations, poster sessions, and a free pizza lunch for everybody who attends. Until now, the talks and posters have only been collected on our servers but were not assembled in a citable document.

This format at present is the next evolutionary step and it aims at eliminating this deficit by compiling the material of the workgroups presented during a project day into a single, citable document of unified format. We will see which steps can be taken in the future to enhance the presentation quality of this material.

Frank Kirchner

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

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 extend 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.

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 review the of state of the art in robot locomotion. In 2015 a modular test track based on the ASTM standard for evaluating emergency response robots was devised within the discussions of the workgroup. The behavior library from the LIMES project and the locomotive capabilities of the SherpaTT hybrid wheeled-leg rover designed in the project TransTerrA were two more topics discussed regularly in the workgroup 'Locomotion & Mobility' in 2015. 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. This year's project day presentations of the workgroup 'Locomotion & Mobility' encompass these topics with the first hardware experiences with SherpaTT and a behavior library for walking robots. Furthermore the new project Vipe was introduced in one presentation and an external presentation on the leg design for the humanoid robot ARMAR-IV were part of the second half of the project day.

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.

Leif Christensen, Florian Cordes

2 ‘Navigation & Planning’

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

Leif Christensen [(1)]

(1) Robotics Innovation Center, DFKI GmbH, 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.

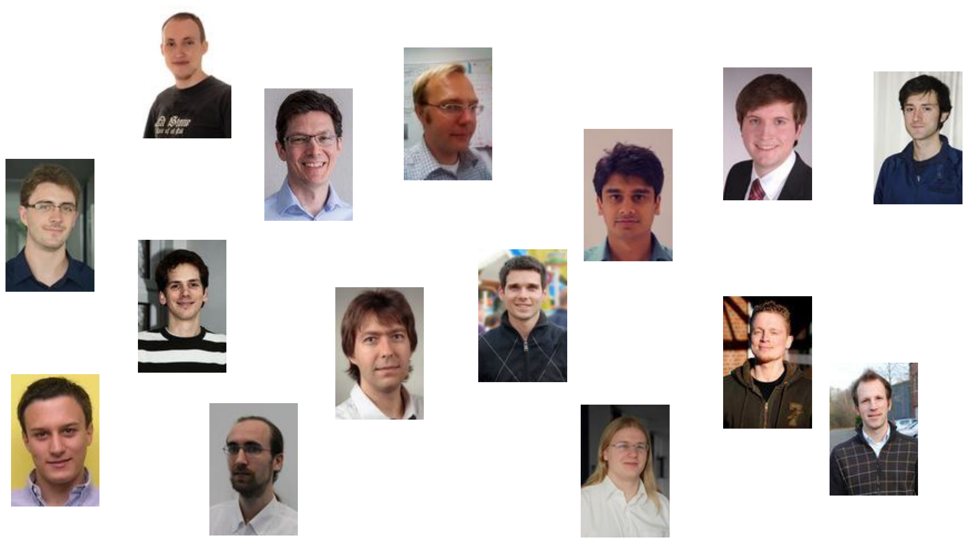
AG Navigation & Planning

Project Day
17.09.2015

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

Universität Bremen

AG Navigation & Planning



Universität Bremen

2

Agenda

Start	End	Title	Presenter	Duration
9:30	9:35	**Introduction AG Navigation & Planning**	Leif Christensen	0:05
9:35	10:05	SpaceBot Cup Qualifying - Recap	Sascha Arnold, Janosch Machowinski	0:30
10:05	10:20	Mission planning for reconfigurable multi-robot systems	Thomas Röhr	0:15
10:20	10:35	Environment Representation: Antecedents and Directions	Javier HidalgoCarrió	0:15
10:35	10:45	*Coffee Break*		0:10
10:45	11:00	Mid-water localization for Autonomous Underwater Vehicles	Dr. Lashika Medagoda	0:15
11:00	11:15	AUV Docking in the EuropaExplorer Project	Dr. Marc Hildebrandt	0:15
11:15	11:30	Distortion-Robust Distributed Magnetometer for Confined UUVs	Leif Christensen	0:15
11:30	11:45	Cooperative Map-Building: An approach to distributed, multi-modal SLAM	Sebastian Kasperski	0:15
11:45	12:00	Monocular Self-Referenced Line Structured Light	Alexander Duda	0:15
12:00	12:15	*Coffee Break*		0:15
12:15	12:20	**Introduction AG Locomotion & Mobility**	Florian Cordes	0:05
12:20	12:35	SherpaTT: First Experiences with the Hardware	Florian Cordes	0:15
12:35	12:55	Leg design for the humanoide robot ARMAR IV	Heiner Peters	0:20
12:55	13:10	Experience-Based Adaptation of Locomotion Behaviors for Kinematically Complex Robots in Unstructured Terrain	Alexander Dettmann	0:15
13:10	13:20	Projektvorstellung Vipe	Florian Cordes	0:10
13:20	13:45	*Lunch*		0:25
13:45	14:30	**Postersession**		
		Autonomous underwater vehicle FlatFish	Christopher Gaudig	
		Plan Execution Interchange Language Plexil	Martin Fritsche	
		Integrating Environment Representation and Simulation: Towards an Internal Simulator for Rock using Mars	Raúl Domínguez	
		An Experience-Based Interface for Abstracting the Motion Control of Kinematically Complex Robots	Alexander Dettmann, Sebastian Bartsch	
		SherpaTT - Adaptive Suspension and Locomotion Coordinate Systems	Florian Cordes, Ajish Babu, Daniel Kühn	

Universität Bremen

3

2.2 'Spacebot Cup 2015 qualification recapitulation' (NP-T-02)

Sascha Arnold[(1)], *Janosch Machowinski*[(1)]

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

Contact: sascha.arnold@dfki.de, janosch.machowinski@dfki.de

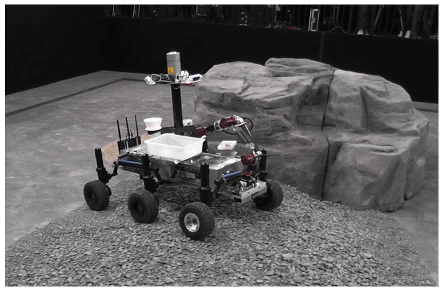
Abstract

This talk explains the requirements of the three tasks of the the Spacebot Cup qualifying 2015 and how they where solved by the Artemis team. If gives an overview on which algorithms and sensors were used to perform mapping and localization, global path planning, exploration, far distance object detection, object position validation and close distance object detection. It also shows the state machines that were used in each of the tasks and how the internal states of the robot where visualized for the human observers.

Spacebot Cup Qualifying

Recap

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



Universität Bremen

Spacebot Cup Qualifying

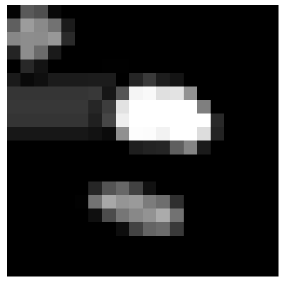
- Three tasks
- 15 minutes time window for each task
- Two attempts per task
- Two equal 10x10 meters fields
- 10 teams

Universität Bremen

2

Qualifying Task 1

- Exploration in almost unknown terrain
- Generate a more accurate map of the environment
- Identify the position of two known objects (battery and cup)
- Mark the postion of the objects in the map

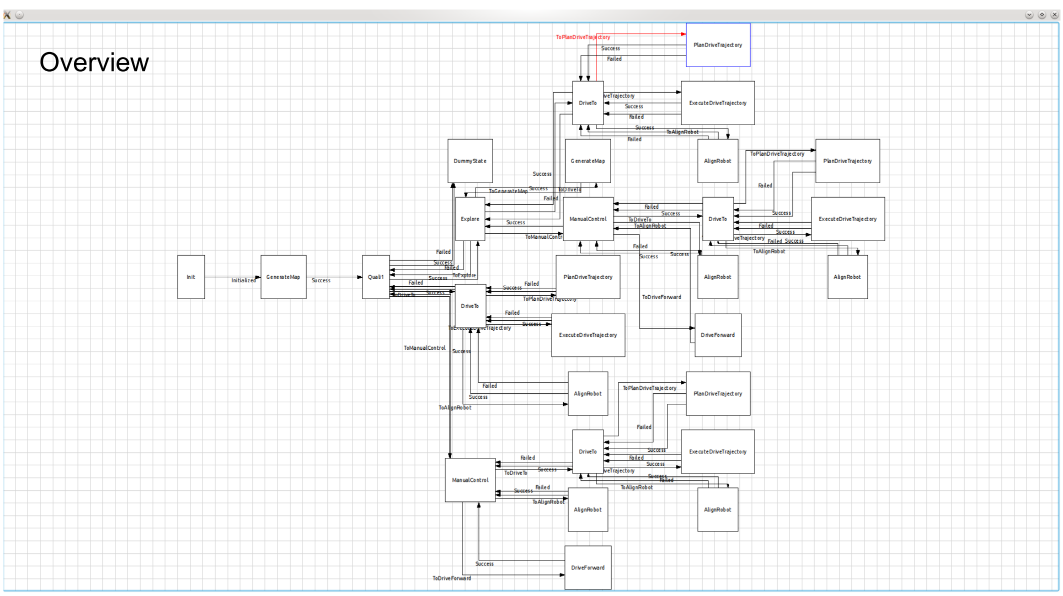


A-priori available map

Universität Bremen

3

Task Management – Task 1

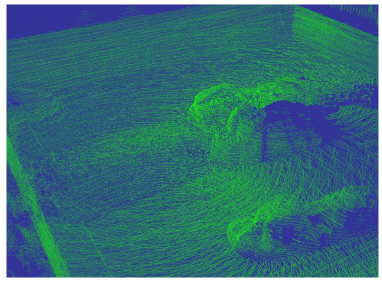


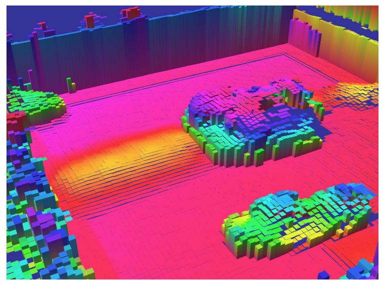
Universität Bremen

4

Mapping and localization

- Velodyne HDL-32E Lidar
- GICP algorithm to identify transformations betweens scans
- GICP and odomety based transformations are modelled in a graph
- Graph relaxation to achive a consistent result
- Pointclouds are projected to a Multi-Level Surface Map
- Voxel grid based subsampling of the scans has proven very beneficial



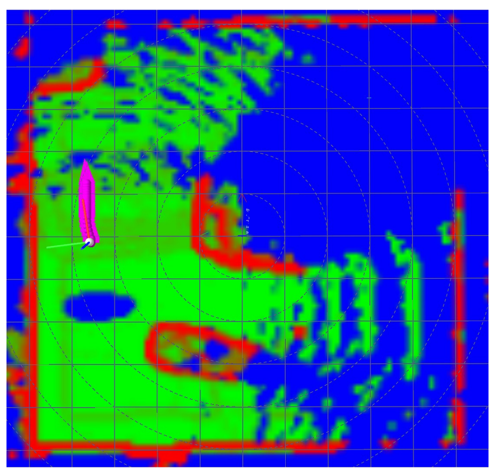


Universität Bremen

5

Global path planning

- Traversability grid as basis for the global path planning
- The traversability grid is generated on basis of the Multi-Level Surface Map
- OMPL and SBPL Sample-Based Planning

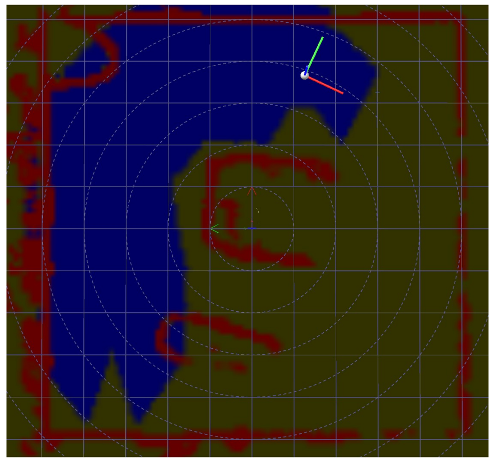


Universität Bremen

6

Exploration

- Exploration on basis of the traversability grid
- Camera based footprint
- Next waypoint depends on the distance, reachability and size of the unknown area

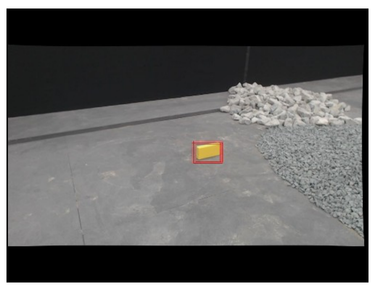


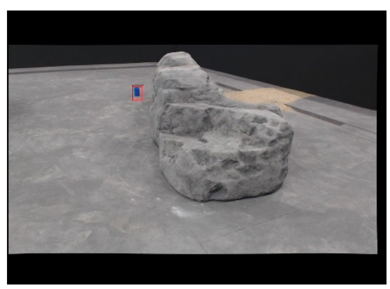
Universität Bremen

7

Far distance object detection

- Color based segmentation
- Template based object detection using the LineMod approach



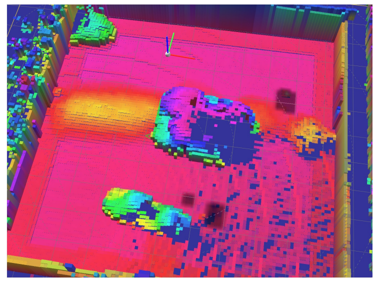


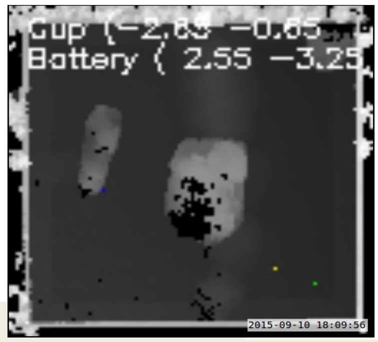
Universität Bremen

8

Object position validation

- Intersection between object position in the camera image and the MLS map to determin postion in the map
- Probability grid to identify the most-likely postition of the object
- Projection of the MLS map and object positions to an image



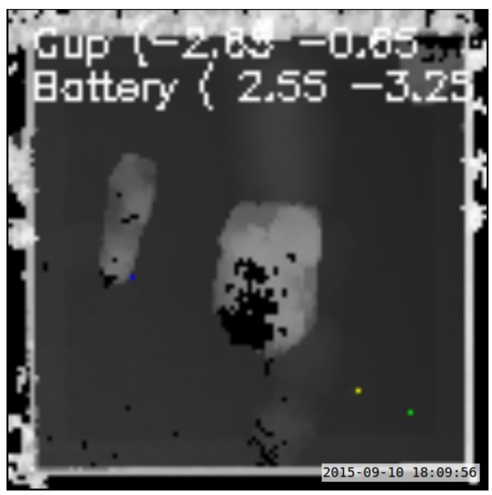


Universität Bremen

9

Qualifying Task 2

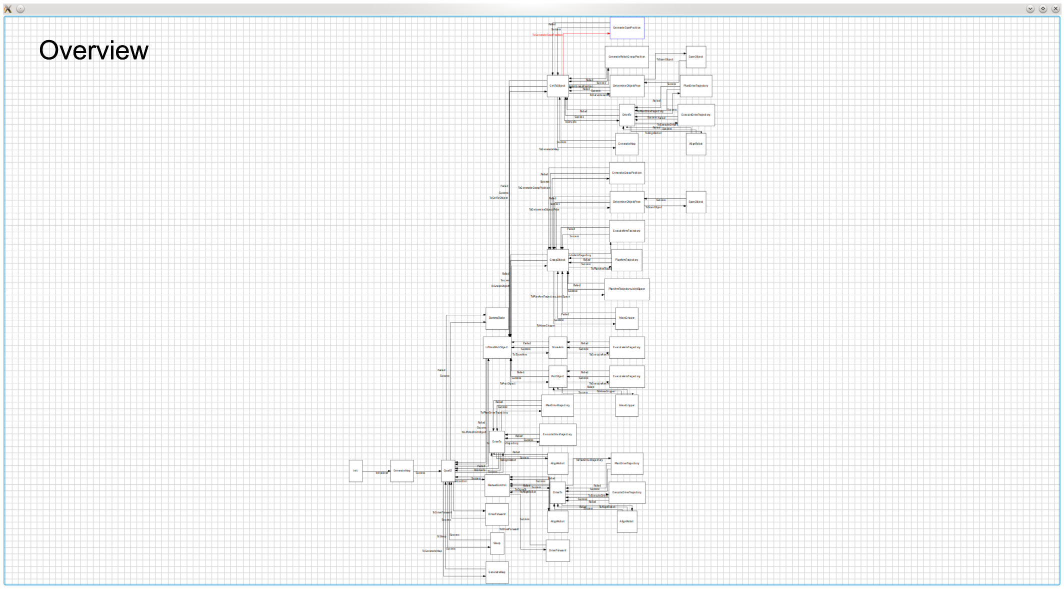
- Plan and traverse a path to both obejcts
- The map and object positions of task 1 must be used
- Each object needs to be liftet up and put back on the ground



Universität Bremen

10

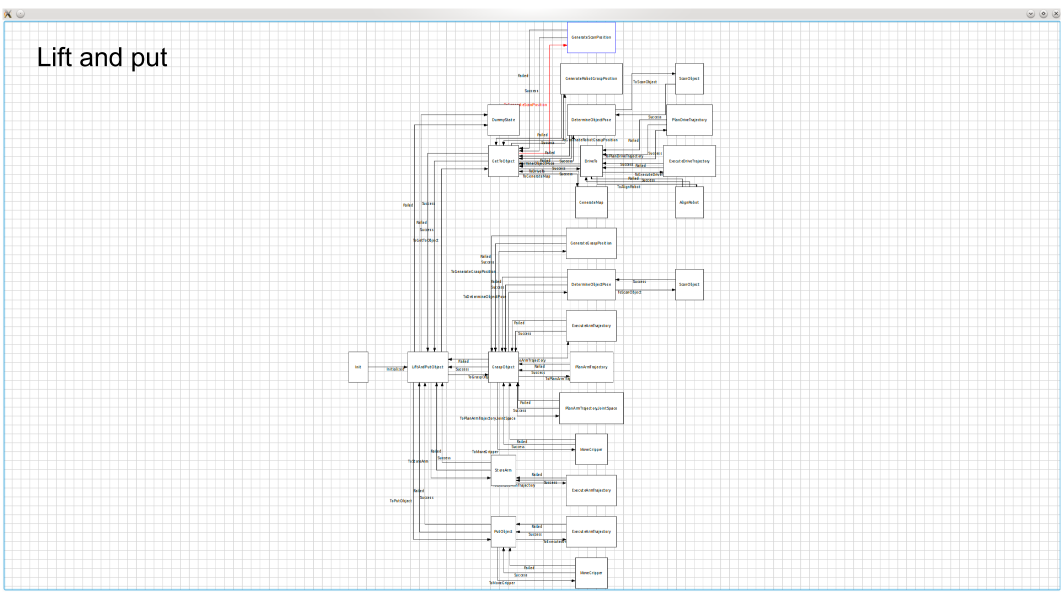
Task Management – Task 2



Universität Bremen

11

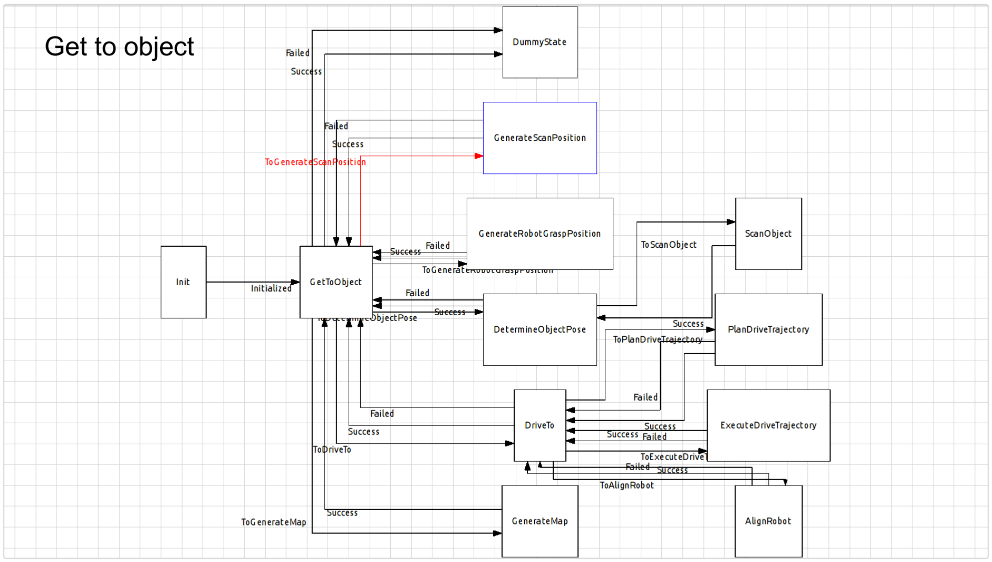
Task Management – Task 2



Universität Bremen

12

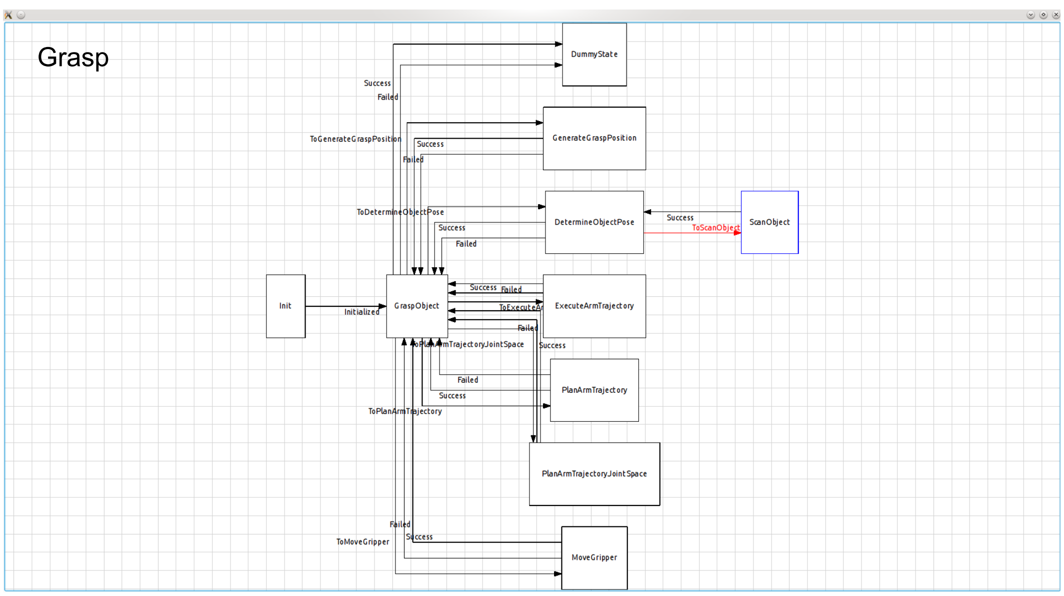
Task Management – Task 2



Universität Bremen

13

Task Management – Task 2

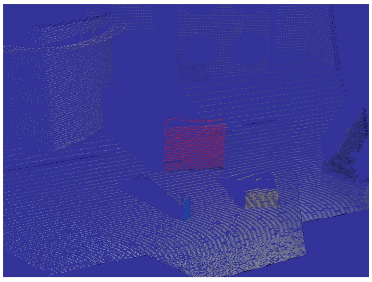


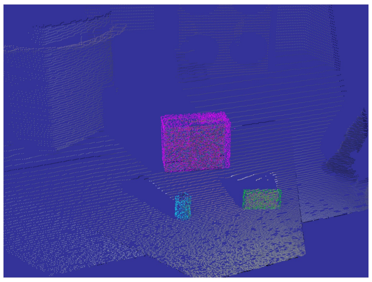
Universität Bremen

14

Close distance object detection

- Colored pointclouds using two front cameras
- Segmentation of candidates using the color
- Identification of initial object pose by the size and orientation of the surfaces
- Correction of pose using an ICP algorithm
- Color segmentation needs to be improved





Universität Bremen

15

Logs of task 2

<A video was shown on this slide>

File: spacebot_qualification_task_2_sensordata.mp4

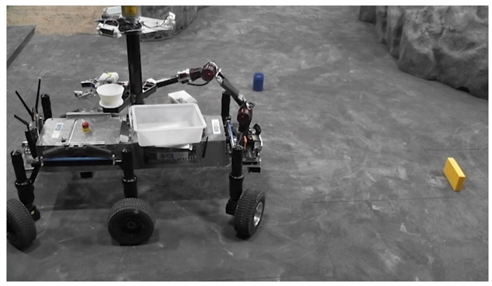
Content: The video shows the output of the main software components while the robot performes task 2. The pose of the robot in the generated maps, Multilevel-Surface map, the traversability map, exploration map and the object detection probability maps, are visualized. Also the output the for cameras and the image based object detection and the traversed path of the robot is shown.

Universität Bremen

16

Qualifying Task 3

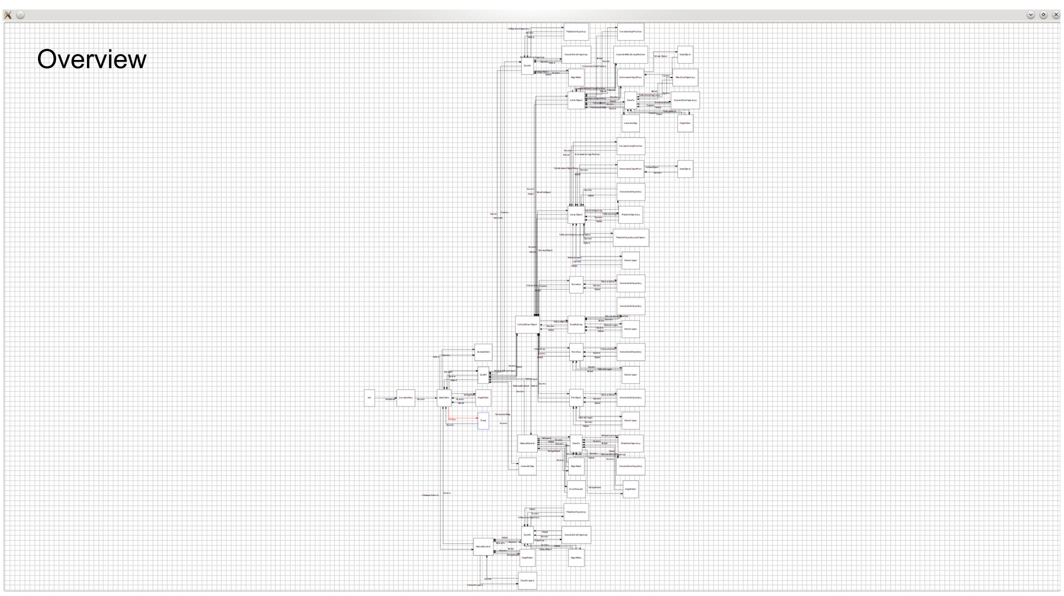
- Both objects are inside a 3 m radius around the robot
- Both objects need to be picked up
- The robot drives with the objects to a a-priori known target position
- The environment was altered by a smaller boulder after task 2



Universität Bremen

17

Task Management – Task 3

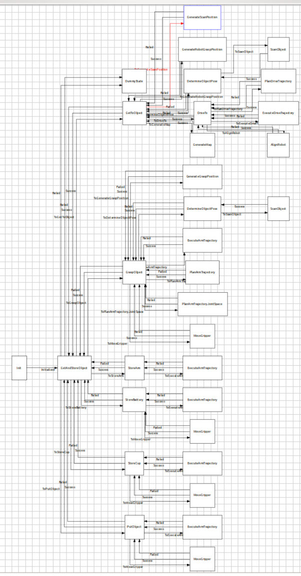


Universität Bremen

18

Task Management – Task 3

Get and store



Video of task 3

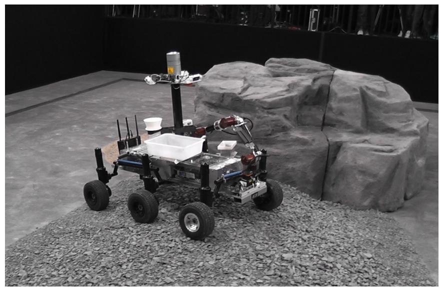
<A video was shown on this slide>

File: spacebot_qualification_task_3.avi

Content: The video shows the robot performing task 3. Finding and collecting two objects which are placed around the robot.

Thank you!

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



Universität Bremen

2.3 ‘Mission planning for reconfigurable multi-robot systems’ (NP-T-03)

Thomas M. Roehr[(1)]

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

Contact: thomas.roehr@dfki.de

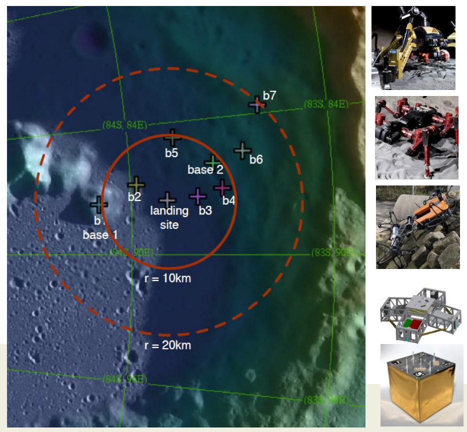
Abstract

This talk present an approach to mission planning for reconfigurable multi-robot systems. It briefly introduces some formal background to the topic, and illustrates the current work-in-progress for developing a temporal mission planning system. The planning system operates on an OWL-based organization model in order to fully exploit reconfigurability. The planner implementation relies on a large collection of state of the art technologies and combines them in a novel way to solve the problem at hand.

Mission planning for reconfigurable multi-robot systems

by Thomas M. Roehr

Project Day 17.9.2015
Workgroup Navigation & Planning



Universität Bremen

Do what you can, with what you have, where you are.

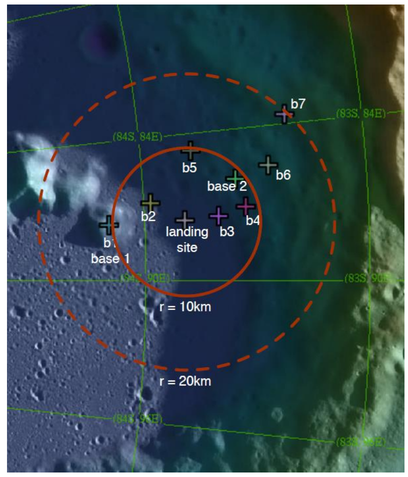
Theodore Roosevelt

Universität Bremen

2

Mission

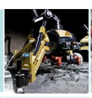
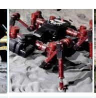
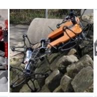
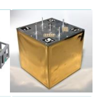
- autonomous multi-robot exploration of the lunar surface driven by science targets
- Example science targets
  - take samples at location b_3, b_4, b_5
  - take pictures from location b_3, b_4, b_5
  - map area around *landing site*
  - place infrastructure elements/sensor equipment at *base 1* and *2*



Universität Bremen

3

The set of available resources

Robots / Capabilities					
Locomotion	✓	✓	✓		
Manipulation	✓		✓		
Imaging	✓	✓			✓
Power	✓	✓	✓	✓	✓
Mapping	✓	✓	✓		
…					
Count *(Example Scenario)*	*1*	*1*	*1*	*3*	*10*

Universität Bremen

4

A reconfigurable multi-robot system

Definition 1.1
A physical robotic system represents an **atomic actor** $a \in A$, when it cannot be separated into two or more robotic systems

Definition 1.2
A physical coalition of two or more atomic actors is a **composite actor** CA, i.e.

$$CA = \{a_i, \dots, a_j\}, where\ a_i, \dots, a_j \ \in A, |CA| = 1$$

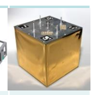
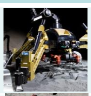
Definition 1.3
Atomic and composite actors are single minded, individual robotic actors.

Definition 1.4
A **reconfigurable multi-robot system** $RMRS$ is a set of fully cooperative atomic actors that can temporarily from composite actors

Universität Bremen

5

A reconfigurable multi-robot system

Robot + Robot					
	✓	✓	✓	✓	✓
	✓				✓
	✓			✓	✓
	✓		✓		✓
	✓	✓	✓	✓	✓

|CA| <= |A|
possible combinations $\leq 2^{|A|}$

The number of available and compatible electro-mechanical interfaces limits the possible combinations, but, e.g., finding an optimal coalition is $O(2^N)$

Universität Bremen

6

Modelling the robotic system

- Organization model to represent
  - atomic actor capabilities and services
  - reconfigurability with other robots
  - Inference of composite actor capabilities and services
- Implementation using Description Logic (DL) related Web Ontology Language (OWL)
  - qualified cardinality constraints

$$PayloadItem \sqsubseteq Actor \sqsubseteq Resource \sqsubseteq \top$$
$$EmiActive \sqsubseteq Interface \sqsubseteq Resource \sqsubseteq \top$$
$$EmiActive \sqcap EmiPassive \equiv \bot$$
$$PayloadItem \equiv Actor \sqcap 1 has.EmiActive \sqcap 1 has.EmiPassive$$
$$EmiPassive \sqsubseteq Interface \sqsubseteq Resource \sqsubseteq \top$$

Universität Bremen 7

Defining the planning problem

- Mission description
  - $M = (A_a, STR, C)$, where
    - A_a is the set of available atomic actors
    - STR is the set of spatio-temporally qualified requirements
    - C is the set of (temporal) constraints
  - $r \in STR$ is a spatio-temporally qualified expression ($steq$) of the form $(S, A_r)@[l, t_s, t_e]$, where
    - S is the set of required services
    - A_r is the set of required atomic actors
    - l is a location variable
    - t_s and t_e are temporal variables, such that $t_s < t_e$

Universität Bremen 8

Defining the planning problem

- Mission description example:
  - Constants:
    - locations $L = \{lander, b_1, \dots, b_n\}$; timepoints $T = \{t_0, \dots, t_n\}$
  - $(S, A_r)@[l, t_s, t_e] \rightarrow$ $(\{ImageLocationProvider, EmiPowerProvider\}, \{\})@[lander, t_0, t_1]$


```
  - <location>
      <id>b7</id>
      <radius>moon</radius>
      <latitude>-83.34083</latitude>
      <longitude>84.64467</longitude>
    </location>
  </constants>
- <requirements>
  - <requirement>
    - <spatial-requirement>
          <!-- where it is required -->
      - <location>
          <id>lander</id>
        </location>
      </spatial-requirement>
        <!-- when it is required / mixing qualitative and quantitative information -->
    - <temporal-requirement type="persistence-condition | event">
        <from>t0</from>
        <to>t1</to>
      </temporal-requirement>
        <!-- what is required at this very position -->
    - <service-requirement>
        <service>http://www.rock-robotics.org/2014/01/om-schema#LocationImageProvider</service>
        <service>http://www.rock-robotics.org/2014/01/om-schema#EmiPowerProvider</service>
      </service-requirement>
    </requirement>
  - <requirement>
    - <spatial-requirement>
          <!-- where it is required -->
      - <location>
          <id>b1</id>
```


Universität Bremen 9

Solving the planning problem

- Planning algorithm:
  (1) *typing*
  assign actor types that fulfill the (service and resource) requirements for each spatio-temporal tuple
  (2) *role assignment*
  pick a solution from (1) and instantiate, i.e. assign roles to each atomic actor type
  (3) *timeline construction*
  for each role create a timeline
  (4) *time-expanded network construction*
  create a transport network from system movements
  (5) *flow optimization for immobile systems (e.g. payload)*
  compute flow/"transport lines"
  (6) *assign roles to robots*

Universität Bremen 10

Typing

(1) Example: typing for
$(\{ImageLocationProvider, EmiPowerProvider\}, \{\})@[lander, t_0, t_1]$

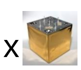
feasible atomic actor types *feasible composite actor types*

Robots / Capabilities							
Locomotion	✓	✓	✓			✓	
Imaging	✓	✓			✓	✓	
Power	✓	✓	✓	✓	✓	✓	. . .
ImageLocation-Provider	✓	✓				✓	
EmiPowerProvider	✓	✓	✓	✓	✓	✓	

Universität Bremen 11

Role assignment

(2) Example role assignment

- composite actor that fulfills requirements: 
  - Coyote III + (Camera)-Payload
- 1 x  available → role: $coyote_0$
- 10 x  available → role: $payload_0, \dots, payload_9$

This is not a direct assignment to a particular system and allows:

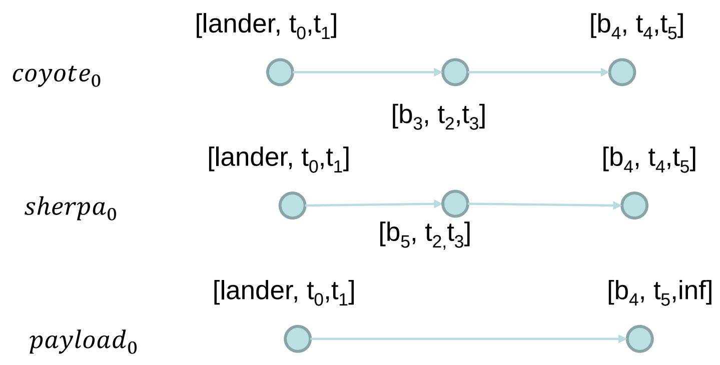
- optimization of particular actor assignment
- timeline construction

Universität Bremen 12

Timeline construction

(3) Example timeline construction

- time-ordered (temporally qualified) path of a system's locations



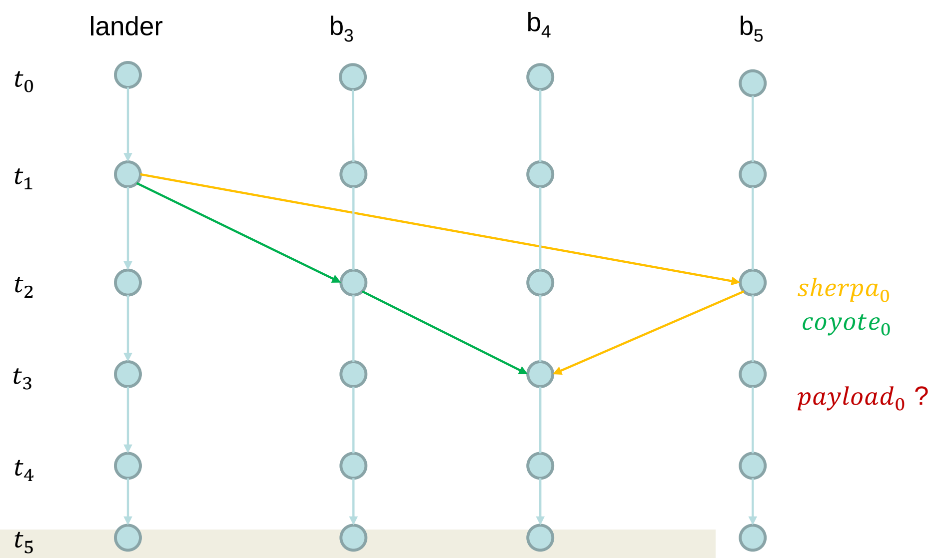
$$t_0 < t_1 < t_2 < t_3 < t_4 < t_5$$

Universität Bremen

13

Time-expanded network construction

(4) construction for mobile systems

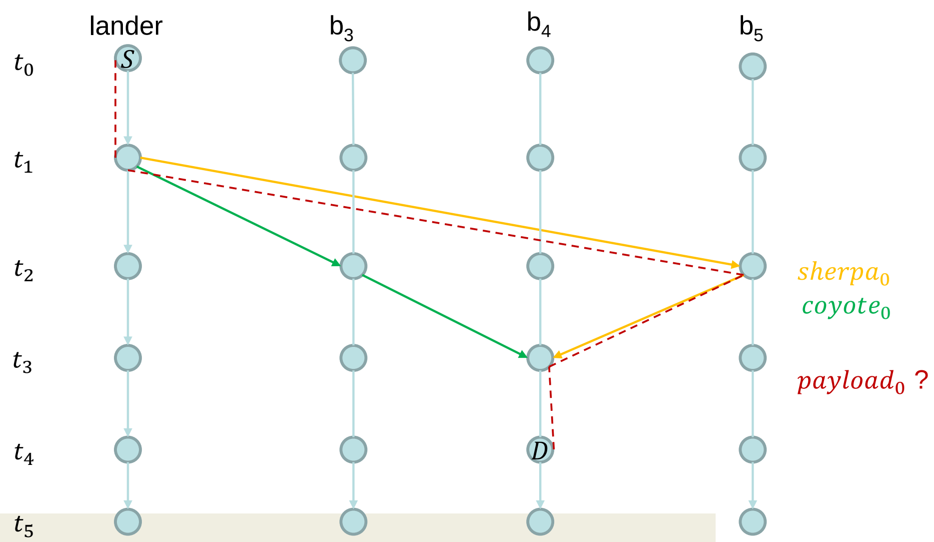


Universität Bremen

14

Flow optimization

(5) For payload transport assign supply S to origin location, demand D to destination and solve for min-cost flow



Final assignment

(6) Find a good assignment to actual robots

- What is good?
  - efficient: minimum energy cost
  - safe: keep a high or given level of redundancy to guarantee mission success

Conclusion

- Looks like mission planning for reconfigurable multi-robot systems is doable
  - current implementation yet lacks the construction of the time expanded network
  - flow optimization has been implemented as linear program, thus in this form likely not scalable

- Technologies involved:
  - knowledge-based reasoning (OWL) (using my C++ implementation of owlapi)
  - constraint-based problem solving (using Gecode)
  - flow optimization, linear programming (using GLPK)
  - temporal constraint satisfaction (using my C++ implementation)
  - graphs and graph algorithms (integration using my graph_analysis library – a wrapper for lemon, SNAP, and boost)

Universität Bremen

17

NP

2.4 ‘Environment Representation: Antecedents and Directions’ (NP-T-04)

Javier Hidalgo [(1)], *Sascha Arnold* [(1)], *Raul Dominguez* [(1)], *Yong-Ho Yoo* [(1)], *Arne Boeckmann* [(1)], *Anna Born* [(1)], *Behnam Asadi* [(1)]

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

Contact: `javier.hidalgo_carrio@dfki.de`

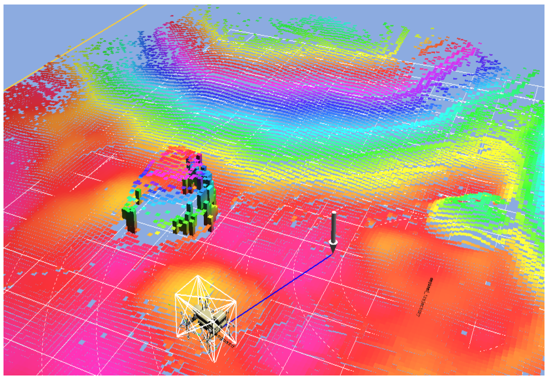
Abstract

Environment perception is a key functionality for the robot to navigate across unknown environments. State-of-the-Art representations of such environments are suitable for the robot to navigate and construct the environment while driving (e.g.: SLAM). However the interchange of such information among robotic subsystems is mostly limited or some cases impossible. The robot collects and generates rich amount of perceptive data while driving across the terrain. When performing isolated or complicated tasks like localization and mapping the same environment representation might be used with almost zero cost. Conversely, when robots perform complex mission scenarios other subsystems (i.e.: perception, planning, internal simulation, telemetry, etc.) have the requirements to actively inter and exchange information in an effective manner. Environment Representation (EnviRe) technologies are meant to close the gap and provide techniques to store, operate and interchange information within a robotic system. The application of EnviRe mainly focus to support navigation, simulation and operations and simplify the interchange of algorithms among software components.

Environment Representation

AG Navigation & Planning

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



Universität Bremen

Content

- Environment Representation (EnviRe 2.0)
  - What is it?
  - Motivation for a reimplementation
- The current implementation
  - Localization
  - Visualization
  - Simulation
- The way to collaborate

Universität Bremen

Envire: what is it?

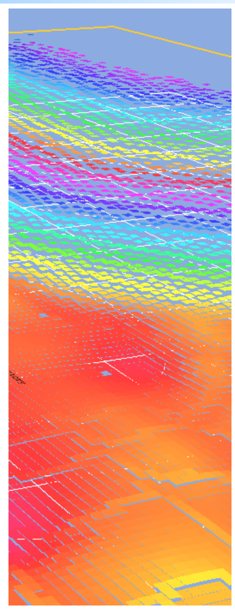
*The **Environment** representation is a **model** of the world defined by several different **objects** and their **relations** to each other*

- Model: graph and tree
- Objects: maps, point coulds, robot poses, vision features, descriptors, meshes, physical objects, semantic, etc..
- Relations: so far spatial-temporal relationships

Universität Bremen

Environment Representation

- Same concept as for EnviRe 1.0:
  - Deliberative systems require Environment Representation (ER) for path planning/motion planning
  - ER is required for localisation and mapping (and of course SLAM)
  - A lot of algorithms exist to operate on ER, but there are a limited number of ways to represent an environment
  - Developing libraries that can be used by different projects can lead to:
    - Easier transfer of Algorithms
    - A common visualisation



Universität Bremen

Motivation for reimplementation

- We need a better code structure/organization
- Generalization to store any type of objects (no only maps)
- Reimplementation of the serialization mechanism (Rock)
- Interface with simulation (e.g. Mars)
- Visualization is separated from the internal representation

EnviRe 2.0 structure:

- envire-core: graph, transformation and abstract classes
- envire-maps: basic grid map library and MLS maps
- envire-slam: slam integration of envire with GTSAM
- envire-mars: integration with internal simulation
- envire-gis: integration with GIS (e.g. GRASS)

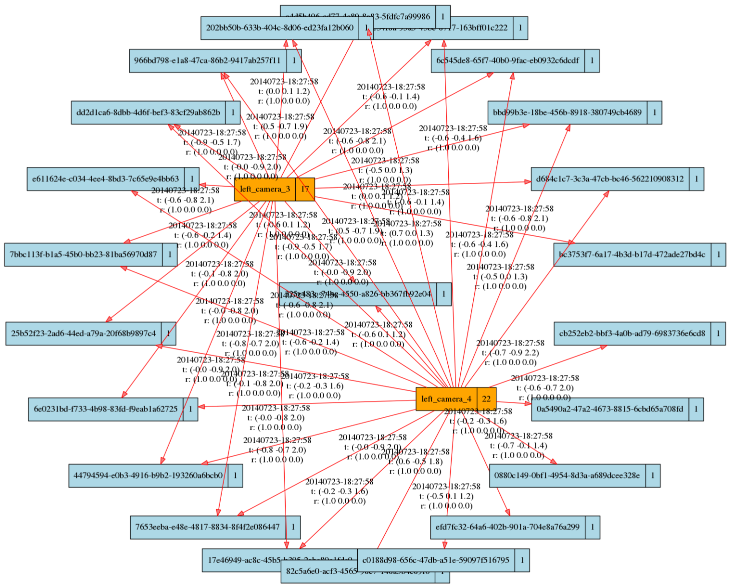
Universität Bremen

Current Implementation

- Startin point for the code exists EnviRe1.0
- Plugin system using class_loader (standard in roboitics and well documented)
- Abstract visualization with GraphViz
- Graph and Tree representation with boost graph
- Grid maps and MLS library is ready to use (serialization pending).

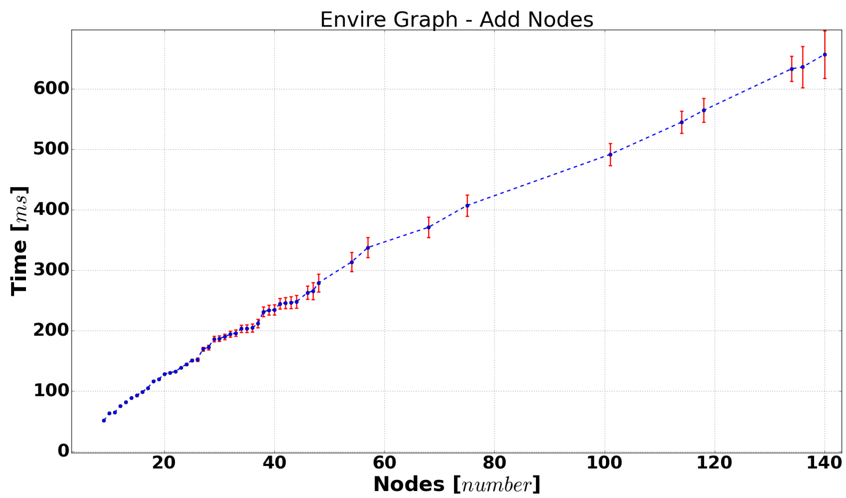
Universität Bremen

Localization



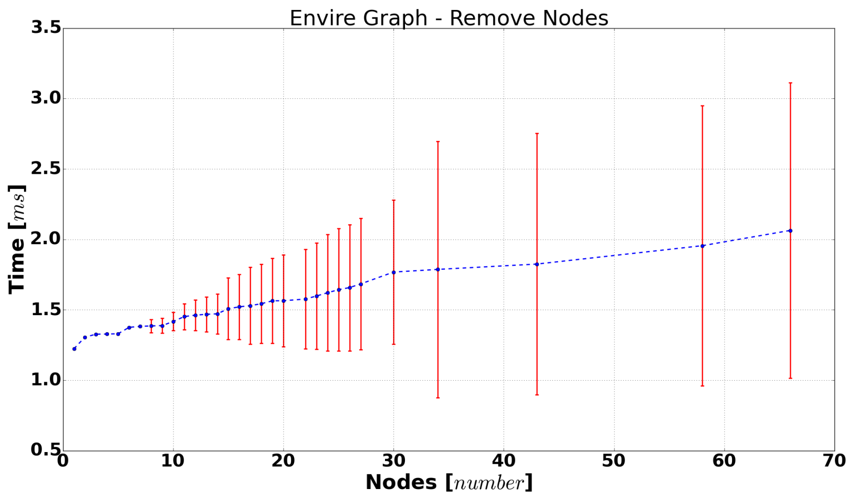
Universität Bremen

Graph Performance



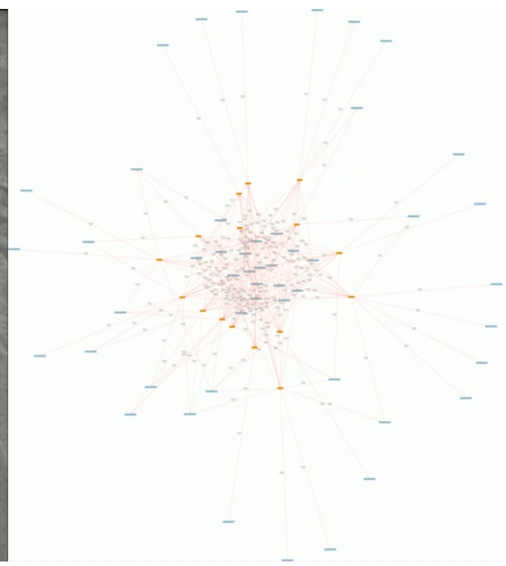
Universität Bremen

Graph Performance



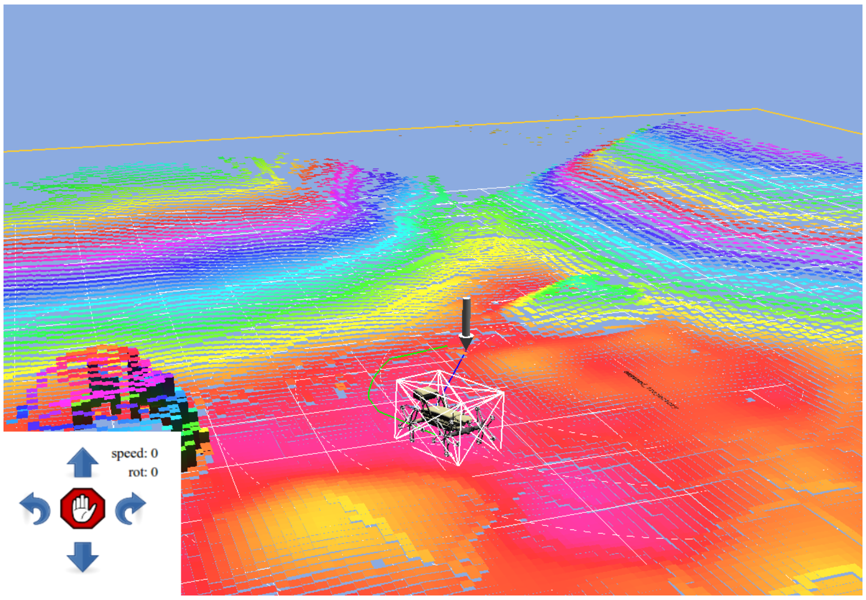
Universität Bremen

Localization



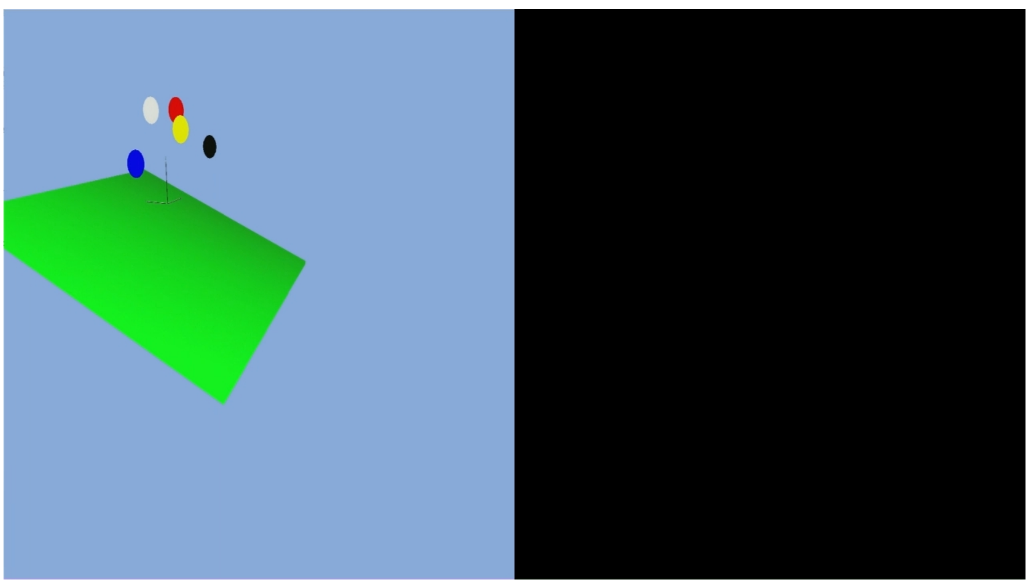
Universität Bremen

Visualization



Universität Bremen

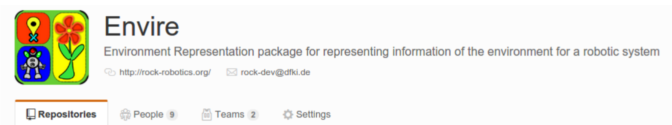
Simulation



Universität Bremen

The way to collaborate

- There are practical issues to inter-project code sharing
- Planning, Simulation, SLAM, Computer Vision, Object Recognition, Visualization, you are also EnviRe 2.0
- Discussion on AG-NavPlan and Entern project
- Great opportunity to inter project collaboration
- GitHub Working Group



Universität Bremen

Thank you!

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

Universität Bremen

2.5 'Mid-water localization for Autonomous Underwater Vehicles' (NP-T-05)

Lashika Medagoda [(1)]

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

Contact: lashika.medagoda@dfki.de

Abstract

Survey class Autonomous Underwater Vehicles typically rely on Doppler Velocity Logs (DVL) for precise navigation near the seafloor. In deep-water, the seafloor depth is generally greater than the DVL bottom-lock range. In this case, 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. This research explores a solution to navigation in the mid-water column that exploits the stability of the water current field 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 sensors, position error growth is constrained. This presentation briefly outlines present methods of localization, and how the addition of the ADCP-aided method allows novel capabilities, including application to the Europa Explorer project.

Mid-water localization for Autonomous Underwater Vehicles

AG Navigation & Planning

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

Universität Bremen

Acknowledgements

- Australian Centre for Field Robotics, University of Sydney
- Woods Hole Oceanographic Institution follow on funded by Air Force Research Laboratory Award

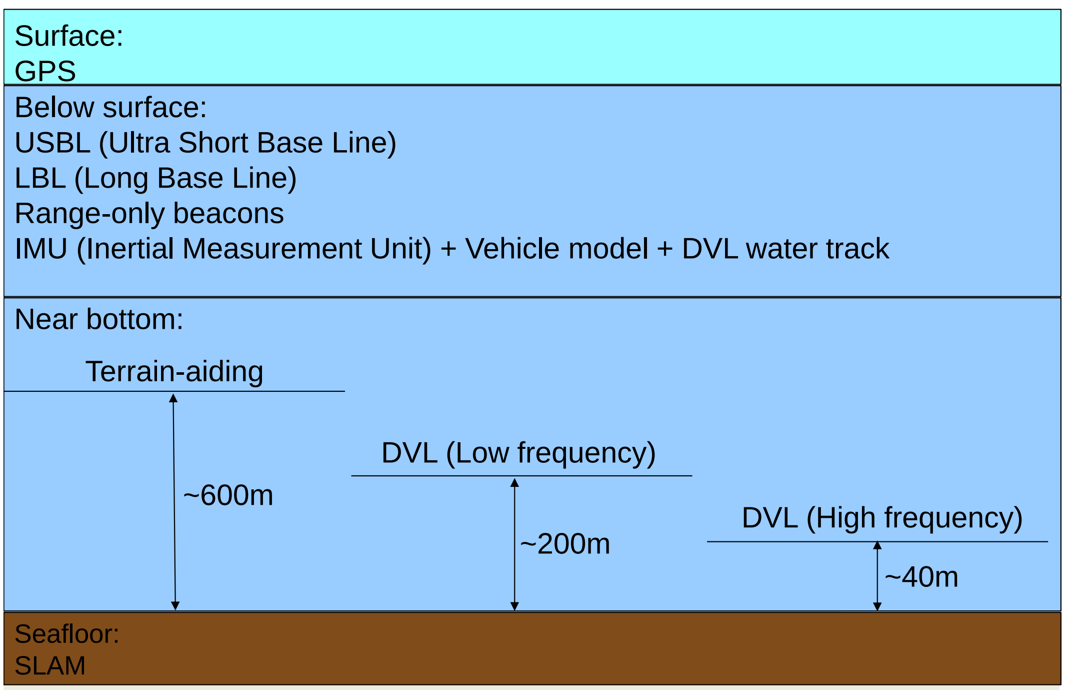
Universität Bremen

Localization for robotics

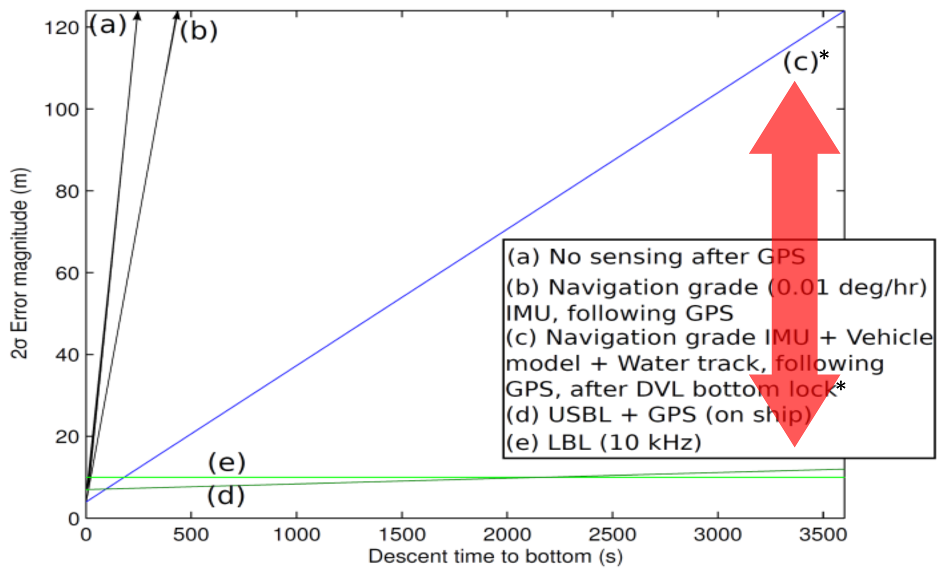
- Mission planning
- Data association
- Revisiting/monitoring

Universität Bremen

Overview



Localization

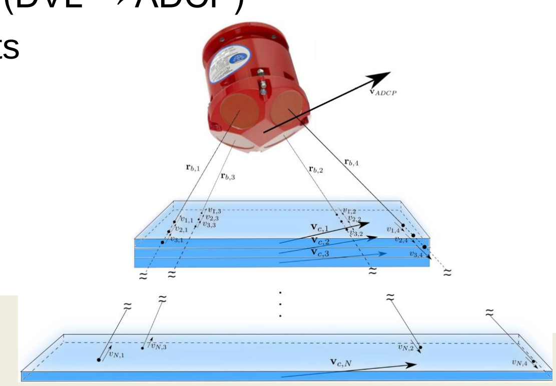


Universität Bremen

* Optimistic extrapolation from 30 mins descent– approaches worst case water current (O. Hegrenaes and E. Berglund. IEEE OCEANS – EUROPE, 2009

ADCP-aiding

- Acoustic signal reflects off scatterers
- Doppler shift → water current velocity
- Spatial variability and temporal stability in water currents
- Dead-reckoning in mid-water
- Reduced reliance on acoustics
- Relies on existing sensing (DVL → ADCP)
- Local map of water currents



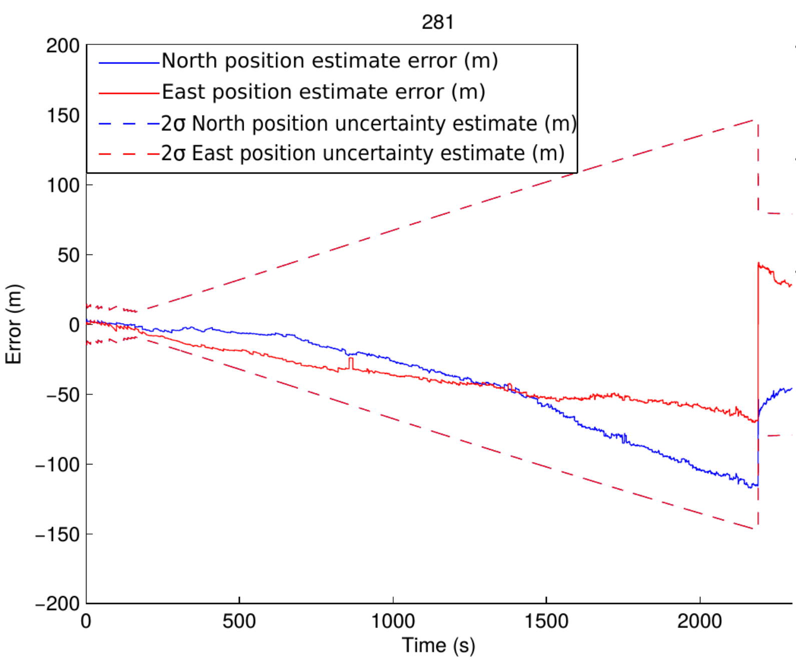
Universität Bremen

Results

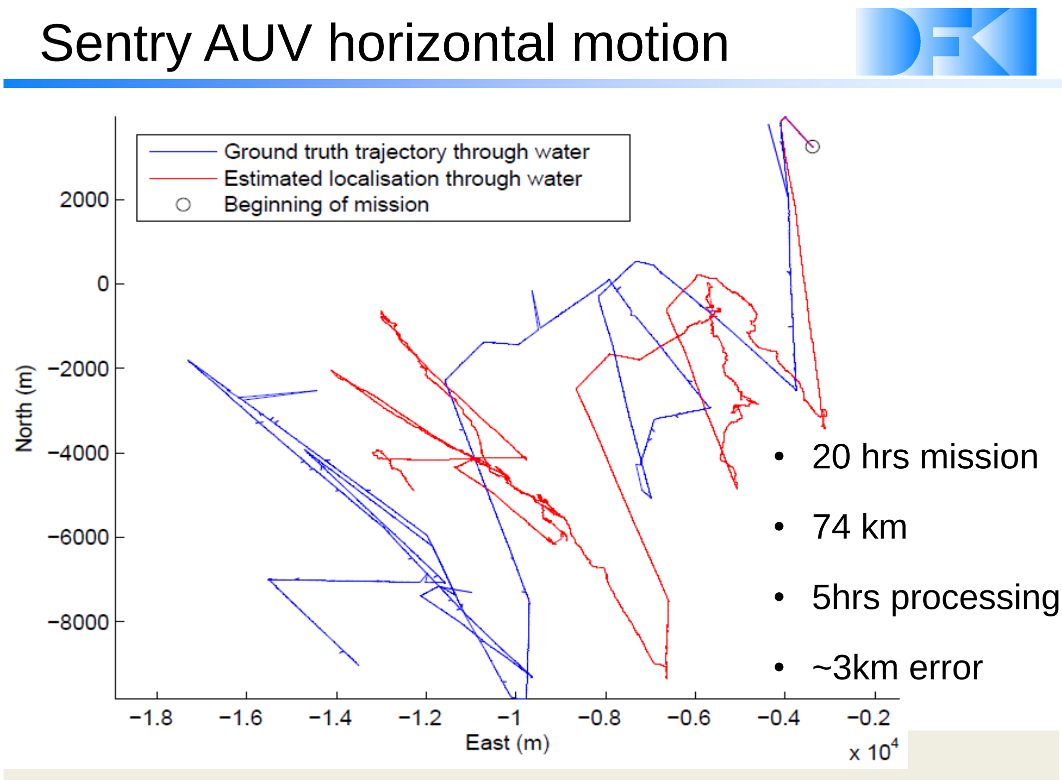
Video: ADCP + SLAM

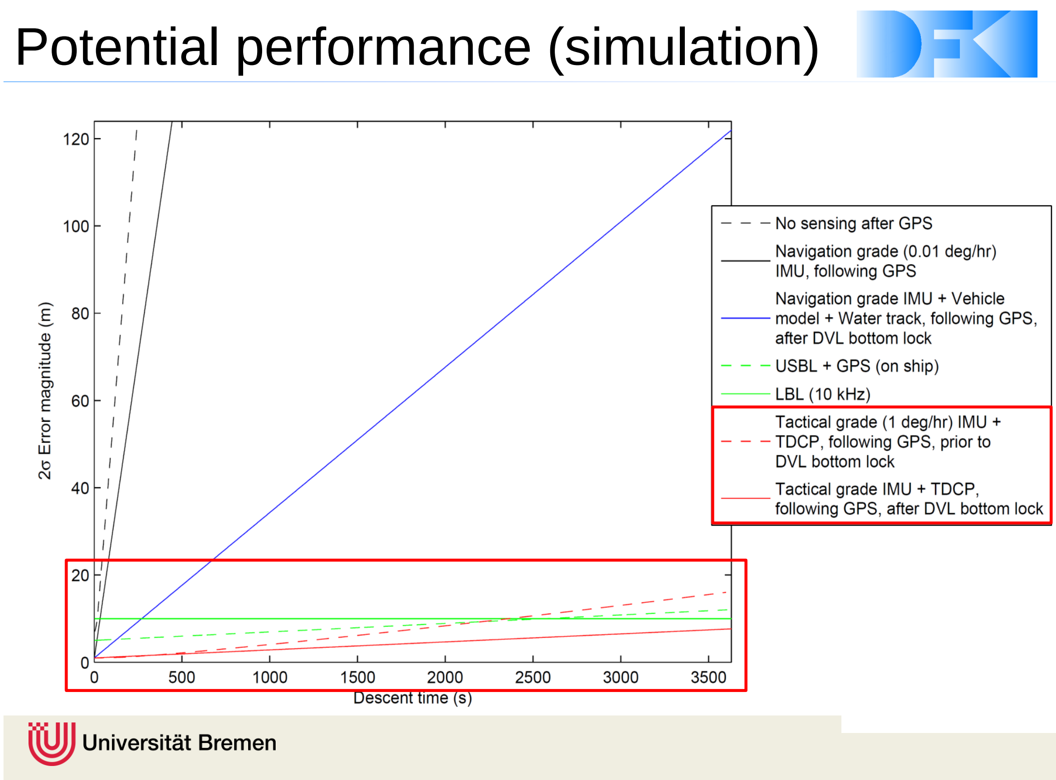
Universität Bremen

Sentry AUV vertical descent



- No IMU aiding
- 1.5 km descent
- ~50m error


Sentry AUV horizontal motion
Ground truth trajectory through water
Estimated localisation through water
Beginning of mission
North (m)
East (m)
x 10^4
• 20 hrs mission
• 74 km
• 5hrs processing
• ~3km error


Potential performance (simulation)
2σ Error magnitude (m)
Descent time (s)
No sensing after GPS
Navigation grade (0.01 deg/hr) IMU, following GPS
Navigation grade IMU + Vehicle model + Water track, following GPS, after DVL bottom lock
USBL + GPS (on ship)
LBL (10 kHz)
Tactical grade (1 deg/hr) IMU + TDCP, following GPS, prior to DVL bottom lock
Tactical grade IMU + TDCP, following GPS, after DVL bottom lock
Universität Bremen

Novel capabilities

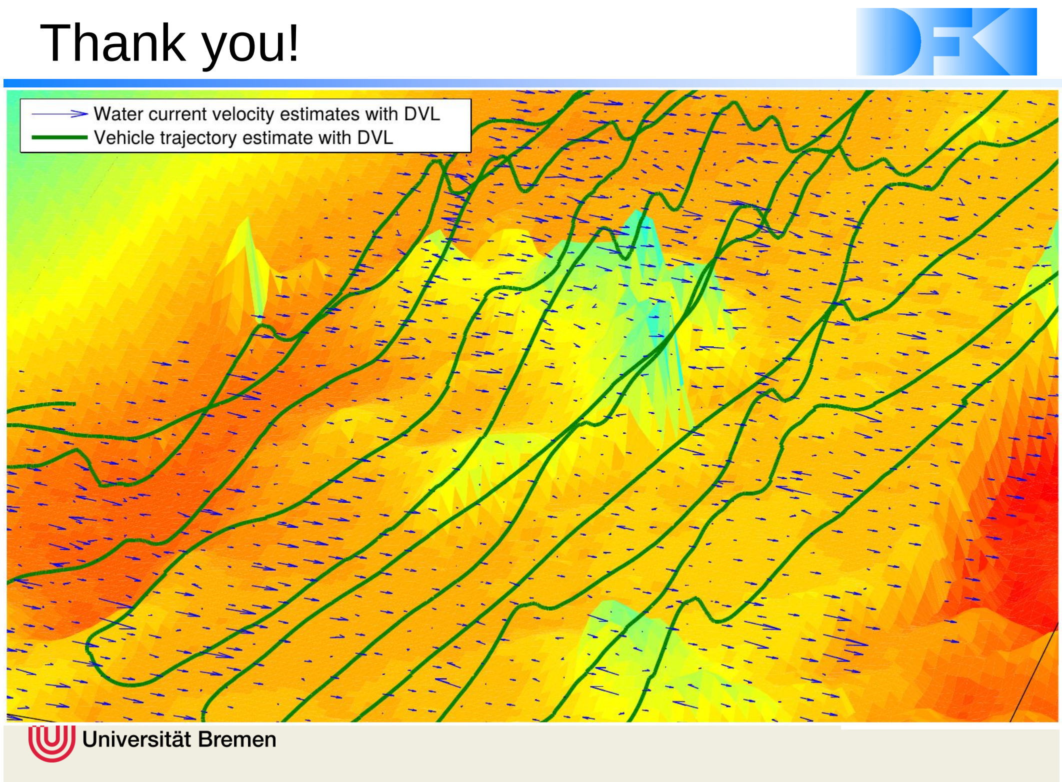
- Redundancy
- Performance
- Operate away from acoustics
- Under-ice
- Local water currents → control/planning
- Reduces drift between matching environmental signals

Universität Bremen

Ongoing work

- Making this all real-time
  - Extending filter at DFKI, including IMU
  - Opens research avenues such as on-line water current estimation and control/planning within estimated field
  - Application to Europa Explorer project
    - Redundant measurement for acoustic beacon dropouts.
    - Can allow homing behaviour to the beacons.

Universität Bremen


Thank you!
Water current velocity estimates with DVL
Vehicle trajectory estimate with DVL
Universität Bremen

2.6 'AUV Docking Concept and First Experiences in the Europa-Explorer Project' (NP-T-06)

Marc Hildebrandt[(1)]

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

Contact: marc.hildebrandt@dfki.de

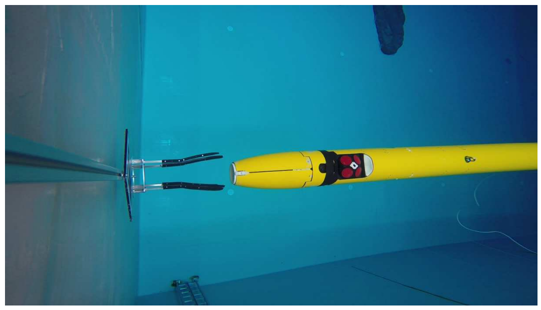
Abstract

This presentation shows current state of AUV mid-water docking in the project Europa-Explorer. After a short description of the scenario the difficulties are summarized and a number of experiments are presented with video footage.

AUV Docking in the Europa-Explorer Project

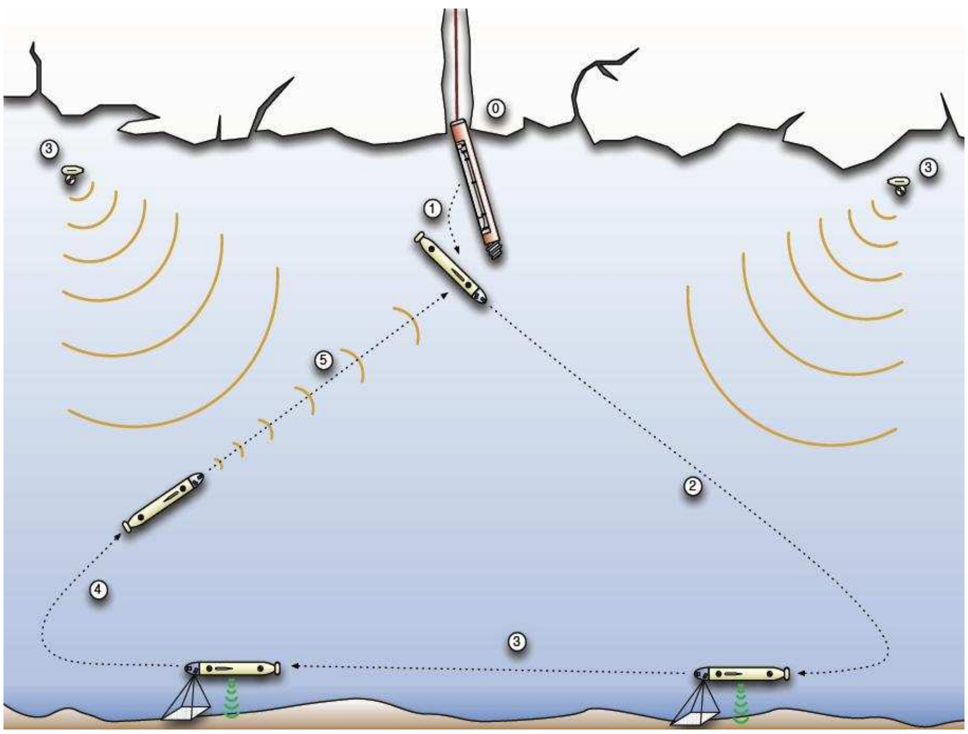
Dr. Marc Hildebrandt

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



Universität Bremen

1



Scenario & Requirements

- Vehicle should be under ice for long periods of time
  - Docking necessary for recharge and mission update
- Due to underwater scenario limited amount of actuators on docking side
- Due to small diameter of ice-shuttle docking mechanism needs to be compact
- All externally used devices need to be retractable into ice-shuttle
- Vehicle needs to be towed back into ice-shuttle

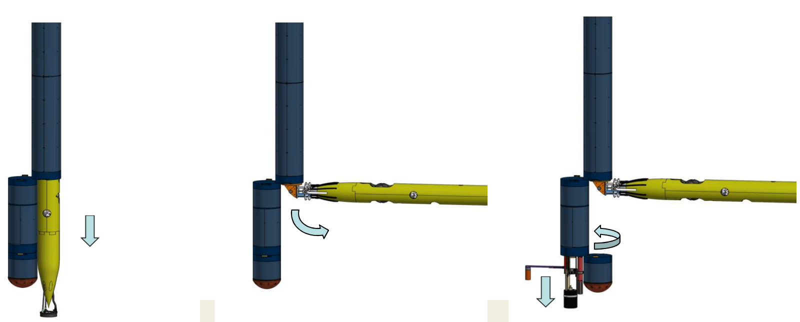
➢ Vehicle assisted docking and parking

Universität Bremen | Marc Hildebrandt – Docking in the Europa-Explorer Project
Project Day 18.09.2015 | 3

Docking Strategy

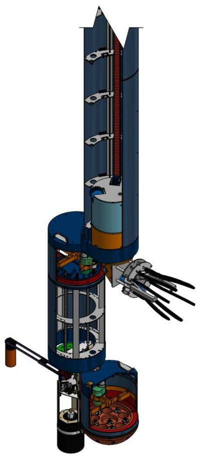
Multi-Stage approach

1. Use LBL and stereo hydrophone to reach 2 km vicinity of ice-shuttle
2. Use USBL to home within 5m (visual detection range)
3. Use visual markers to orient with docking adapter and dock
4. Use vehicle buoyancy cells to get AUV into near-vertical position
5. Use parking elevator to tow the vehicle back into ice-shuttle

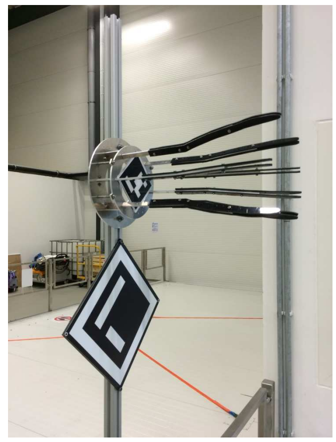


Universität Bremen | Marc Hildebrandt – Docking in the Europa-Explorer Project
Project Day 18.09.2015 | 4

Sensor Approach



- Use existing vehicle sensors as much as possible
  - DVL, USBL, LBL, IMU, FOG, DPS, cameras
- Vehicle was equipped with docking camera during design phase
- For final approach this docking camera should be used for vehicle control



Universität Bremen

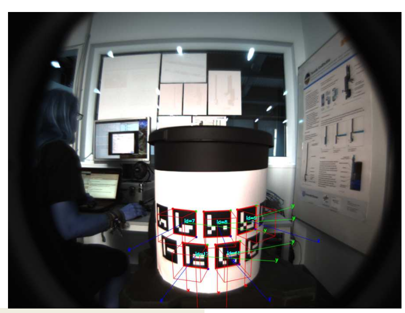
Marc Hildebrandt – Docking in the Europa-Explorer Project
Project Day 18.09.2015

5

Visual Marker Tests

- Marker detectors usually work with planar markers
  - Aruco, April etc.
- No larger planar space available on ice-shuttle
- Can planar markers be used on a 1-dimensionally bent surface?

Size (cm)	5	7.5	10	14	16
Max distance	190 cm	310 cm	320 cm	400 cm	500 cm
Angle error	2°	2°	13°	15°	17°
Max angle	60°	55°	45°	20°	15°



Universität Bremen

Marc Hildebrandt – Docking in the Europa-Explorer Project
Project Day 18.09.2015

6

Experiment: Indoors

- Conducted in big basin
- Docking station-mockup fixed at side
- Two markers: one inside docking-cone, one bigger on top
  - Both markers flat
- Vehicle was controlled manually
  - First camera-only docking was attempted, failed
  - Docking with sight of the vehicle successful
  - After some experience camera-only docking possible as well

Universität Bremen | Marc Hildebrandt – Docking in the Europa-Explorer Project
Project Day 18.09.2015 | 7

Experiment: Outdoors

- Conducted in Unisee
- Docking station-mockup fixed at pier
- Two marker sets:
  - One marker inside docking-cone as before
  - One set of markers around the circular ice-shuttle mock-up
- Vehicle was controlled manually
  - Due to failure of rear strafing thruster no strafing possible
    - Vehicle controlled docking impossible
  - Vehicle was guided by hand in order to create datasets

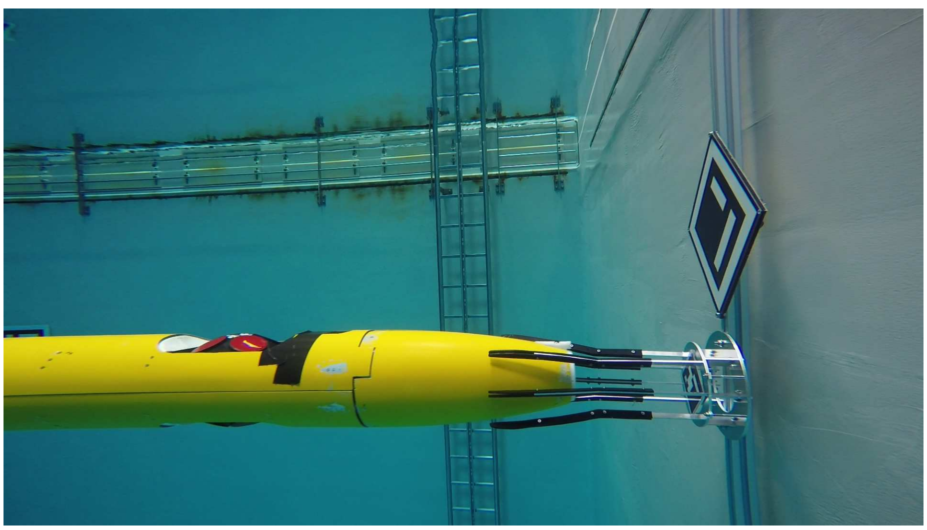
Universität Bremen | Marc Hildebrandt – Docking in the Europa-Explorer Project
Project Day 18.09.2015 | 8

Conclusions

- Marker-based visual docking should be possible
- Docking cone needs to be improved, vehicle can slip out while attempting to dock
  - Additionally the retention needs to be implemented
- Water quality can be an issue, maybe pre-processing necessary
- Docking with vehicle control difficult because
  - Forward motion induces roll
  - Very long vehicle, camera mounted at tip
  - Size of docking cone limited

Universität Bremen Marc Hildebrandt – Docking in the Europa-Explorer Project
Project Day 18.09.2015 9

Thank You!



Universität Bremen Marc Hildebrandt – Docking in the Europa-Explorer Project
Project Day 18.09.2015 10

2.7 ‘Underwater Distributed Magnetometers’ (NP-T-07)

Leif Christensen [(1)]

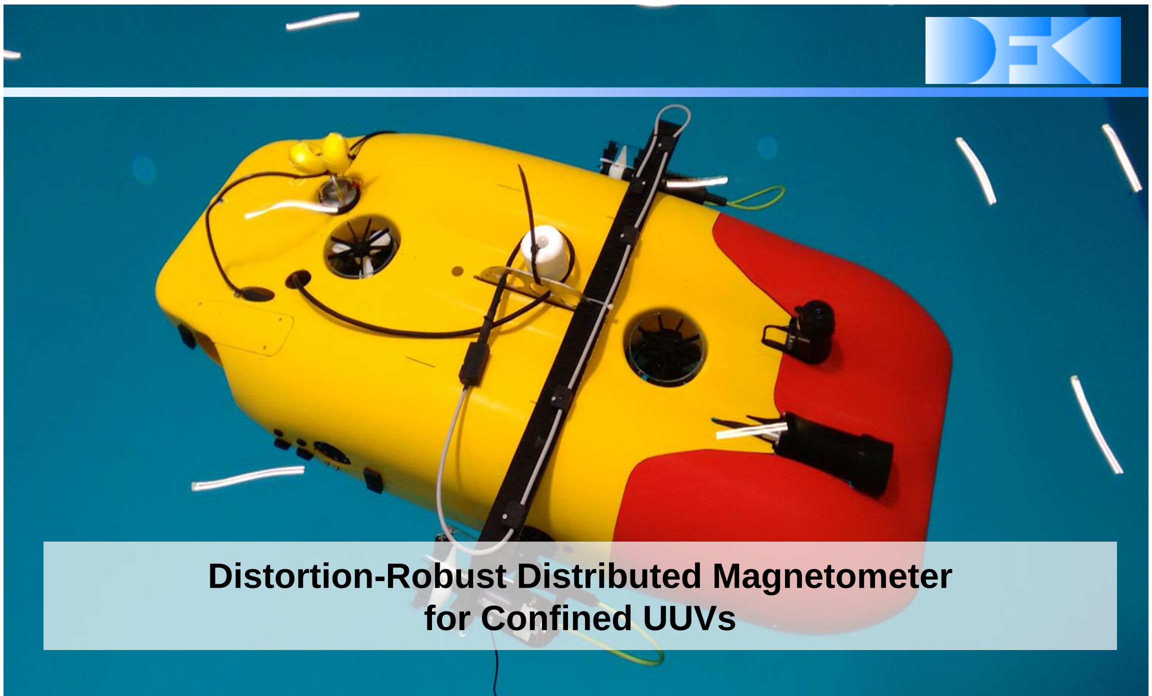
(1) Robotics Innovation Center, DFKI GmbH, Robert-Hooke-Straße 1, 28359 Bremen, Germany

Contact: `leif.christensen@dfki.de`

Abstract

This talk outlines a new approach to deal with dynamic distortions of the ambient magnetic field often leading to errors in orientation estimation in confined unmanned underwater vehicles. In such systems, the space to mount magnetometer sensors is strictly limited and the sensors are often in the vicinity of distortion sources like ferromagnetic material, sonar transducers or strong electric currents flowing through nearby supply lines. The talk describes a threefold approach to deal with these magnetic field distortions: the use of multiple distributed magnetometers for robustness, the use of very small pressure-neutral sensors to get rid of mounting restrictions inside pressure compartments and the development and application of a multi-magnetometer fusion algorithm using von Mises-Fisher distributions to compute undistorted orientation information.

This talk is a preliminary version of the talk that was presented at the MTS/IEEE OCEANS’15 conference in Washington DC in conjunction with the paper ”Distortion-Robust Distributed Magnetometer for Underwater Pose Estimation in Confined UUVs” authored by Leif Christensen, Christopher Gaudig and Frank Kirchner.



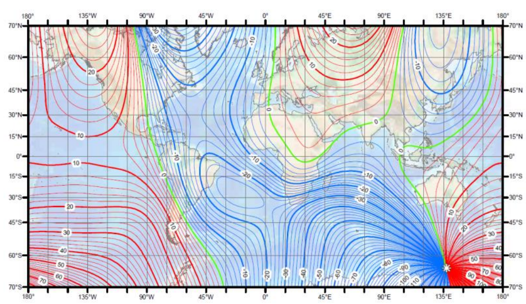
Distortion-Robust Distributed Magnetometer for Confined UUVs

Universität Bremen

Leif Christensen (DFKI Robotics Innovation Center)
AG Navigation & Planning Project Day Talk – 17.09.2015

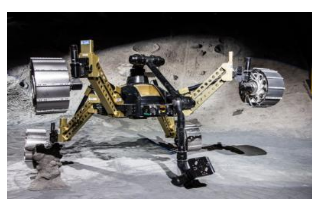
Introduction

- No GPS due to strong attenuation
- Simple IMU setup:
  - Accelerometers (pitch, roll)
  - Gyros (pitch, roll, yaw)
  - Challenge: stable heading / yaw



Magnetic Declination Map © NOAA 2010

- Supplement with magnetometers
  - Absolute sensor
  - Measures (3D) flux density
  - Magnetoresistive sensor
  - Challenge: magnetic field not evenly distributed at all
  - Multiple Contributors
    - Geodynamo, Earth crust, vehicle material
    - WMM / IGRF models

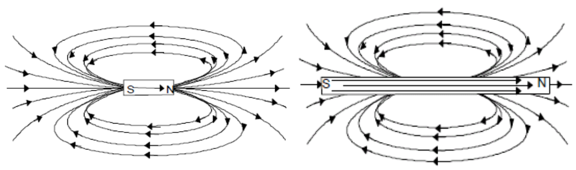


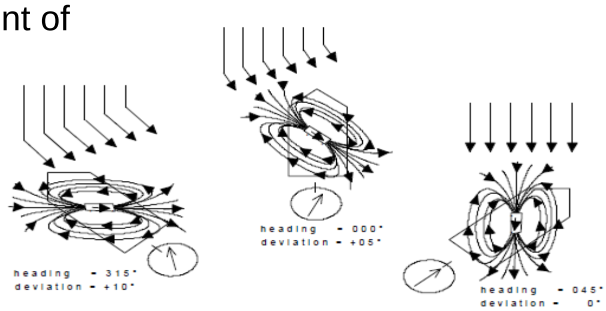
Universität Bremen

Leif Christensen (DFKI Robotics Innovation Center)
AG Navigation & Planning Project Day Talk – 17.09.2015

Hard Iron / Electromagnetic Effect

- Permanent constant offset
- Steel ships retain magnetic field direction during building phase
- Electromagnetic field around wire depending on amount of current

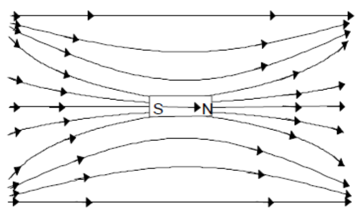


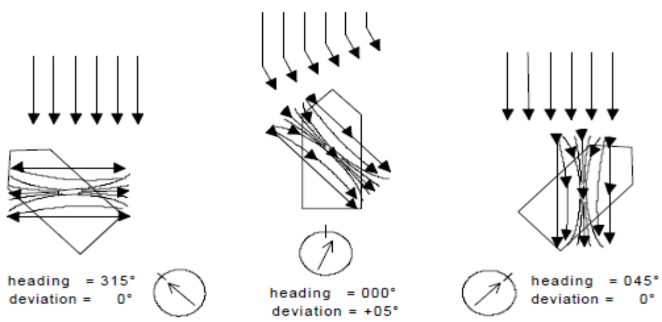


Images © KVH Industries

Soft Iron Effect

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





Images © KVH Industries

Approach

- Especially challenging on compact UUVs / robots
- Restricted mounting options (pressure hulls)
- A priori calibration only for static distortions
  - Strong currents
  - Moving battery packs (Gliders)

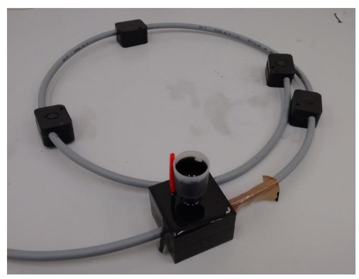
- Threefold approach here:
  - Use multiple sensors (locality of distortions)
  - Pressure-neutral waterresistant sensors (get rid of mounting restrictions)
  - Multi-Magnetometer fusion algorithm using von Mises-Fisher distributions

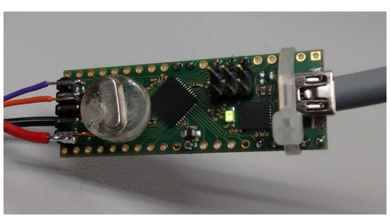
Universität Bremen

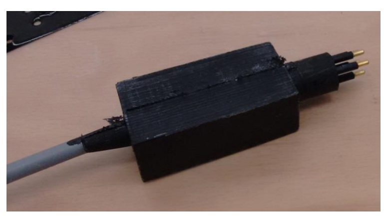
Leif Christensen (DFKI Robotics Innovation Center)
AG Navigation & Planning Project Day Talk – 17.09.2015

Distributed Magnetometer Hardware

- 5x ST LSM303D magnetometer
- ATmega 644P
- Single cable whip
- Polyurethane casting
- Sensor to µC: SPI (i2c address restrictions)
- µC to Outside: RS485
- Special treatment of crystal oscillator (epoxy resin)





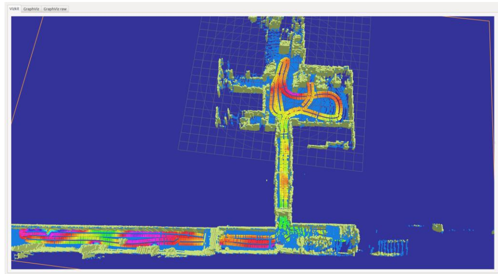


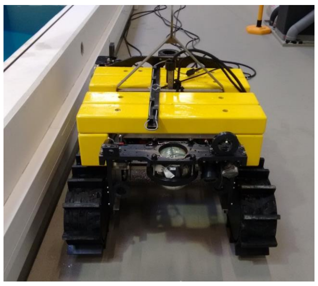
Universität Bremen

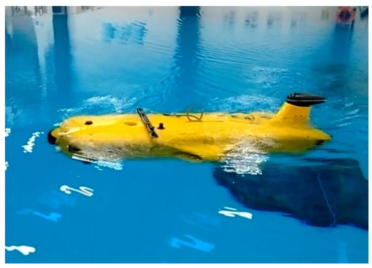
Leif Christensen (DFKI Robotics Innovation Center)
AG Navigation & Planning Project Day Talk – 17.09.2015

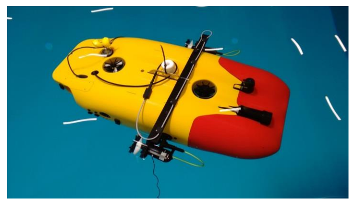
System deployment

- Artemis
- Wally
- FlatFish
- Dagon





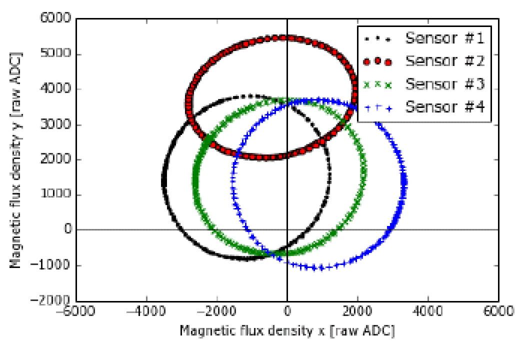




Universität Bremen

Leif Christensen (DFKI Robotics Innovation Center)
AG Navigation & Planning Project Day Talk – 17.09.2015

Why you should calibrate



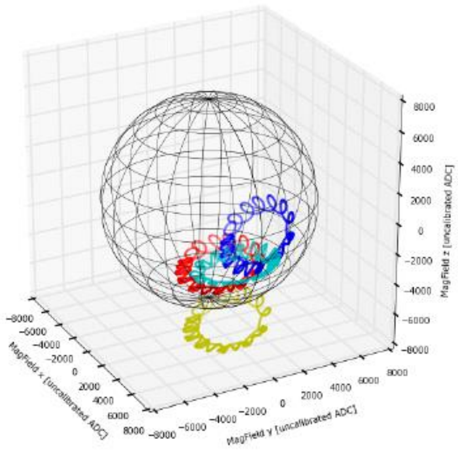
$$\begin{pmatrix}\hat{x}\\ \hat{y}\\ \hat{z}\end{pmatrix} = M_{align} \cdot \begin{pmatrix} sc_x & 0 & 0 \\ 0 & sc_y & 0 \\ 0 & 0 & sc_z \end{pmatrix} \cdot M_{si} \cdot \left(\begin{pmatrix} x \\ y \\ z \end{pmatrix} - b_{hi} \right)$$

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

Universität Bremen

Leif Christensen (DFKI Robotics Innovation Center)
AG Navigation & Planning Project Day Talk – 17.09.2015

Static Calibration



$$\frac{(x-x_{hi})^2}{a^2} + \frac{(y-y_{hi})^2}{b^2} + \frac{(z-z_{hi})^2}{c^2} = R^2$$

$$\begin{pmatrix} x & y & z & -y^2 & -z^2 & 1 \end{pmatrix} \cdot X = x^2$$

$$X = \begin{pmatrix} 2x_{hi} \\ \frac{a^2}{b^2} 2y_{hi} \\ \frac{a^2}{c^2} 2z_{hi} \\ \frac{a^2}{b^2} \\ \frac{a^2}{c^2} \\ a^2R^2 - x_{hi}^2 - \frac{a^2}{b^2} y_{hi}^2 - \frac{a^2}{c^2} z_{hi}^2 \end{pmatrix}$$

$$H \cdot X = w = x^2$$

Universität Bremen

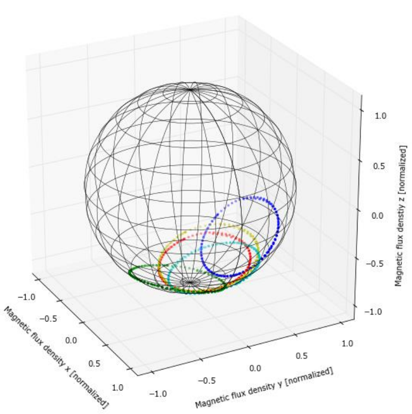
Leif Christensen (DFKI Robotics Innovation Center)
AG Navigation & Planning Project Day Talk – 17.09.2015

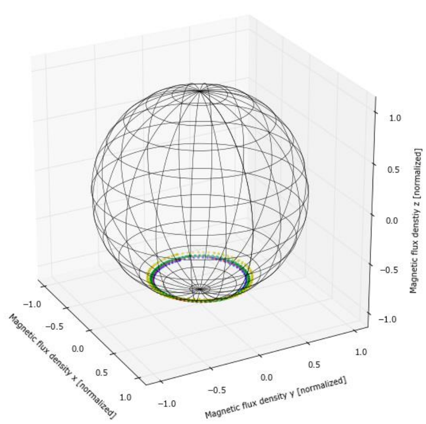
Compensation & Alignment

$$\mathbf{v}_{\text{rot}} = \mathbf{v}\cos\theta + (\mathbf{k} \times \mathbf{v})\sin\theta + \mathbf{k}(\mathbf{k}\cdot\mathbf{v})(1-\cos\theta)$$

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

$$\mathbf{K} = \begin{bmatrix} 0 & -k_3 & k_2 \\ k_3 & 0 & -k_1 \\ -k_2 & k_1 & 0 \end{bmatrix}$$



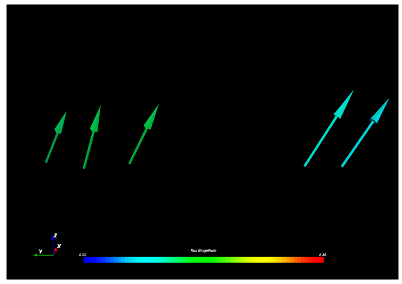


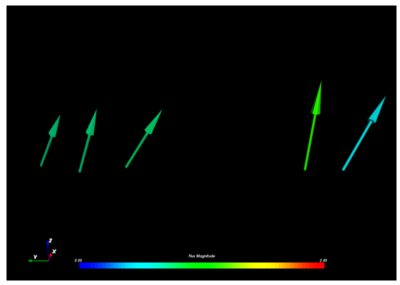
Universität Bremen

Leif Christensen (DFKI Robotics Innovation Center)
AG Navigation & Planning Project Day Talk – 17.09.2015

Dynamic Distortion Filter

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





Universität Bremen

Leif Christensen (DFKI Robotics Innovation Center)
AG Navigation & Planning Project Day Talk – 17.09.2015

vMF Filter

- Gaussian distribution L2 norm for strength component
- Von Mises-Fisher distribution on S^2 in R^3
- Concentration parameter kappa
- Estimator for mean

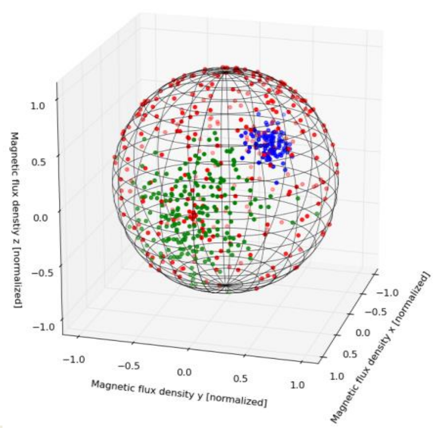
$$\hat{\mu}_{dir} = \frac{\mathbf{r}}{\|\mathbf{r}\|} = \frac{\sum_{i=1}^{n} \mathbf{x_i}}{\|\sum_{i=1}^{n} \mathbf{x_i}\|}$$

- Estimator for kappa

$$\hat{\kappa} = \frac{\bar{r}d - \bar{r}^3}{1 - \bar{r}^2} \qquad \frac{\|\mathbf{r}\|}{n} = \bar{r}$$

$$p(\mathbf{x_i}|\mu_{st}, \sigma) = \frac{1}{\sigma\sqrt{2\pi}} e^{-\frac{(x-\mu_{st})^2}{2\sigma^2}}$$

$$p(\mathbf{x_i}|\mu_{dir}, \kappa) = \frac{\kappa}{4\pi \sinh \kappa} \exp(\kappa \mu_{dir}^T \mathbf{x_i})$$

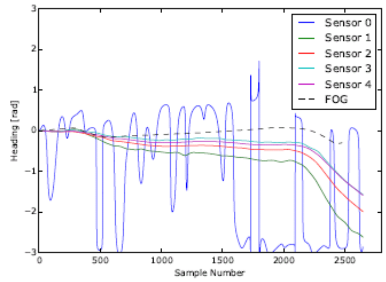


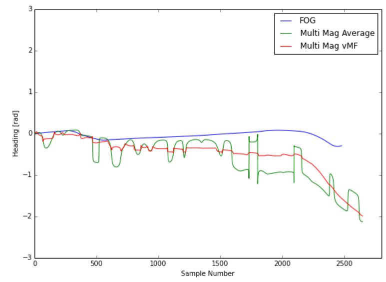
Universität Bremen

Leif Christensen (DFKI Robotics Innovation Center)
AG Navigation & Planning Project Day Talk – 17.09.2015

Distortion Filter Results

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





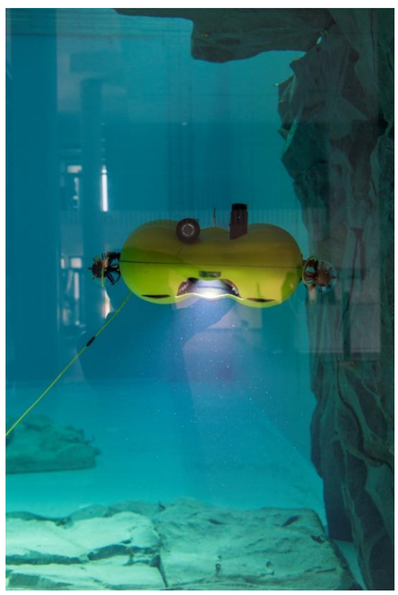
- Standalone with weighted sum according to PDF
- Integrated in higher level sensor fusion algorithm with per-sensor confidence values

Universität Bremen

Leif Christensen (DFKI Robotics Innovation Center)
AG Navigation & Planning Project Day Talk – 17.09.2015

Thank you!

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



Universität Bremen

Leif Christensen (DFKI Robotics Innovation Center)
AG Navigation & Planning Project Day Talk – 17.09.2015

2.8 'Cooperative map building: An approach to distributed, multi-modal SLAM' (NP-T-08)

Sebastian Kasperski[(1)]

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

Contact: sebastian.kasperski@dfki.de

Abstract

The talk will present the work that is currently done towards distributed map-building with teams of mobile robots in the project TransTerrA. A brief explanation of the core concept of graph-based SLAM is followed by an overview of the mapping currently developed at DFKI. It will then discuss why graph-based approaches to the SLAM problem are inherently well suited for cooperation in an heterogeneous team of robots equipped with different types of sensors.

Cooperative map building

An approach to distributed, multi-modal SLAM

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

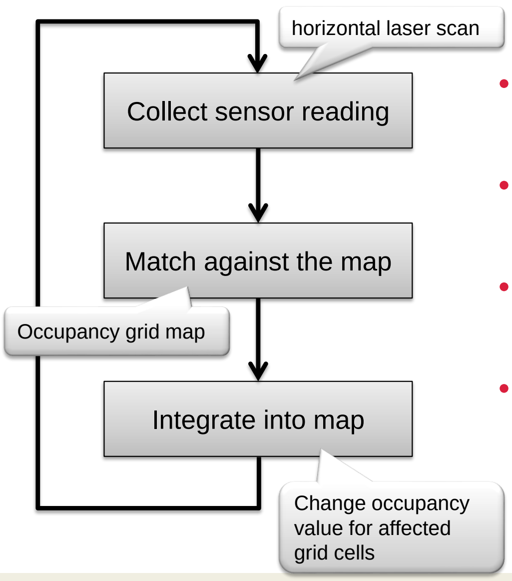
Universität Bremen

Outline

- **Concept:** Basics of graph-based SLAM
- **Graph-Optimization:** The SLAM-Backend
- **Projection:** Build maps for navigation
- **Sensor-Fusion:** Using different channels
- **Cooperation:** Distributing the map between agents

Universität Bremen 2

Classical mapping

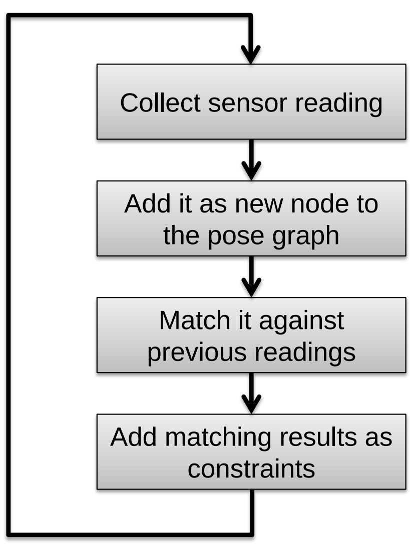


- Map is also the world model
- Specific to a sensor type
- Integration is irreversible
- Drift errors accumulate over time and lead to a globally inconsistent map

Universität Bremen

3

Delayed integration

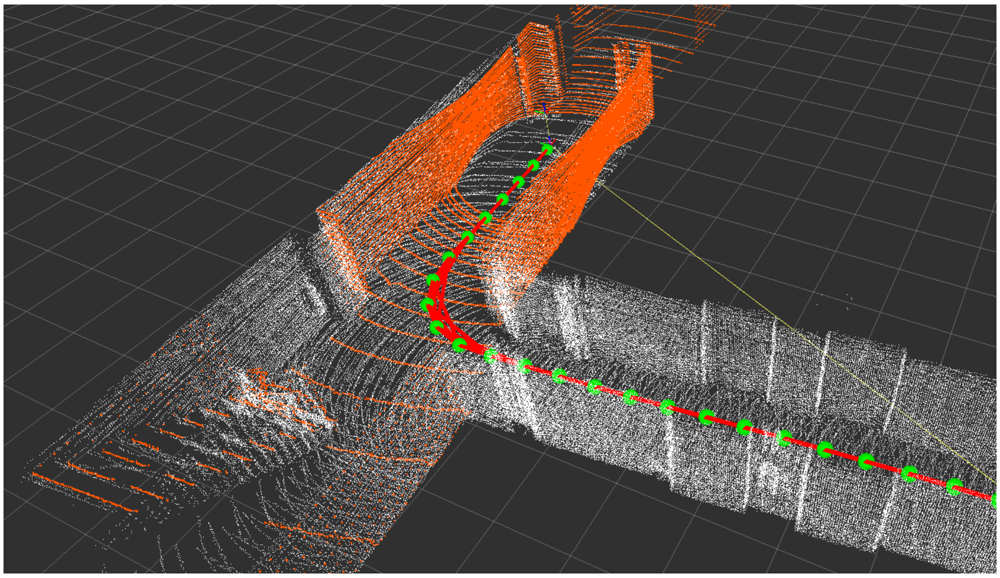


- Creates a collection of:
  - Sensor readings (nodes)
  - Spatial constraints (edges)
- No integration is done
  - Readings are not registered in a common coordinate frame
  - A map cannot be build yet
- Constraints contradict with each other

Universität Bremen

4

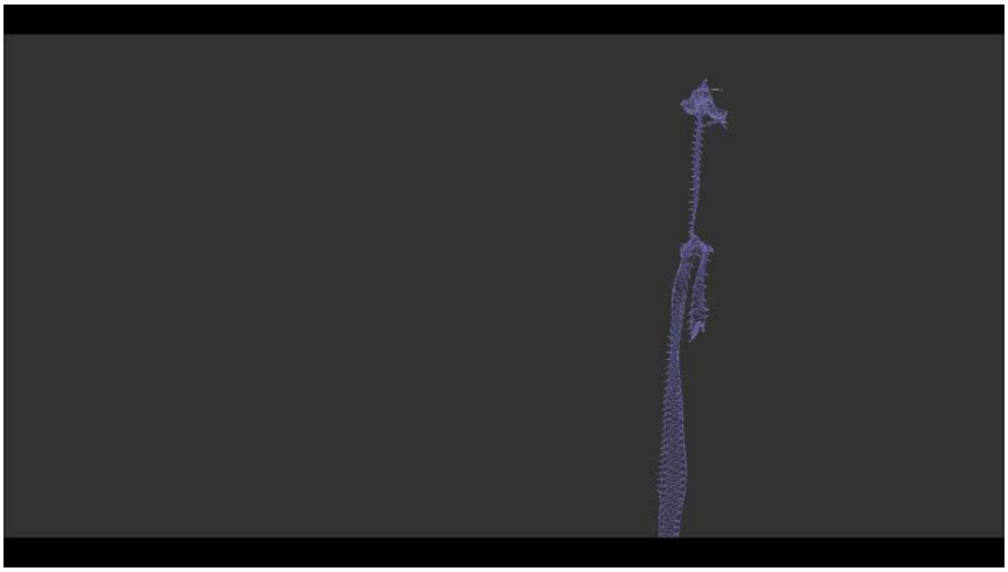
Pose-Graph and Pointcloud



The SLAM-Backend

- Integration is done by a generic graph-optimizer (Backend)
- The Backend uses only the spatial constraints to minimize the global error in the graph
  - Completely ignores sensor readings
  - Finds pose in world coordinated for all readings, so that all constraints are maximally fulfilled
- Newly added constraints (e.g. after a loop-closure) can completely change the structure of the map

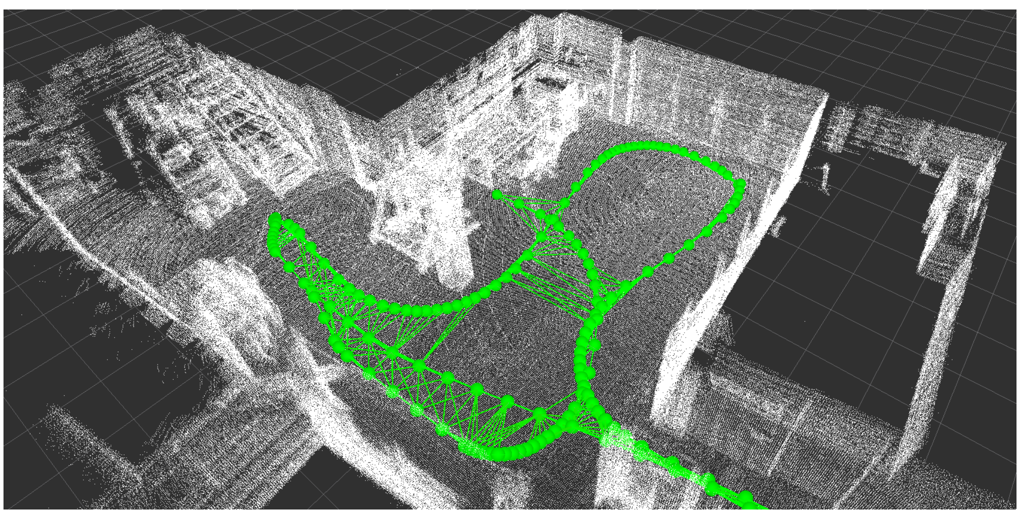
Graph-Optimization (g2o)



Universität Bremen

7

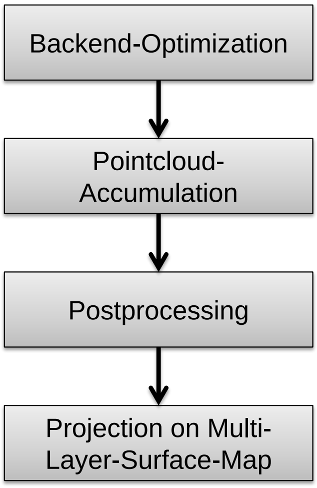
Optimization result



Universität Bremen

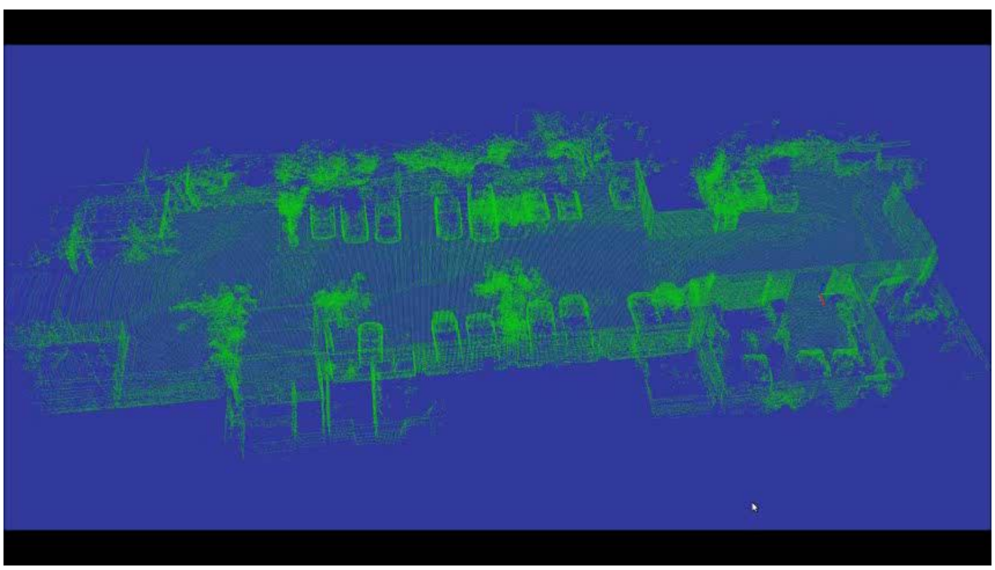
8

Map Projection (pointclouds)

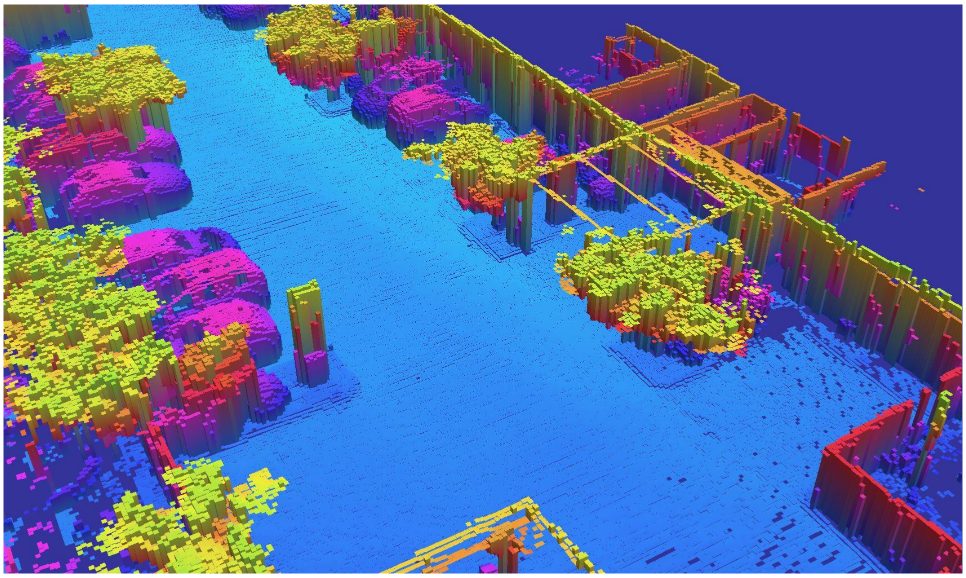


- Optimization alignes readings with a global reference frame
- Post-processing includes:
  - Outlier removal
  - Downsampling
- Points are then projected to a grid-map
  - Dense representation
  - Suiteable for navigation

Pointcloud after optimization



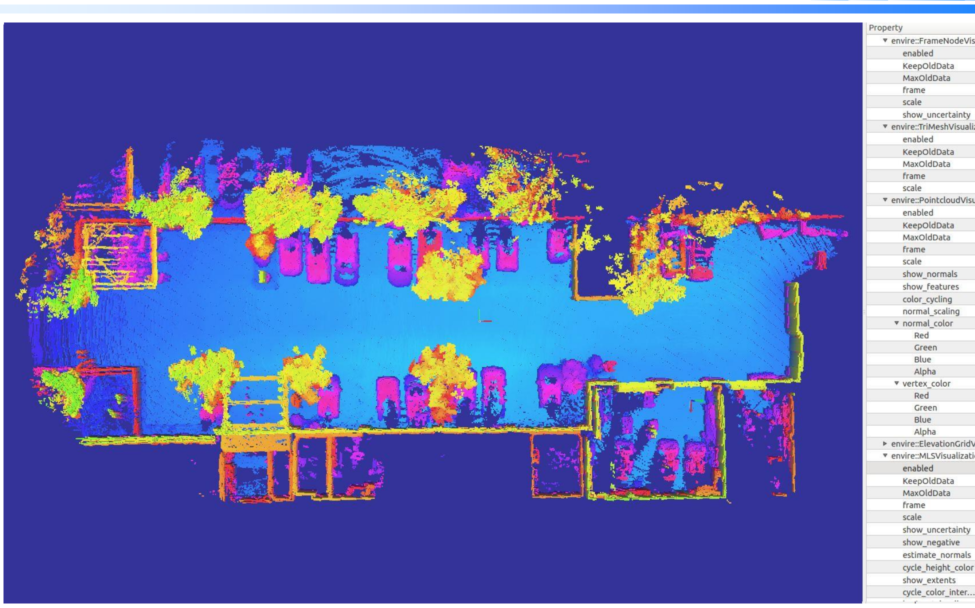
Building a map for navigation



Universität Bremen

11

Building a map for navigation



Universität Bremen

12

Using additional sensors

- Until now, only one sensor channel was used to map
- Generic structure allows adding from different channels
  - Must be possible to create spatial relationships between readings from a sensor
  - Position measuring like odometry, localization or GPS can be used to create constraints between different types
- Different maps can be created from different channels
  - Uses only nodes of a certain type
  - Different maps are still consistent with each other

Universität Bremen

13

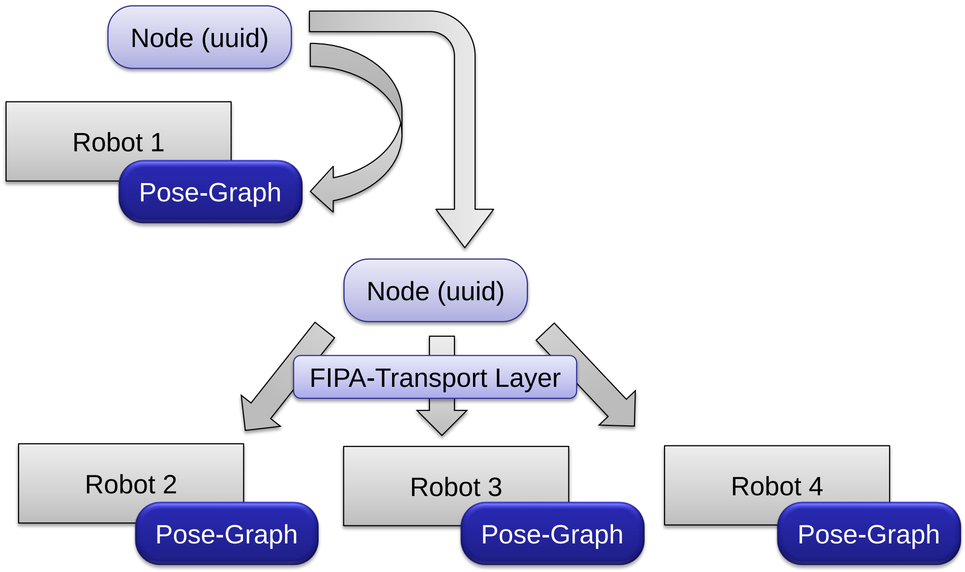
Mapping with teams of robots

- Graph-based approaches to SLAM well suited for cooperative, distributed map building.
  - New data can be shared between agents
  - Integration is done locally
  - Structure can be extended at different points
- Possible to use data from another agent's sensors
- Cooperation is managed using the shared world model
  - Requires global identification of graph-elements
  - Realized with UUIDs for graph nodes

Universität Bremen

14

Distribution of nodes



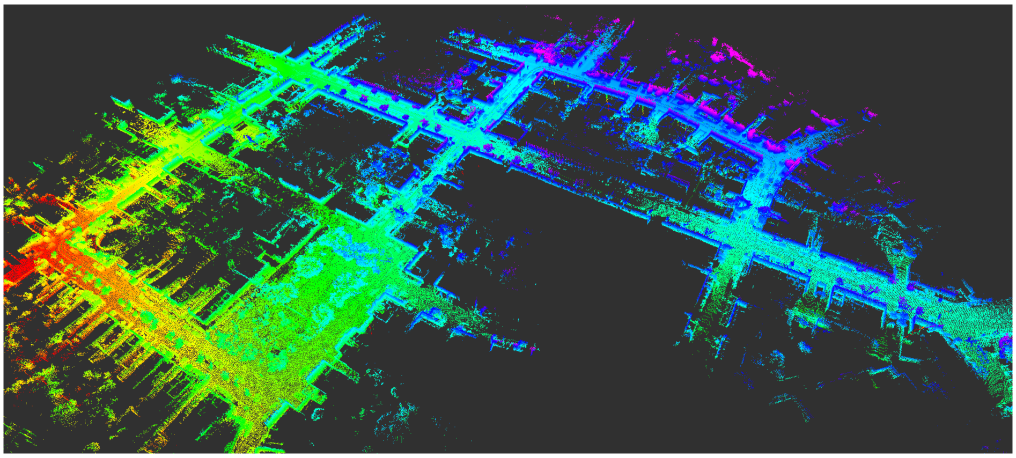
Universität Bremen 15

Availability

- DFKI-internal project on „git.hb.dfki.de“
  - Library: dfki-slam/slam3d
  - Rock-Module: dfki-slam/orogen-slam3d
- Already implemented (stable):
  - Pointcloud-Sensor
  - Odometry using Rock-Transformer
  - Multi-Level-Surface-Map Projector
  - Distributed map building using FIPA-Transport
- Next steps
  - Integrate more sensors and map projectors

Universität Bremen 16

Thank you for your interest!



Pointcloud created with data from a vehicle driving on public roads
Source: „KITTI Vision Benchmark Suite”

Universität Bremen

17

2.9 'SRSL: Monocular Self-Referenced Line Structured Light' (NP-T-09)

Alexander Duda [(1)]

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

Contact: alexander.duda@dfki.de

Abstract

Sensing of environment geometry and texture is a key requirement for mobile robotic systems. In the underwater domain, difficult environmental conditions restrict the applicability of many existing methods for 3D sensing. A new method is proposed, which uses a visible laser line projected onto a monocular camera image to perform 3D scene reconstruction. The method fuses Structured Light with Structure from Motion in an integrated process, which allows for the capturing of dense 3D point clouds on moving systems in situations with low texture and minimal scene structure.

SRSL: Monocular Self-Referenced Line Structured Light

Alexander Duda

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

Universität Bremen

3D Sensing in Extrem Environments

Demo Mission: Helmholtz Alliance „Robotic Exploration of Extreme Environments“

Universität Bremen 2

Optical 3D Sensors

Name	Measuring Principle	Type	Data	Frequence
LiDAR	Time of Flight	active	sparse point cloud	IR
Time of Flight Camera	Time of Flight	active	dense point cloud	IR
Structured Light	Triangulation	active	dense point cloud	IR/Visible light
Vision Camera	Triangulation / Focus, Defocus /…	passive	sparse/dense point cloud	Visible light

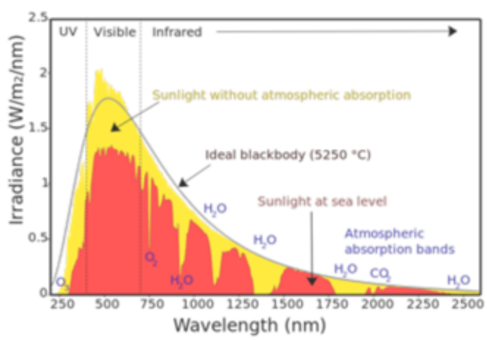
Universität Bremen 3

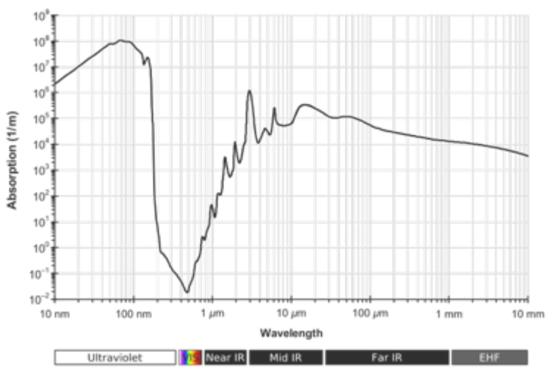
Optical 3D Sensors

Name	Measuring Principle	Type	Data	Frequence
LiDAR	Time of Flight	active	sparse point cloud	IR
Time of Flight Camera	Time of Flight	active	dense point cloud	IR
Structured Light	Triangulation	active	dense point cloud	IR/Visible light
Vision Camera	Triangulation / Focus, Defocus /…	passive	sparse/dense point cloud	Visible light
RGB-D Camera	Time of Flight/ Triangulation	active	dense point cloud	IR/Visible light

Universität Bremen 4

Power Limitation Active Sensors





[9]

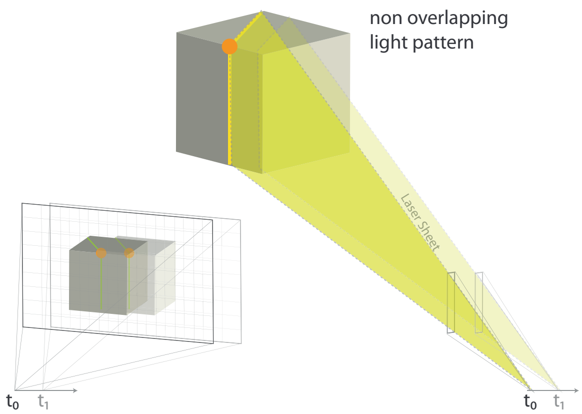
Optical 3D Sensors

Name	Measuring Principle	Type	Data
LiDAR	Time of Flight	active	sparse point cloud
Time of Flight Camera	Time of Flight	active	dense point cloud
Structured Light	Triangulation	active	dense point cloud
Vision Camera	Triangulation / Focus, Defocus / …	passive	sparse/dense point cloud
RGB-D Cam	Time of Flight / Triangulation		e point cloud

Off-the-shelf systems use IR-Band

Uses IR-Band for depth measurements

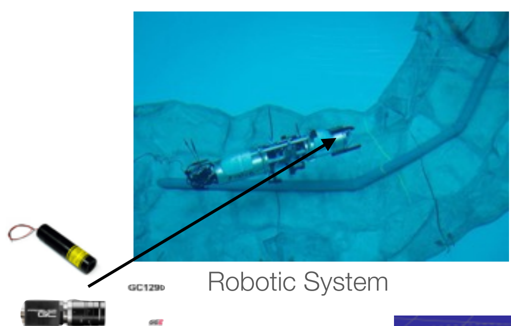
Self-Referenced Structured Light



Universität Bremen

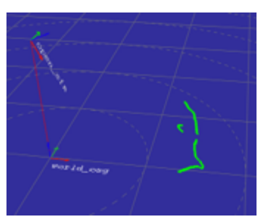
7

Self-Referenced Structured Light



Robotic System

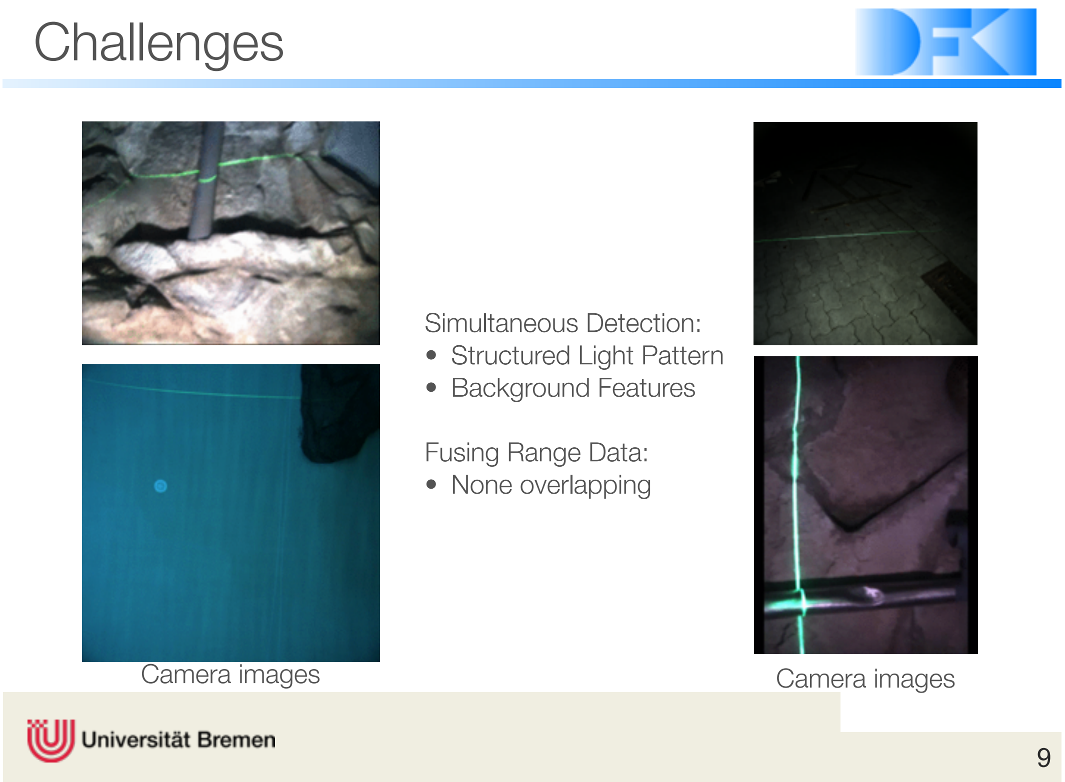
Onboard Camera

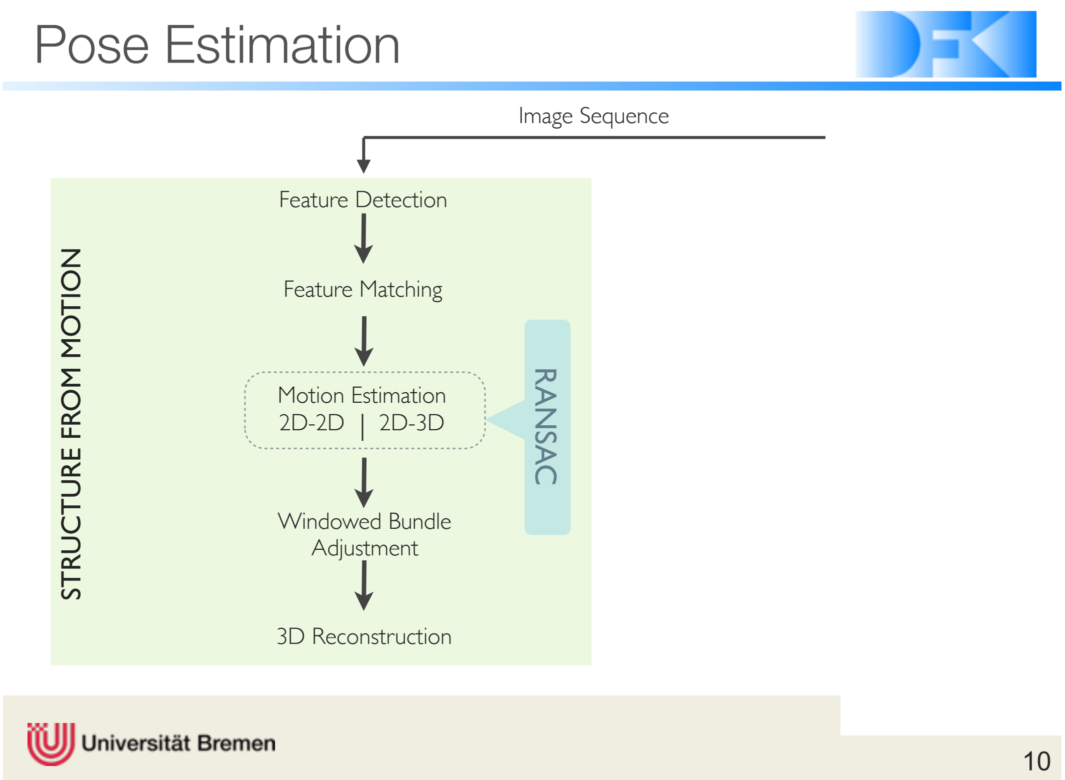


3D Range Profile

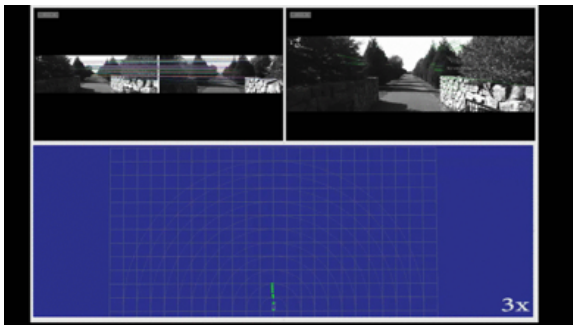
Universität Bremen

8


Challenges
Simultaneous Detection:
• Structured Light Pattern
• Background Features
Fusing Range Data:
• None overlapping
Camera images
Camera images
Universität Bremen
9


Pose Estimation
Image Sequence
STRUCTURE FROM MOTION
Feature Detection
Feature Matching
Motion Estimation
2D-2D | 2D-3D
RANSAC
Windowed Bundle
Adjustment
3D Reconstruction
Universität Bremen
10

KITTI Vision Benchmark

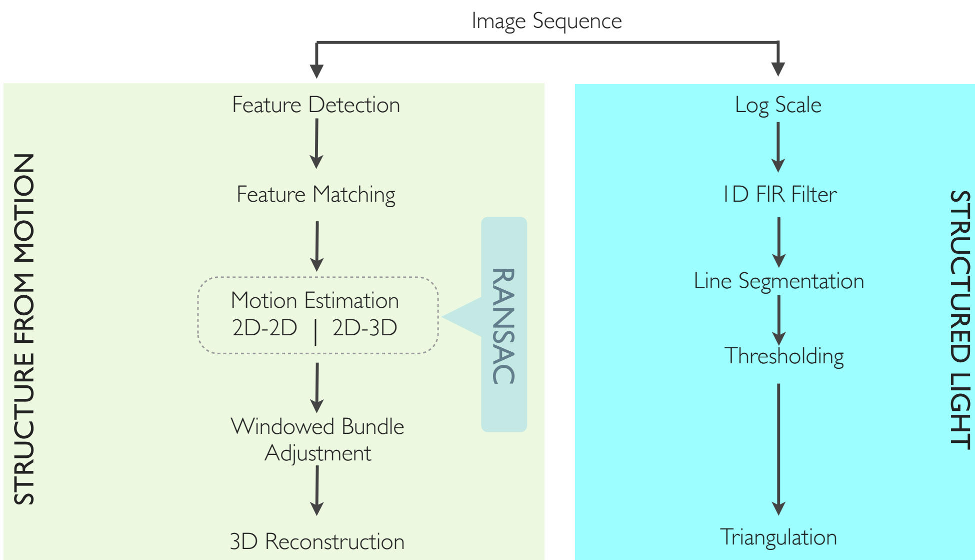


Rank	Method	Translation error	Rotation error
1	MVO	1.6 %	0.0029 [deg/m]
2	OCG	1.89 %	0.0083 [deg/m]
3	**W-SFM (DFKI)**	**2.16 %**	**0.0033 [deg/m]**
4	FTMVO	2.24 %	0.0049 [deg/m]
5	LCMVO	2.33 %	0.0050 [deg/m]
6	RMCPE+GP	2.55 %	0.0086[deg/m]

Universität Bremen

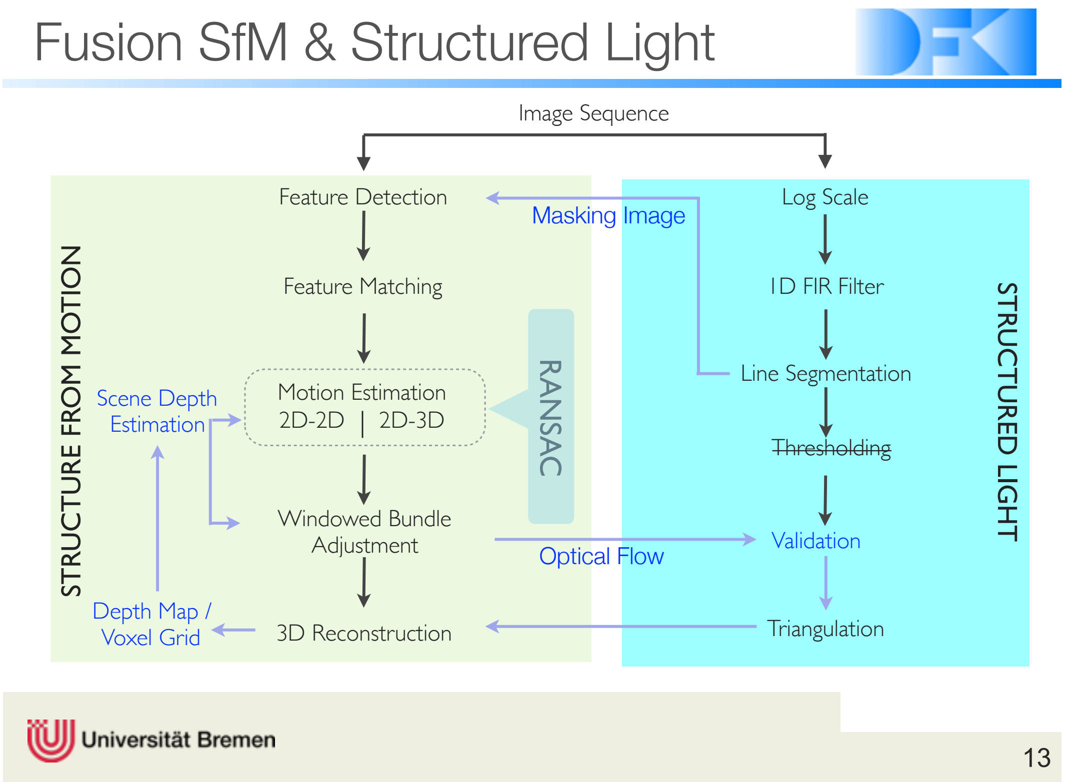
11

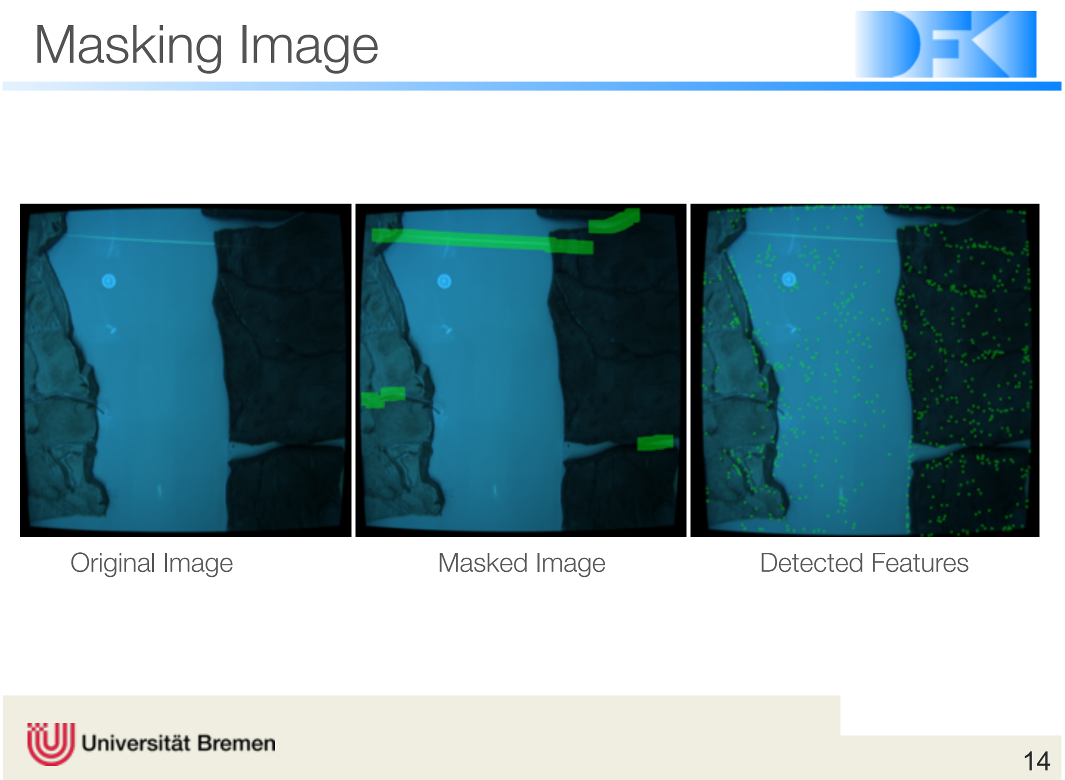
Depth Estimation



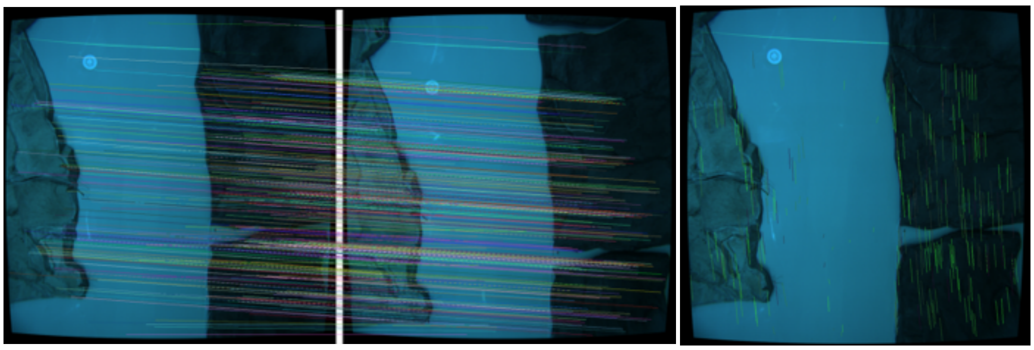
Universität Bremen

12


Fusion SfM & Structured Light
Image Sequence
STRUCTURE FROM MOTION
Feature Detection
Feature Matching
Motion Estimation
2D-2D | 2D-3D
RANSAC
Scene Depth
Estimation
Windowed Bundle
Adjustment
Depth Map /
Voxel Grid
3D Reconstruction
Masking Image
Optical Flow
STRUCTURED LIGHT
Log Scale
ID FIR Filter
Line Segmentation
Thresholding
Validation
Triangulation
Universität Bremen
13


Masking Image
Original Image
Masked Image
Detected Features
Universität Bremen
14

Masking Image



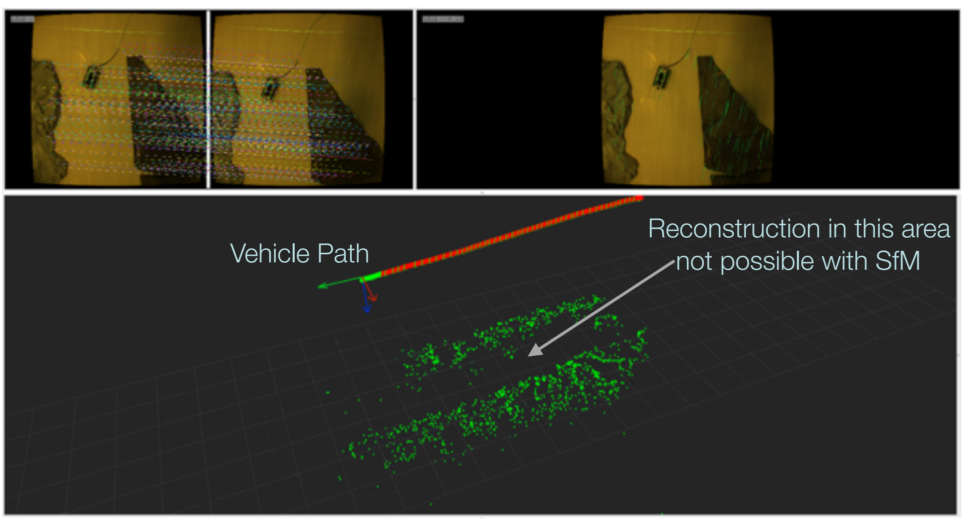
Matches between two key frames

Features Tracks

Universität Bremen

15

SfM

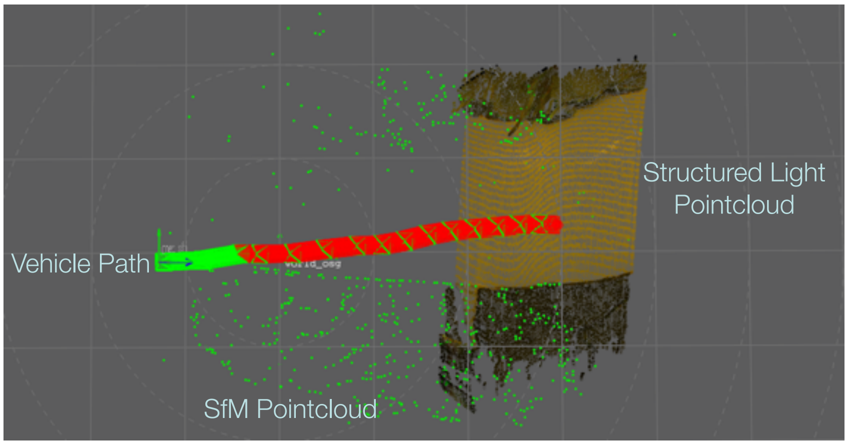


Sparse pointcloud generated by Structure from Motion

Universität Bremen

16

Scale Estimation



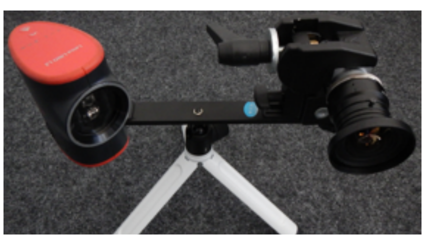
For each key frame ~10-20 features are used to fix the scale

Universität Bremen 17

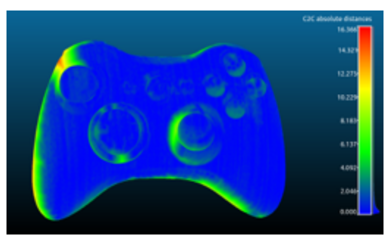
Results

Photo of the Experiment

3D Reconstruction



Scanner

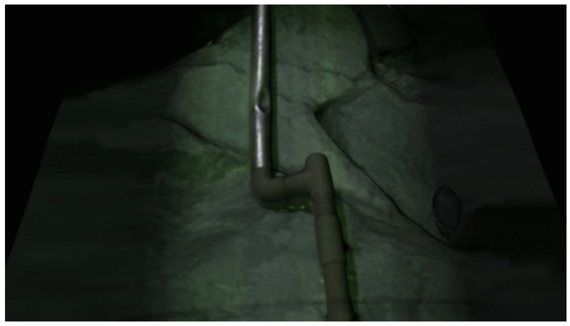


Comparison to turntable scan

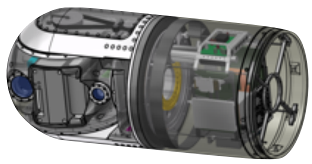
Universität Bremen 18

Results

Photo of the Experiment



3D Reconstruction



Robotic System

Universität Bremen

19

Results

Photo of the Experiment

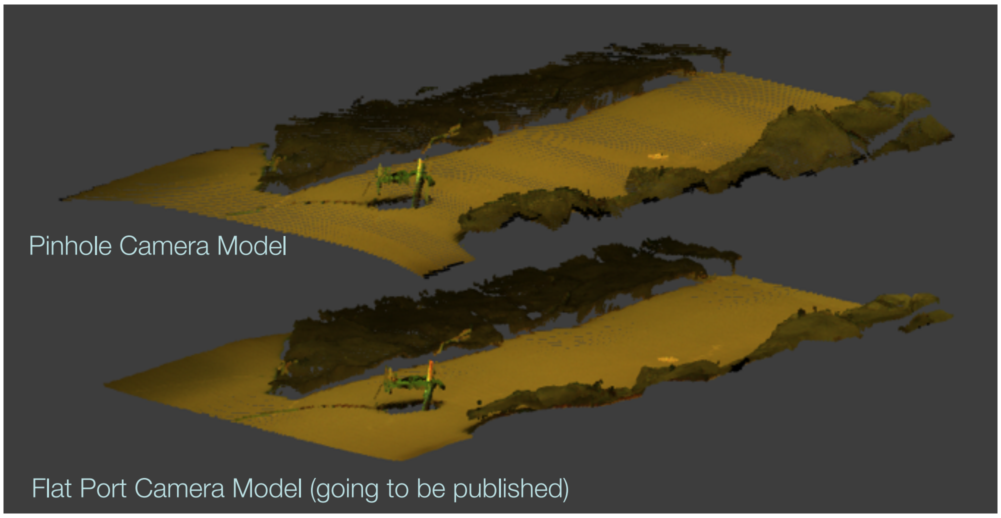
3D Reconstruction

Robotic System

Universität Bremen

20

Outlook



Universität Bremen

21

[1] Nistér, D., Naroditsky, O., & Bergen, J. (2004). Visual odometry. Computer Vision and Pattern

[2] Newcombe, R., & Davison, A. (2011). KinectFusion: Real-time dense surface mapping and tracking (ISMAR), 2011 10th

[3] Thomas Whelan, Michael Kaess, Maurice Fallon, Hordur Johannsson, John Leonard, and John McDonald. Kintinuous: Spatially extended kinectfusion. Technical report, Computer Science and Artificial Intel- ligence Laboratory (CSAIL), Massachusetts Institute of Technology (MIT), 2012.

[4] Peter Henry, Dieter Fox, Achintya Bhowmik, and Rajiv Mongia. Patch Volumes: Segmentation-Based Consistent Mapping with RGB-D Cameras. In 3D Vision, pages 398–405. Ieee, June 2013.

[5] Ivan Dryanovski, RG Valenti, and Jizhong Xiao. Fast visual odometry and mapping from RGB-D data. In Robotics and Automation (ICRA), pages 2305–2310, 2013.

[6] Segal, Aleksandr, Dirk Haehnel, and Sebastian Thrun. "Generalized-ICP." Robotics: Science and Systems. Vol. 2. No. 4. 2009.

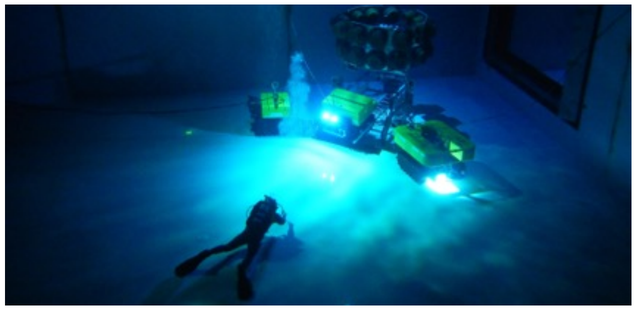
[7] Felix Endres, Jurgen Hess, Nikolas Engelhard, Jurgen Sturm, Daniel Cremers, and Wolfram Burgard. An evaluation of the RGB-D SLAM system

[8] Rusu, Radu Bogdan, Nico Blodow, and Michael Beetz. "Fast point feature histograms (FPFH) for 3D registration." Robotics and Automation, 2009. ICRA'09. IEEE International Conference on. IEEE, 2009.

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

Universität Bremen

Thank you!



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

Universität Bremen

2.10 'PLEXIL - a short overview' (NP-P-17)

Martin Fritsche [(1)]

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

Contact: martin.fritsche@dfki.de

Abstract

This poster gives a short overview of PLEXIL the Plan Execution Interchange Language from NASA Ames Research Center - Autonomous Systems and Robots. It shall give an idea what the language looks like and which tools are available.

German Research Center for Artificial Intelligence

PLEXIL – a short overview

Plan Execution Interchange Language - http://plexil.sourceforge.net/

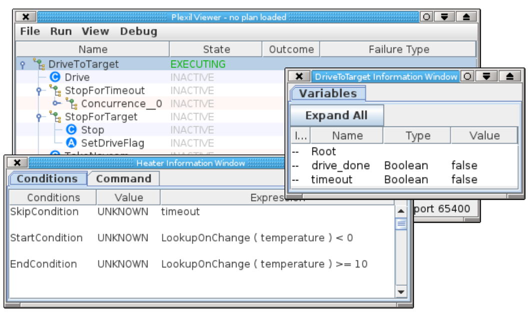
In the D-ROCK project different approaches to model robot behaviour have been examined. One of them is PLEXIL.

What is PLEXIL?

PLEXIL is a language for expressing plans and a set of tools to use it. It is developed by NASA Ames Research Center - Autonomous Systems and Robots and made available on Sourceforge (http://plexil.sourceforge.net/)

Plans

PLEXIL plans can be written in standard PLEXIL syntax or in PlexiLisp. Both need to be translated to XML for plan execution.
A PLEXIL plan consists of multiple state machines (nodes) that are executed in parallel, controlled by gate conditions (start, end, repeat, skip) and evaluated by check conditions (pre, post, invariant)



The PLEXIL simulator

The Language

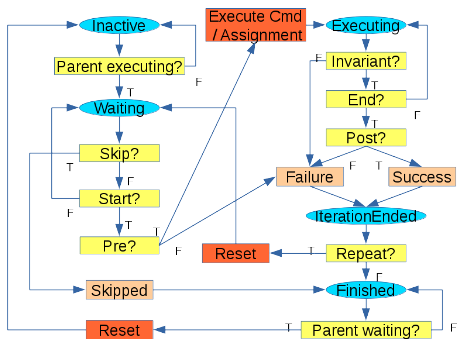
The PLEXIL language allows sequences, concurrence, branching (if-then-else), while and for loops, message passing, variables of different types,…It resembles "normal" programming languages.

Example for a very simple node starting when drive_done is true and executing take_pancam except when timeout is true:

```
TakePancam:
  {
    StartCondition drive_done;
    SkipCondition timeout;
    take_pancam();
  }
```

The PLEXIL executive

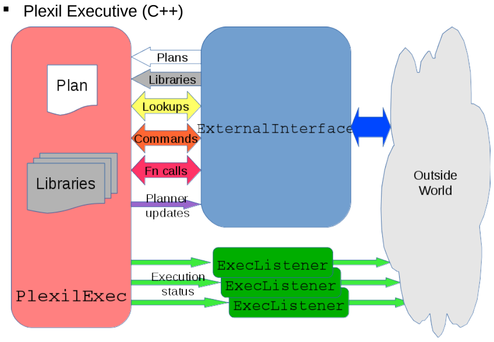
The executive executes the plan and interfaces to systems via an interface adapter framework (C++). It receives the plans from a planner or the user and sends back the execution status.
It sends commands to the system and receives state information.



Node state machine – Picture from "Plexil Workshop Part 1" 2010 USRA

The most important Tools

- Compiler for standard PLEXIL or Plexilisp (Java)
- Simulator to test plans (Java)
  - Simulates the plan execution
  - Displays current position in plan, content of variables and conditions and allows editing
  - External events and data needs to be scripted
- Plexil Executive (C++)



PLEXIL executive architectural overview – Picture from "Plexil Workshop Interfacing External Systems" 2010 USRA

Is this an active project?

PLEXIL is still in development at NASA and was used e.g. for
•K10 Rover Control
•Earth science drilling executive
•Rotorcraft system architecture (SIRCA)

There is not much traffic on the support mailing list but a NASA employee answers questions and gives support.

The documentation consists of a wiki, presentations for different topics and hands on workshop exercises.

Universität Bremen

Contact:
DFKI Bremen & University of Bremen
Robotics Innovation Center

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

NP

2.11 'Integrating Environment Representation and Simulation: Towards an Internal Simulator for Rock Using Mars' (NP-P-18)

Raul Dominguez[1]

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

Contact: raul.dominguez@dfki.de

Abstract

Summary and plan for the ongoing project of integrating the core of the simulator Mars with the Environment Representation library *Envire*. The poster presents the software architecture planned and some of the applications that this integration will be used in (e.g. validation of navigation plans in lava tubes scenarios).

Integrating Environment Representation and Simulation

Towards an Internal Simulator for Rock Using Mars

German Research Center for Artificial Intelligence

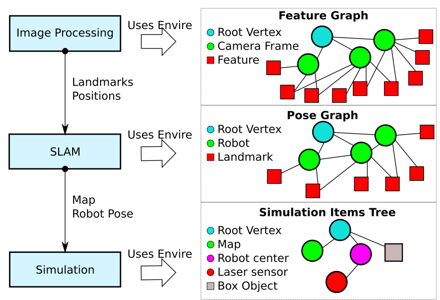
Raúl Domínguez, Yong-Ho Yoo and Arne Böckmann
DFKI GmbH, Robotics Innovation Center
Robert-Hooke-Straße 1, 28359 Bremen, Germany

Motivation for an Internal Simulator

- Robotic missions can require decision taking without operator (e.g. cave mapping)
- Autonomy and reliability
- Limitations and failures detection
- Learn and adapt behavior from internal experiences
- Bring the validation process through simulation from the programmer to the robot itself

Envire and Mars Integration

- Envire representation incorporates all the information about the environment relevant for a task (e.g. SLAM)
- Same base representation among components eases communication, synchronization and code maintenance
- Mars has its own specialized Envire to handle the items of the simulation
- Synchronization via Rock ports and allowing events handling within each component



Envire used by three Rock components (left side). Each one adapts the representation to its needs. The different components share information through Rock ports.

Tool Development

Now

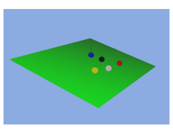
- Management of simple objects in the physics engine
- Update of positions based on interaction in the physics engine
- Node: List of items in the simulation sharing pose
- Edge: Transformation between nodes

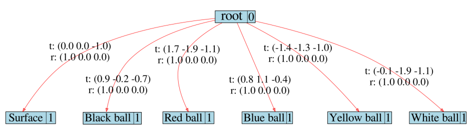
Soon

- Plugin architecture for the different physical objects to be simulated
- Integration of MLS maps and soil models as plugins for this architecture
- Loading of SMURF robot models
- Convert the Node Manager into an event based module which provides access to the Envire tree

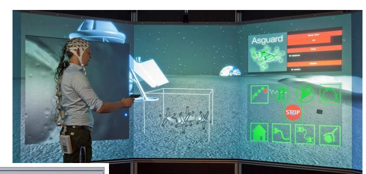
Goals

- Share the environment representation for simulation and real world interactions efficiently
- Automatic generation of simulations to validate motion plans (e.g. move left leg) and mission plans (e.g. take the steep slope path)
- Simulations for assisting human operator's decisions



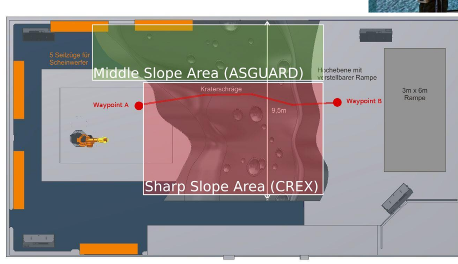


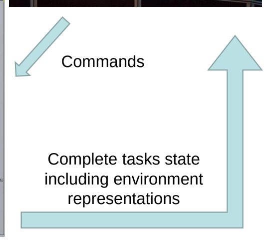
Current state of the tool: Envire Simulation Tree stores the information about the simulation Items and updates it with the computations of the physics engine (ODE)



Proof of Functionality: First Entern Scenario

- Crater navigation through different areas with Asguard IV and Crex
- The robots should traverse the crater in the Space Exploration Hall up and down, through different slopes
- Adaptation of the controller parameters using the internal simulation
- Decision support for the operations center with simulation and real execution being displayed in parallel





For the first demonstration in Entern CREX and ASGUARD IV will traverse the crater in the Space Exploration Hall, the mission will be simulated and operated from the Virtual Reality Lab.

Universität Bremen

Supported by:
Federal Ministry of Economics and Technology
on the basis of a decision by the German Bundestag

DLR
Gefördert von der Raumfahrt-Agentur des Deutschen Zentrums für Luft- und Raumfahrt e.V. mit Mitteln des Bundesministeriums für Wirtschaft und Technologie aufgrund eines Beschlusses des Deutschen Bundestages unter den Förderkennzeichen 50RA1407

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 'Locomotion & Mobility'

3.1 'SherpaTT – First Experiences with the Hardware' (LM-T-01)

Florian Cordes[(1)]

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

Contact: florian.cordes@dfki.de

Abstract

SherpaTT is part of a team of heterogeneous robots developed in the project TransTerrA. The slides of the talk provided here give a first glimpse at the integrated hardware of the robot. During August 2015 the robot's locomotion system was electromechanically integrated, this presentation subsumes the first two weeks of experiences working with the actual hardware of the system.

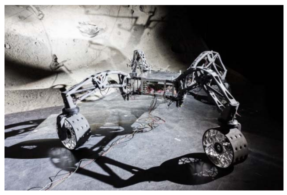
The motion control system (MCS) was already set up and tested in simulation prior to the hardware integration. Setting up the software for the robot's hardware worked flawlessly. Hence qualitative verification of kinematics calculations, forward control of basic functions such as body attitude control was possible to conduct in a short time frame.

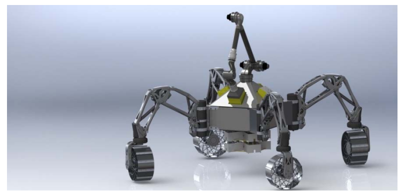
Future work in terms of the very next steps is provided at the end of the presentation. This includes the very next step of setting the active ground adaption to work on the hardware system.

SherpaTT

First Experiences with the Hardware

Florian Cordes
2015-09-17





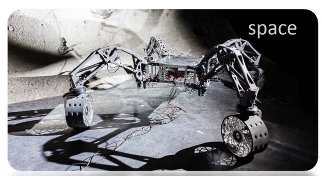
SherpaTT is part of the multi-robot team developed in the project:

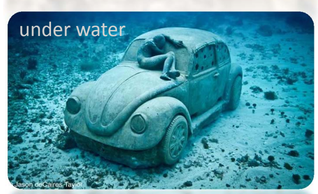
DFKI Robotics Innovation Center Bremen
Robert-Hooke Straße 5
28359 Bremen, Germany

Trans TerrA

Plans for SherpaTT

- *SherpaTT* is the enhancement of Sherpa originating from the project RIMRES
  - TT for Sherpa in project TransTerrA
- SherpaTT will be used for
  - Space Exploration Scenario
  - SAR Scenario (Terrestrial Application Transfer)
  - Underwater Scenario (here: aka *SherpaUW*, 2nd Terrestrial Application Transfer)
- Development goals
  - Improve ground adaption capabilities
  - Reduce number of DoF
  - Enhance body posture control capabilities
  - Make it water proof

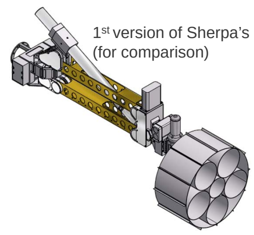




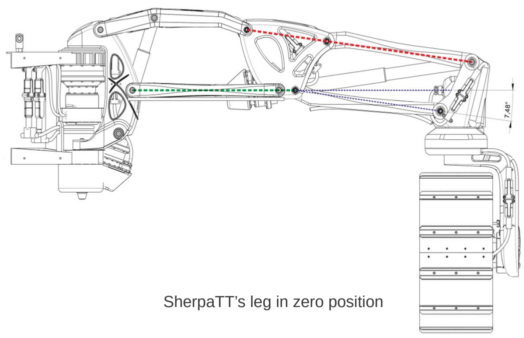
tinyurl.com/imageSource-JdCT

The SherpaTT Active Suspension System

- Four Legs / Suspension Units with 5 active DoF each
  - 3 DoF for positioning the leg end point (LEP) around the body
  - 1 DoF for orienting the wheel
  - 1 DoF for driving the wheel



1st version of Sherpa's legs (for comparison)

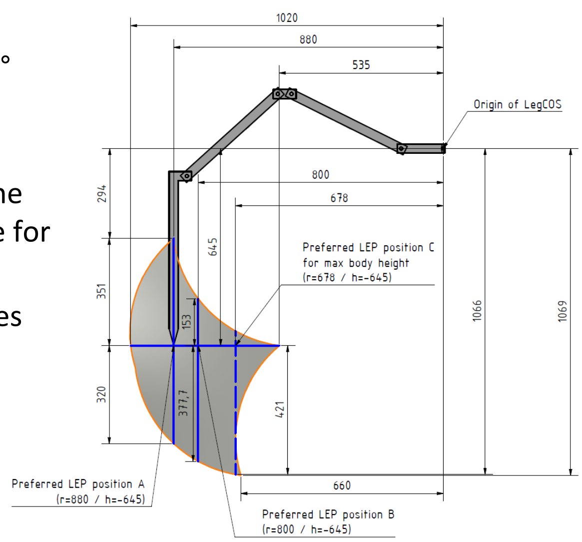


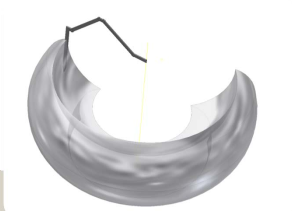
SherpaTT's leg in zero position

SherpaTT's integrated leg main structure

Workspace of Suspension Units

- First joint (Pan) has movement range of -90° <-> + 135°
- Second (InnerLeg) and third (OuterLeg) combine to an area of workspace for each Pan configuration
- Preferred standard poses maximize vertical movement capabilities





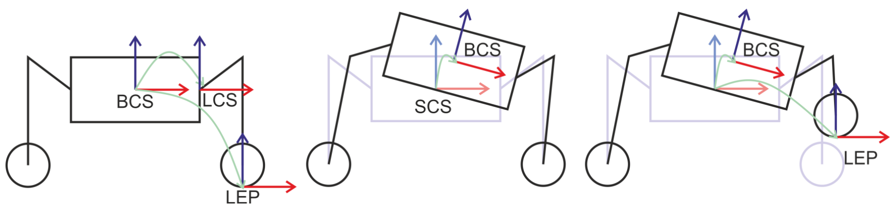
...nces with the Hardware
Project Day 2015-09-17

DFKI RIC Bremen

4

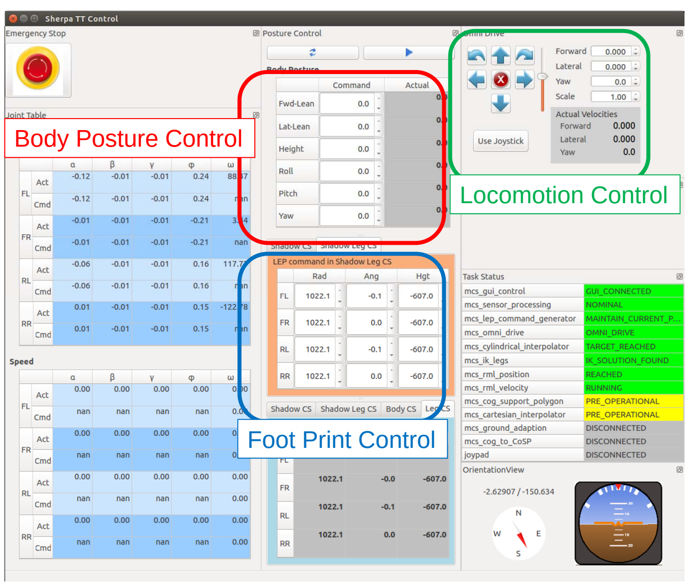
Coordinate Systems for Locomotion Control

- Body Coordinate System (BCS)
  - Attached to center of body, moves with body
  - Internal calculations (i.e. inverse kinematics) are described in BCS
- Shadow Coordinate System (SCS)
  - Virtual coordinate system
  - BCS movements are described in SCS
- Leg Coordinate System (LCS)
  - Cylindrical coordinates (angle, radius, height)



SherpaTT: First Experiences with the Hardware
F. Cordes DFKI Project Day 2015-09-17
DFKI RIC Bremen
5

The MCS Control GUI

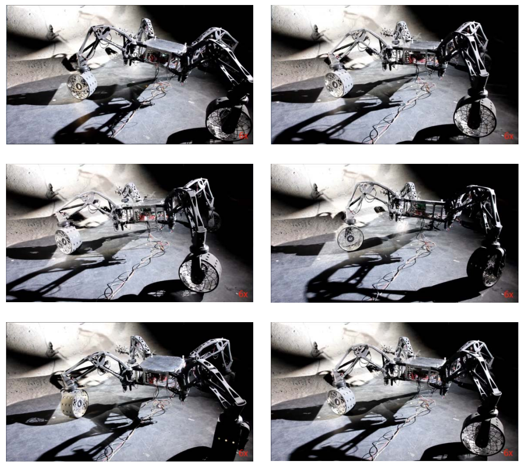


SherpaTT: First Experiences with the Hardware
F. Cordes DFKI Project Day 2015-09-17
DFKI RIC Bremen
6

Body Control

- Body's attitude can be controlled in 6DoF
  - Roll / Pitch
  - Yaw
  - Body shift (forward and lateral)
  - Body height
- Foot print is not altered
- Allows to adjust body relative to terrain
  - Sensor alignment
  - BaseCamp pick-up
  - Manipulator leveling

Video: Body attitude control (screenshots for print version)

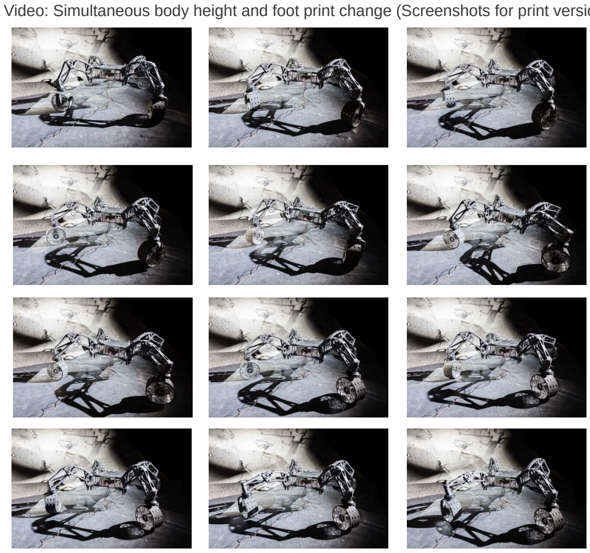


SherpaTT: First Experiences with the Hardware
F. Cordes DFKI Project Day 2015-09-17
DFKI RIC Bremen 7

LEP and Body Control

- Possible to change foot print and body posture simultaneously
- Foot print changes do not alter body pose
- WheelDrive and WheelSteering follow LEP velocity vector

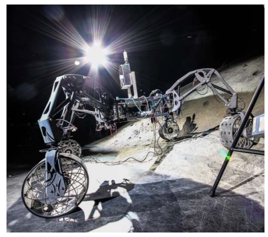
Video: Simultaneous body height and foot print change (Screenshots for print version)

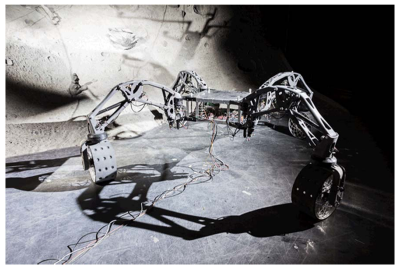


SherpaTT: First Experiences with the Hardware
F. Cordes DFKI Project Day 2015-09-17
DFKI RIC Bremen 8

Next Steps

- Use FTS for active ground adaption
  - Ground Adaption Process (GAP) will include ground plane estimates by incorporating IMU data and internal configuration state
- Roll/Pitch adaption process (RPA)
  - Combine with GAP
- Parametrizable obstacle climbing behavior as preparation for autonomous climbing
- Quantify the system’s capabilities
- Get the robot water proof





SherpaTT: First Experiences with the Hardware
F. Cordes DFKI Project Day 2015-09-17
DFKI RIC Bremen
9

3.2 'Experience-Based Adaptation of Locomotion Behaviors for Kinematically Complex Robots in Unstructured Terrain' (LM-T-02)

Alexander Dettmann[(1)], Anna Born[(1)], Sebastian Bartsch[(2)], and Frank Kirchner[(1) (2)]

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

Contact: alexander.dettmann@dfki.de

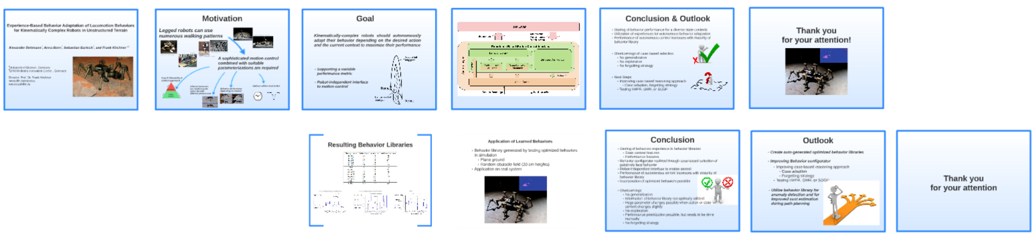
Abstract

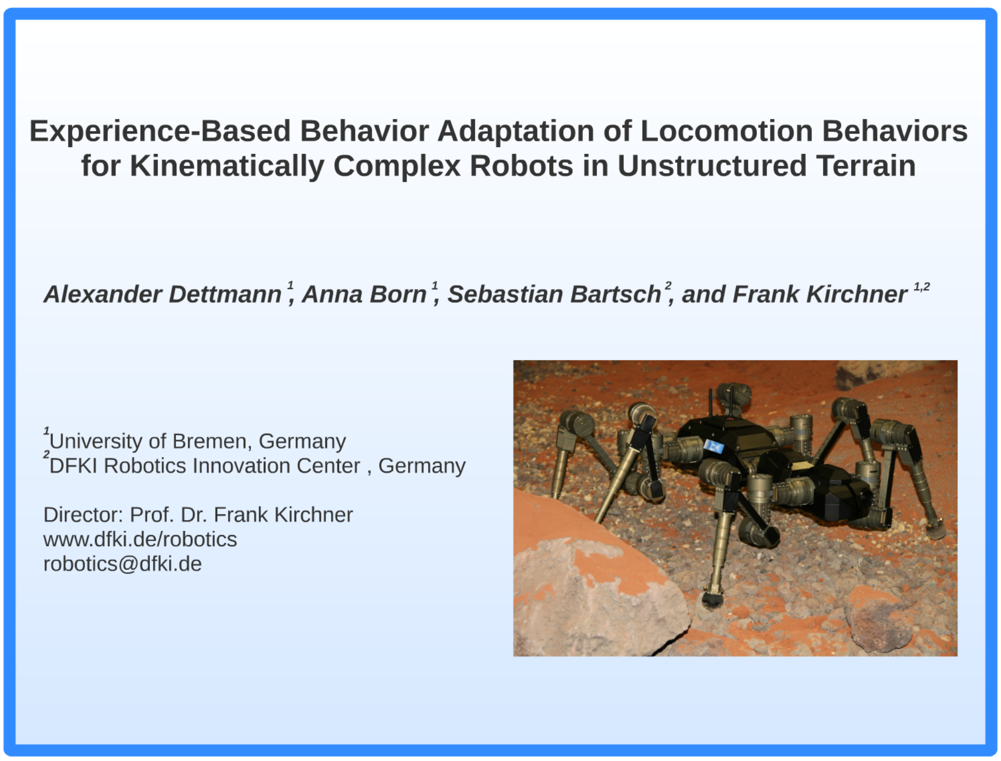
Kinematically complex robots such as legged robots provide a large degree of mobility and flexibility, but demand a sophisticated motion control, which has more tunable parameters than a general planning and decision layer should take into consideration. A lot of parameterizations exist which produce locomotion behaviors that fulfill the desired action but with varying performance, e.g., stability or efficiency. In addition, the performance of a locomotion behavior at any given time is highly depending on the current environmental context. Consequently, a complex mapping is required that closes the gap between robot-independent actions and robot-specific control parameters considering the environmental context and a given prioritization of performance indices.

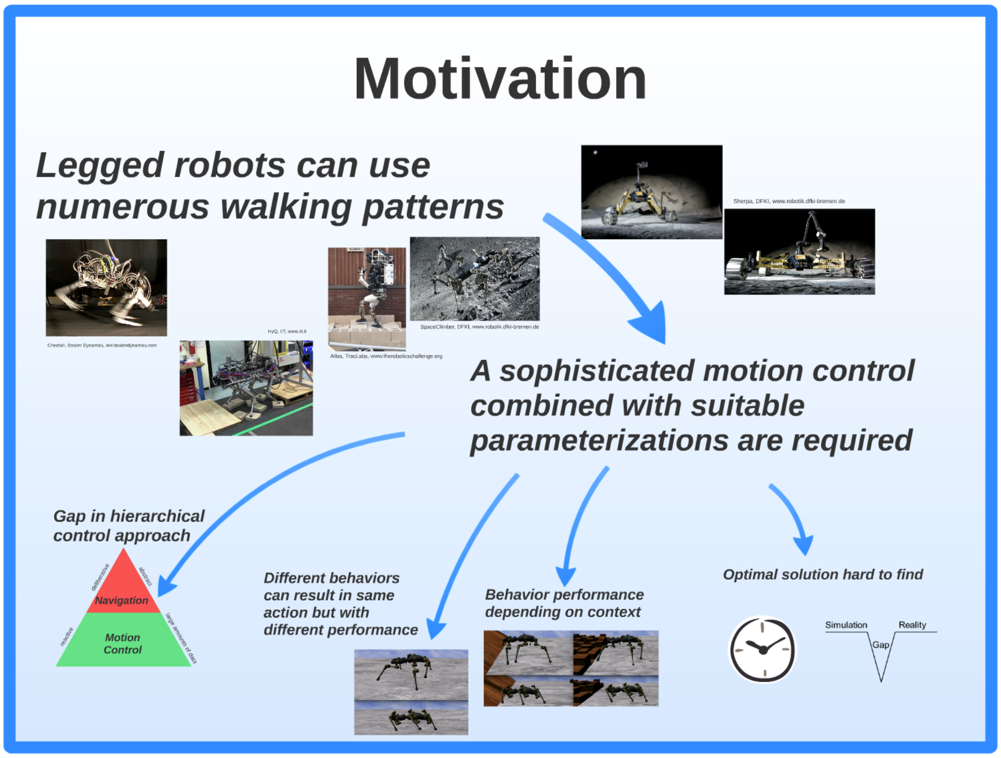
In the proposed approach, the robot learns from experiences made during its interaction with the environment. A knowledge base is created which links locomotion behaviors with performance features for visited contexts. This *behavior library* is utilized by a case-based reasoner to select motion control parameters for a desired action within the current context. The paper provides an overview of the control approach, the algorithms used to determine the current context and the robot's performance, as well as a description of the reasoner which selects appropriate locomotion behaviors.

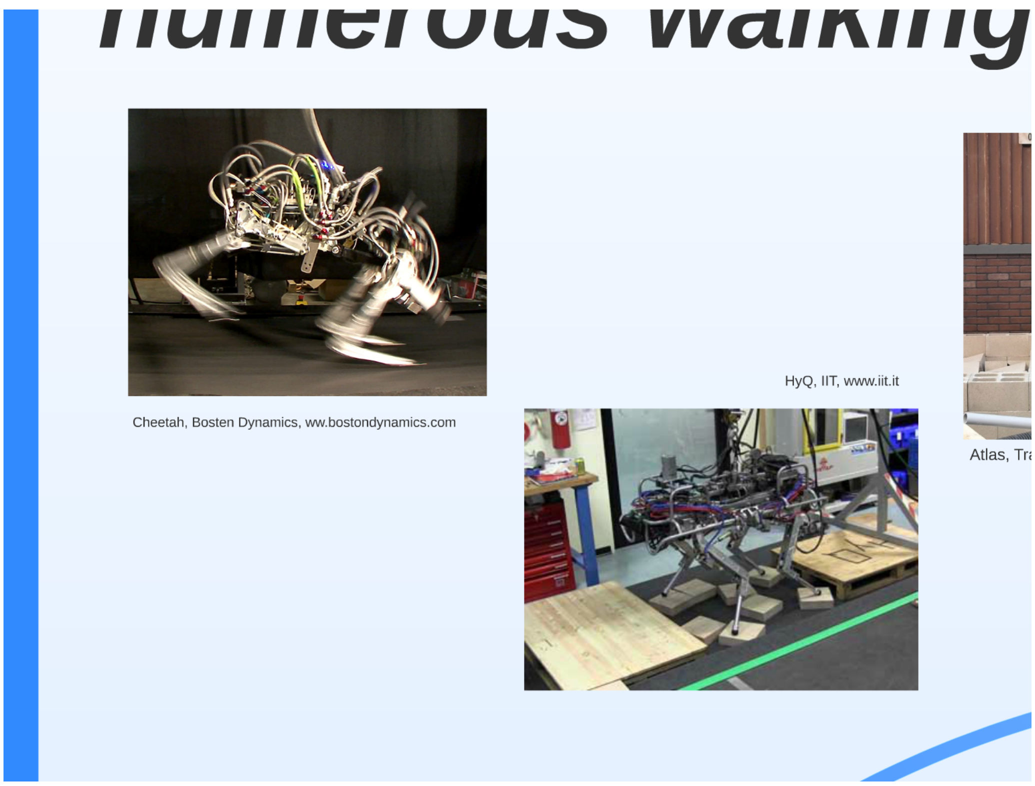
In experiments, different *behavior libraries* were automatically built when operators had to control a walking robot manually through obstacle courses. Afterwards, the collected experiences and a trajectory follower were used to traverse an obstacle course autonomously. The provided experimental evaluation shows the performance dependency of the autonomous control with respect to different sizes and qualities of utilized *behavior libraries* and compares it to manual control.

Please note that the corresponding paper is published in:
Experience-based adaptation of locomotion behaviors for kinematically complex robots in unstructured terrain; A. Dettmann, A. Born, S. Bartsch, and F. Kirchner; In IEEE/RSJ International Conference on Intelligent Robots and Systems (IROS), 2015.

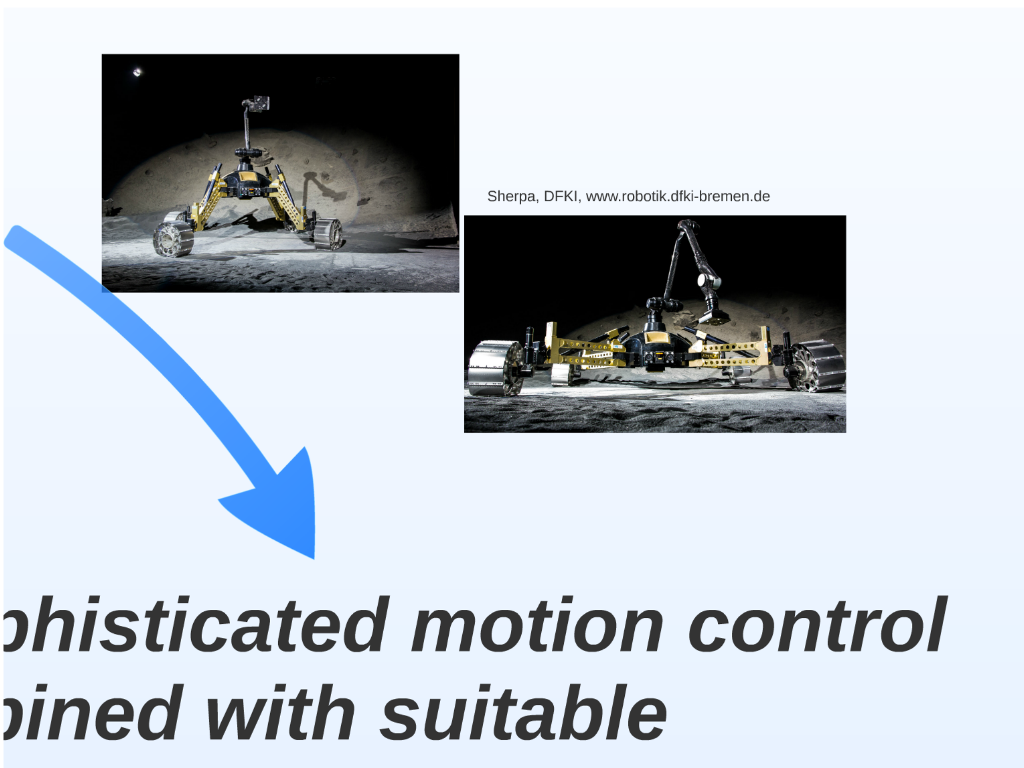

Motivation
Goal
Conclusion & Outlook
Thank you
for your attention!
Resulting Behavior Libraries
Conclusion
Outlook
Thank you
for your attention

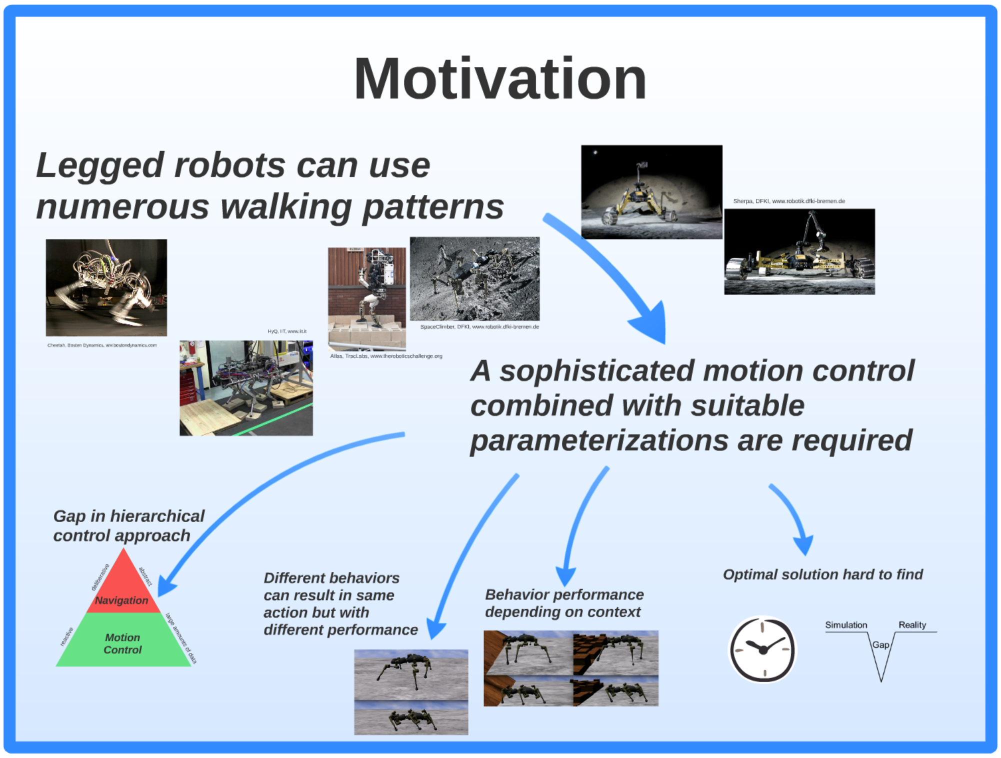

Experience-Based Behavior Adaptation of Locomotion Behaviors
for Kinematically Complex Robots in Unstructured Terrain
Alexander Dettmann [1], Anna Born [1], Sebastian Bartsch [2], and Frank Kirchner [1,2]
[1] University of Bremen, Germany
[2] DFKI Robotics Innovation Center , Germany
Director: Prof. Dr. Frank Kirchner
www.dfki.de/robotics
robotics@dfki.de

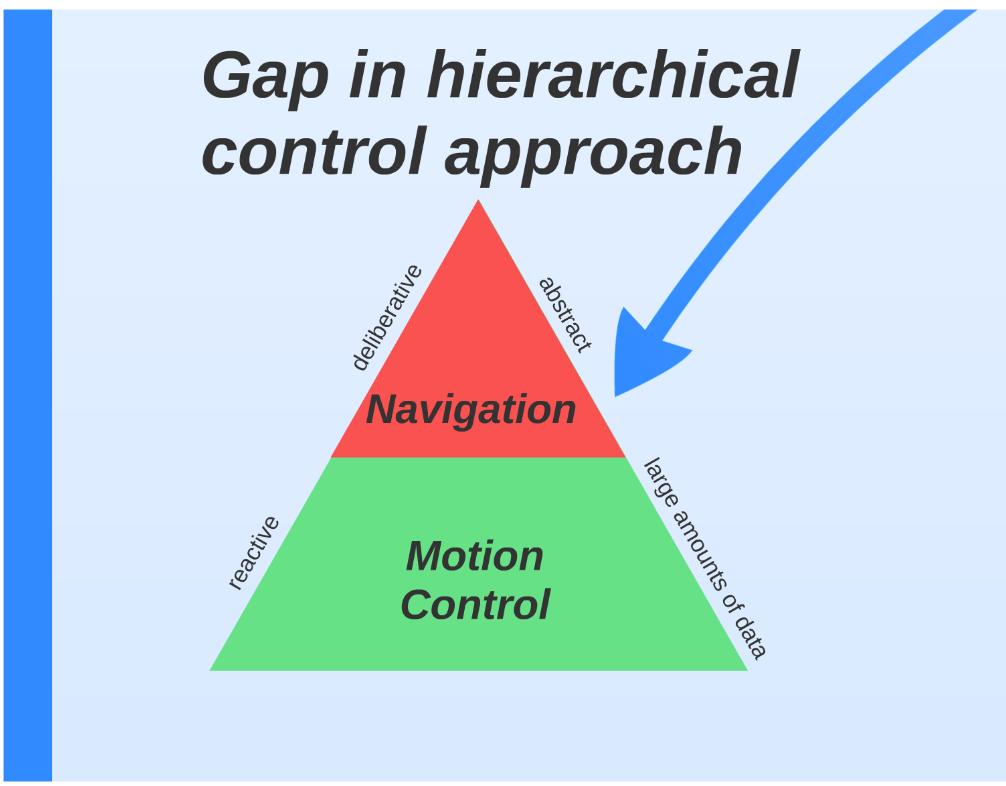

Motivation
Legged robots can use numerous walking patterns
A sophisticated motion control combined with suitable parameterizations are required
Gap in hierarchical control approach
Navigation
Motion Control
Different behaviors can result in same action but with different performance
Behavior performance depending on context
Optimal solution hard to find
Simulation
Reality
Gap

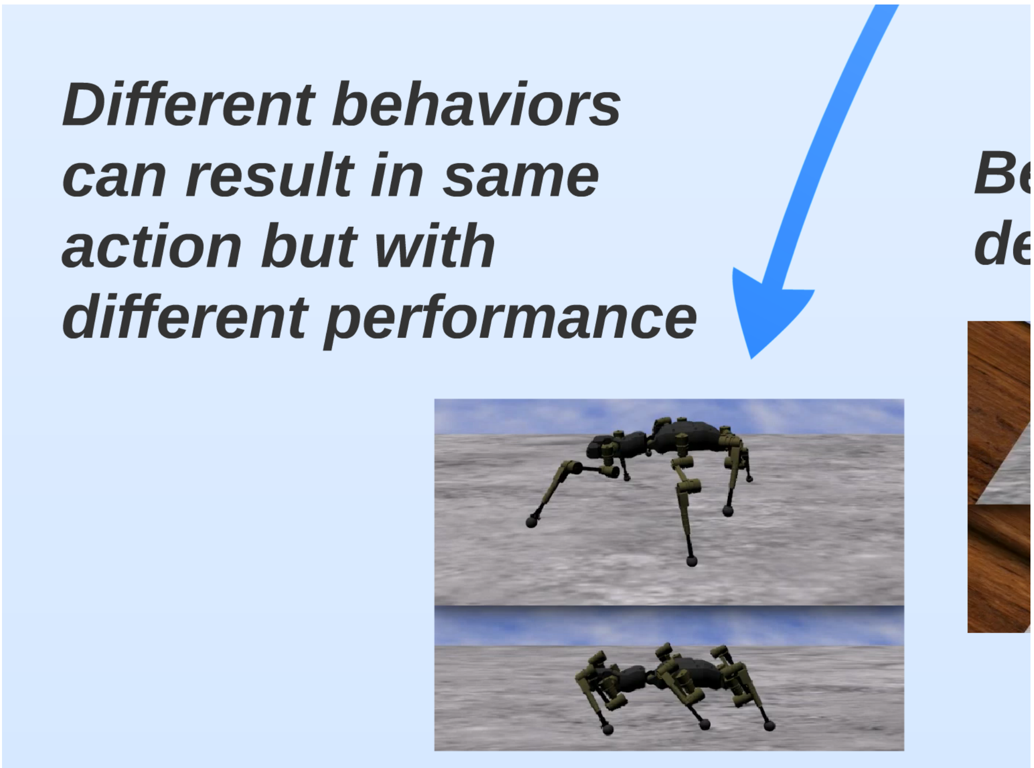

numerous walking
Cheetah, Bosten Dynamics, ww.bostondynamics.com
HyQ, IIT, www.iit.it
Atlas, Tra

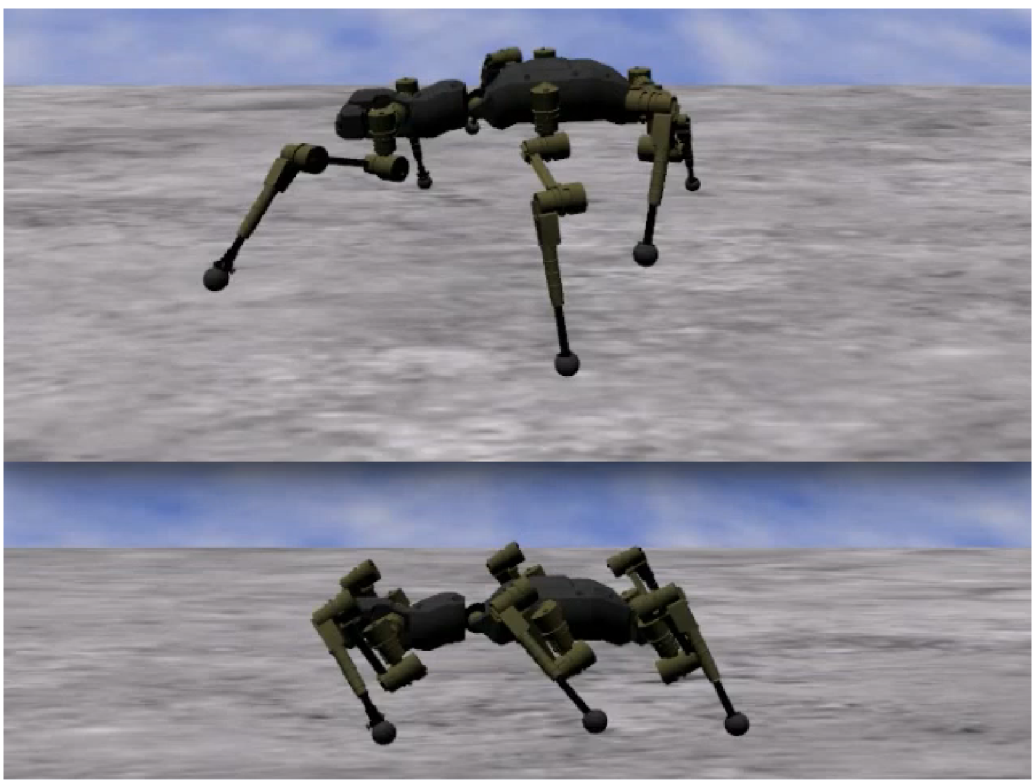

patterns
SpaceClimber, DFKI, www.robotik.dfki-bremen.de
, www.iit.it
Atlas, TracLabs, www.theroboticschallenge.org

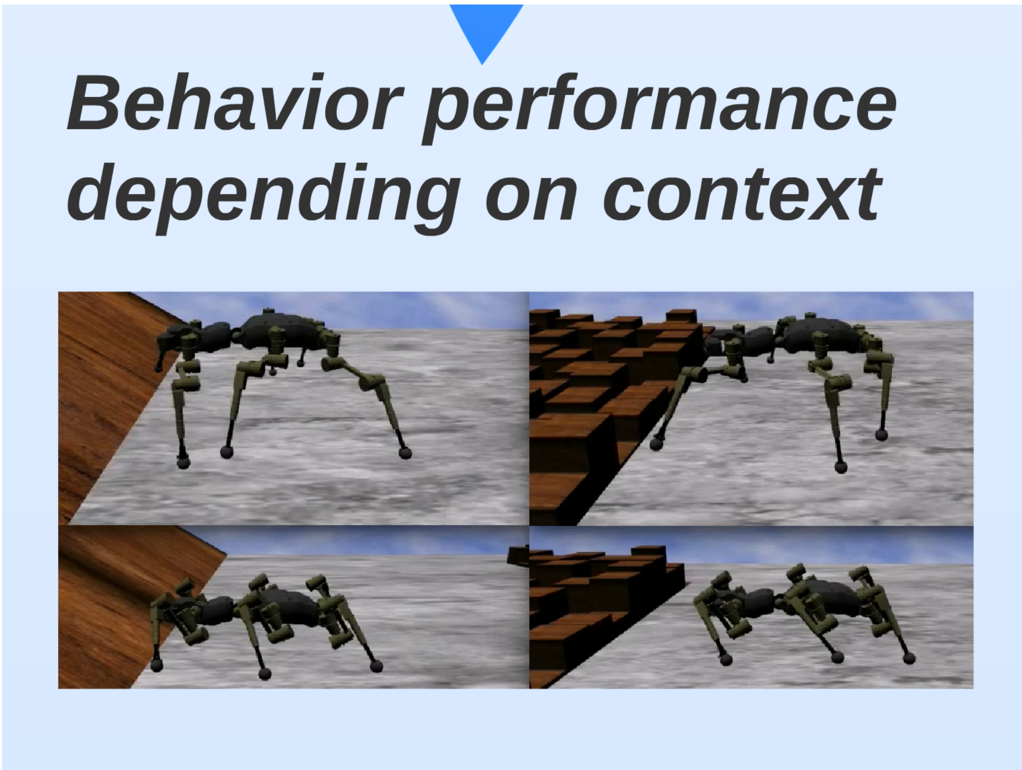

Sherpa, DFKI, www.robotik.dfki-bremen.de
motion control
with suitable

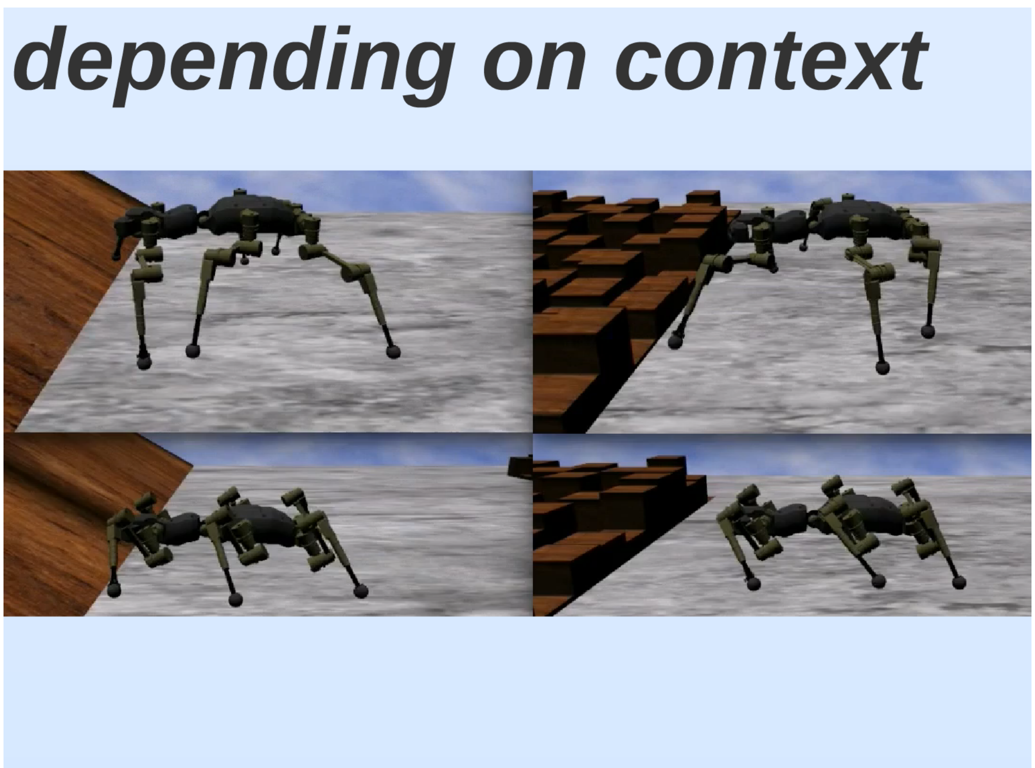

Motivation
Legged robots can use numerous walking patterns
A sophisticated motion control combined with suitable parameterizations are required
Gap in hierarchical control approach
Navigation
Motion Control
Different behaviors can result in same action but with different performance
Behavior performance depending on context
Optimal solution hard to find
Simulation
Reality
Gap

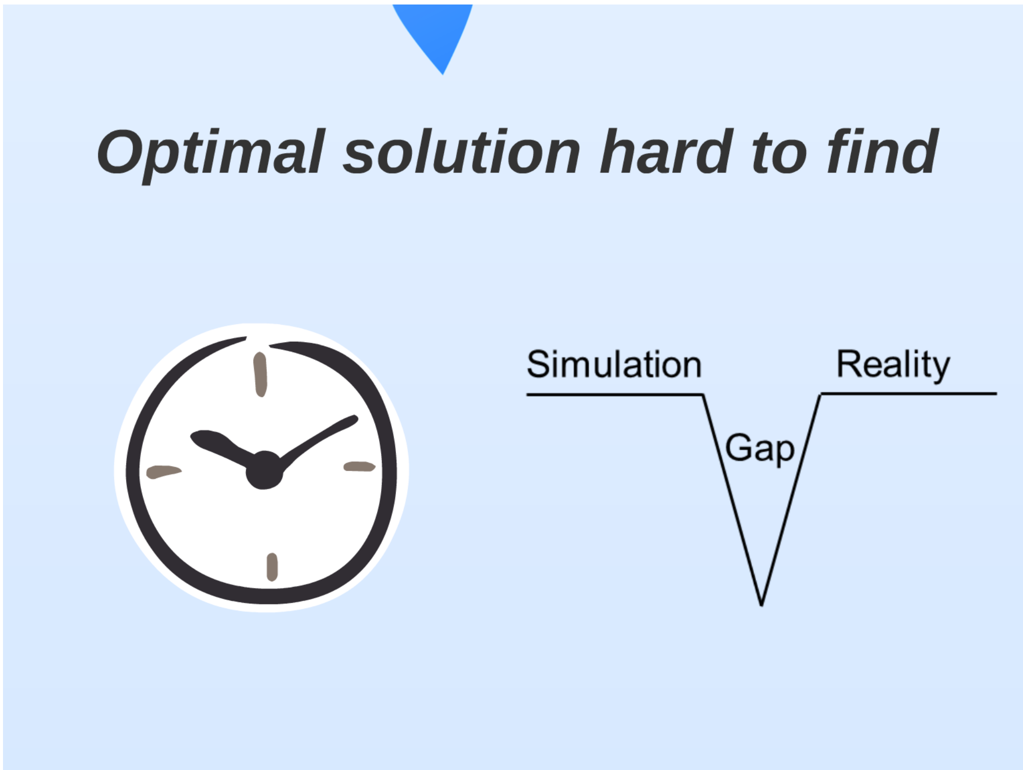

Gap in hierarchical control approach
deliberative
abstract
Navigation
reactive
large amounts of data
Motion Control

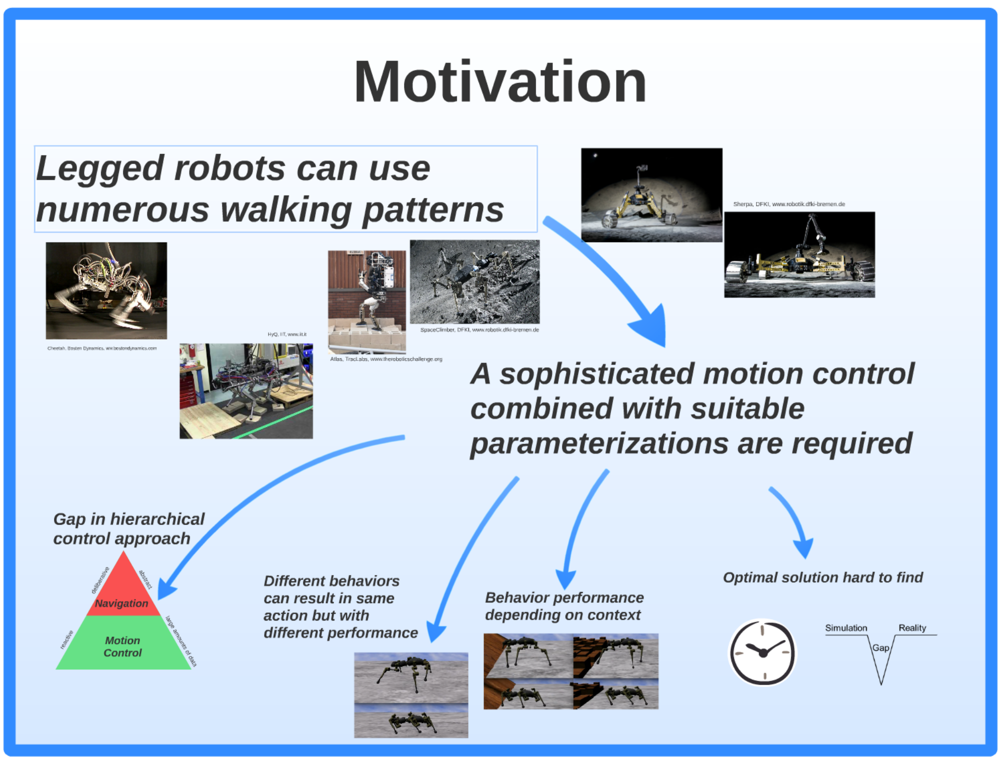

Different behaviors
can result in same
action but with
different performance




Behavior performance
depending on context


depending on context

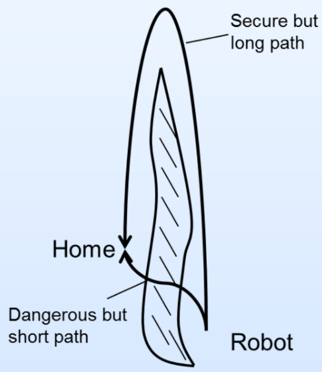

Optimal solution hard to find
Simulation
Reality
Gap

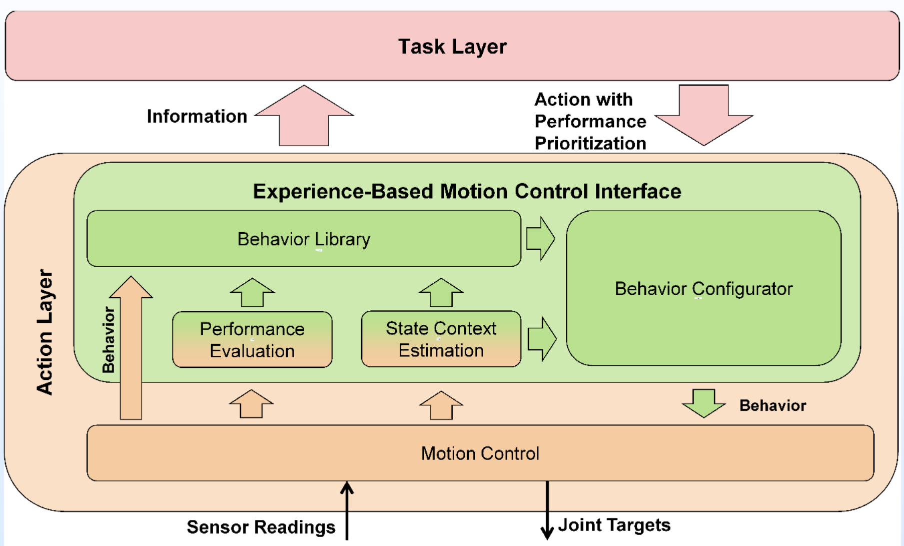

Motivation
Legged robots can use numerous walking patterns
A sophisticated motion control combined with suitable parameterizations are required
Gap in hierarchical control approach
Navigation
Motion Control
Different behaviors can result in same action but with different performance
Behavior performance depending on context
Optimal solution hard to find
Simulation
Reality
Gap

Goal

Kinematically-complex robots should autonomously adapt their behavior depending on the desired action and the current context to maximize their performance

- ***Supporting a variable performance metric***
- ***Robot-independent interface to motion control***

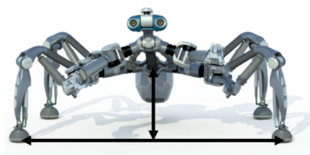




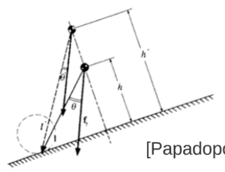
Performance Estimation

Performance features characterize locomotion behaviors

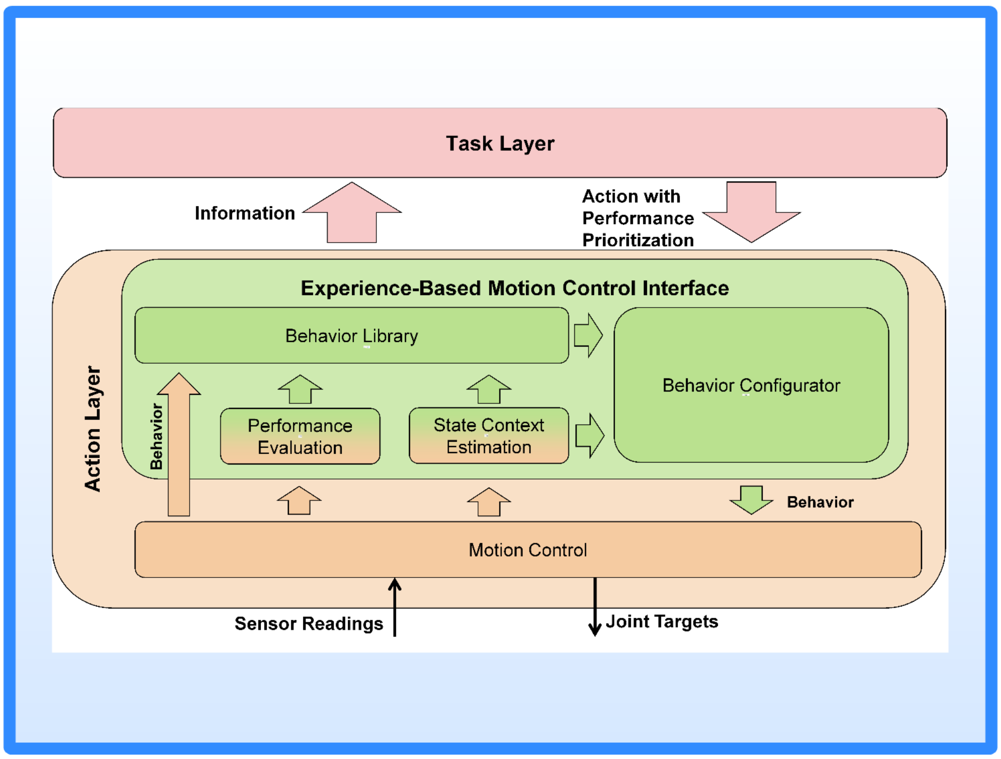
- Action performance features
  - Characterizing movement
    - Velocity x
    - Velocity y
    - Turn rate
  - Characterizing posture
    - Body height
    - Body width



- Meta performance features
  - Characterizing stability
    - Static stability margin (ssm)
    - Force-angle stability measure (dsa)
  - Characterizing efficiency
    - Power
    - Energy per distance (epd)
    - Body vibration



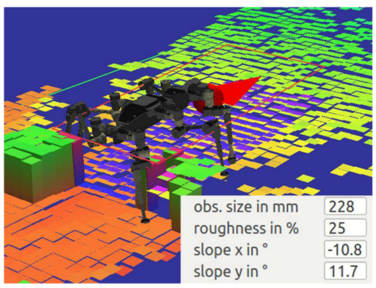
[Papadopoulos2000]

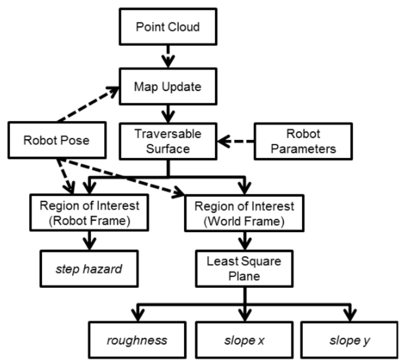


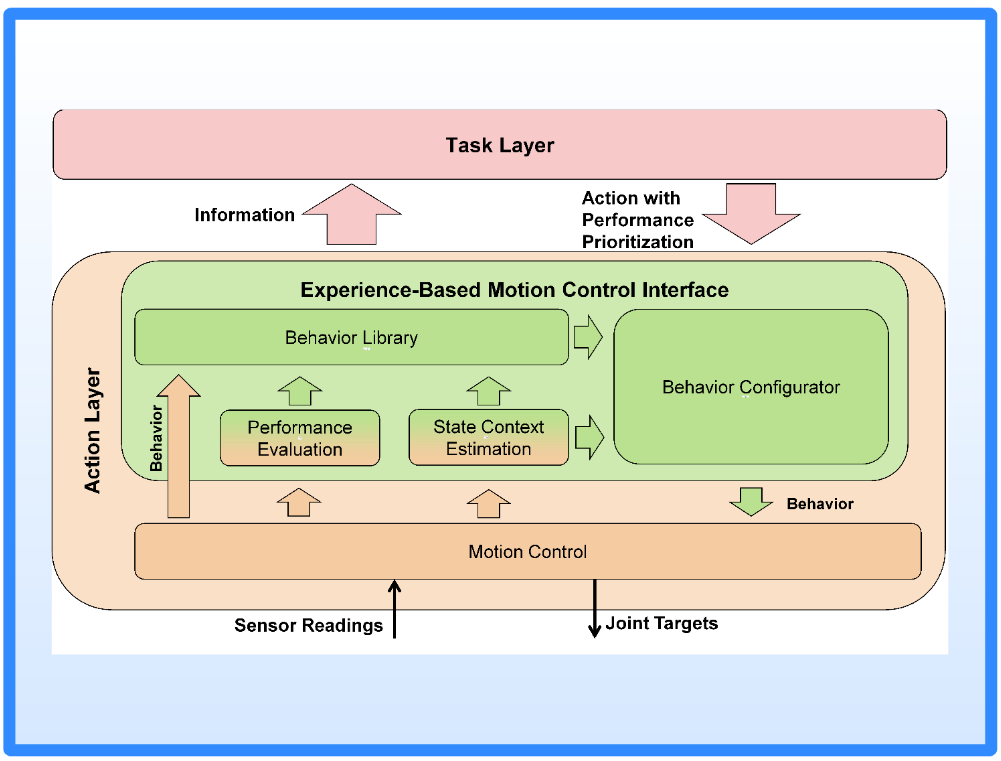
State Context Estimation

State context features characterize the environment

- MLS map from point cloud data and robot pose
- Region of interest
  - Area beneath robot
  - Area in direction of movement within next step cycle
- Max step height, roughness, slope x, slope y

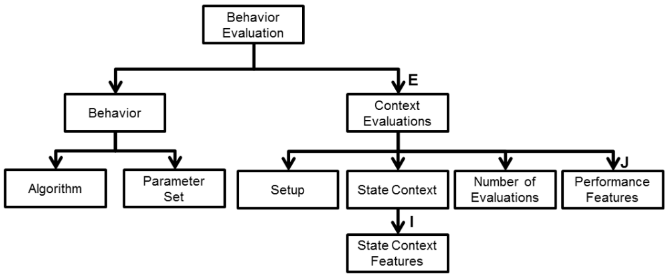






Behavior Library

= Knowledge base of robot



- Behavior experience update
  - Initiated when behavior was constant during evaluation period
  - State context and performance features are averaged and linked to a behavior

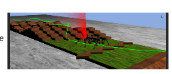
Generating Behavior Libraries

Methodology

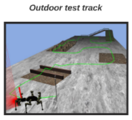
- Learning from demonstration by collecting experiences while operators control SpaceClimber through obstacle courses
- Evaluation of operator skills
  - Path following capability [0.5, 0.1] m
  - Energy efficiency [1.4, 0.14] Wh/m
  - Stability [0, 45]°

Test Tracks

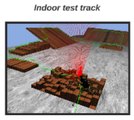
DRC mobility test track replicate for operator selection



Outdoor test track



Indoor test track

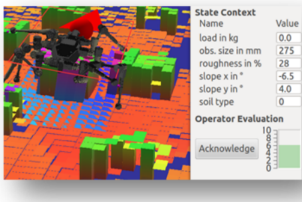


Resulting Behavior Libraries

library name	behaviors	contexts	total evaluations
in_op1	26	15	36
in_op2	26	31	39
in_op3	57	45	174
in_op4	21	14	27
in_op5	24	19	56
inLib	154	93	332
out_op1	41	18	81
out_op2	46	17	86
out_op3	49	24	93
out_op4	52	20	90
out_op5	41	21	63
outLib	229	77	413
fullLib	383	157	745

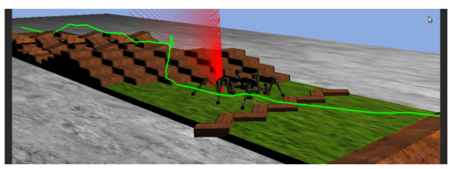
Methodology

- Learning from demonstration by collecting experiences while operators control SpaceClimber through obstacle courses
- Evaluation of operator skills
  - Path following capability [0.5, 0.1] m
  - Energy efficiency [1.4, 0.14] Wh/m
  - Stability [0, 45]°

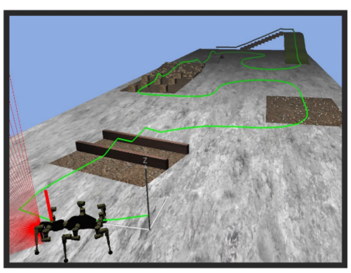


Test Tracks

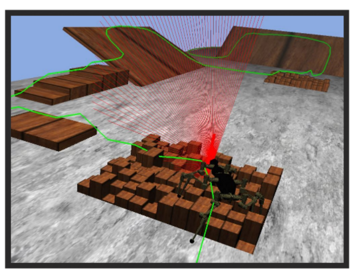
DRC mobility test track replicate for operator selection



Outdoor test track

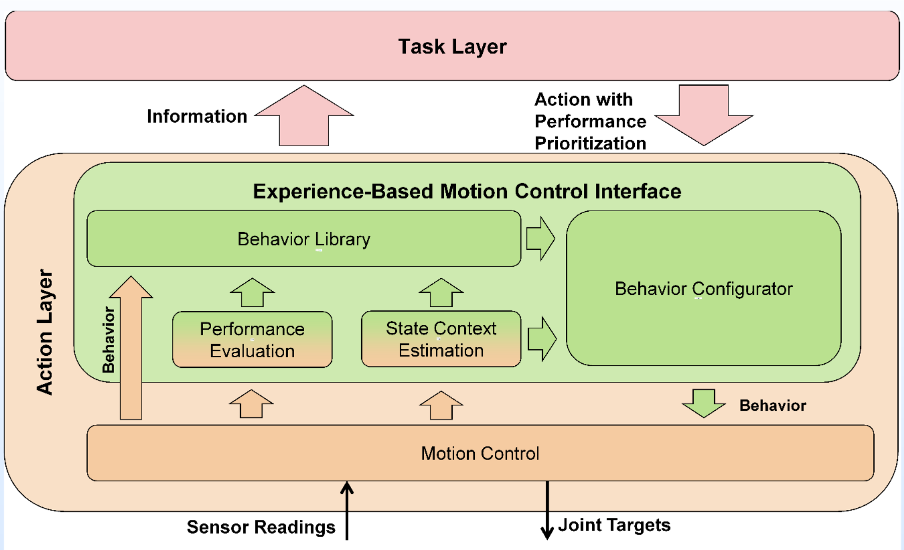


Indoor test track



Resulting Behavior Libraries

library name	behaviors	contexts	total evaluations
in_op1	26	15	36
in_op2	26	31	39
in_op3	57	45	174
in_op4	21	14	27
in_op5	24	19	56
inLib	154	93	332
out_op1	41	18	81
out_op2	46	17	86
out_op3	49	24	93
out_op4	52	20	90
out_op5	41	21	63
outLib	229	77	413
fullLib	383	157	745



Case-Based Selection

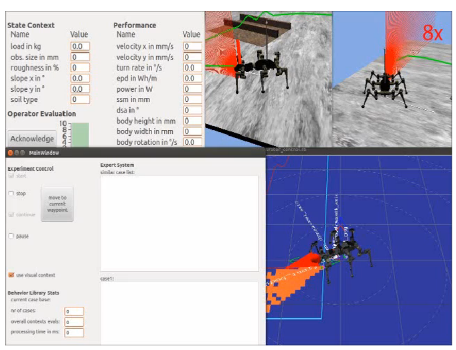
- Input query in form of two vectors
  - Current state context features
  - Current desired action described by action performance features
  - Meta performance features constant at optimum
- Additional weight vectors to manipulate feature importance

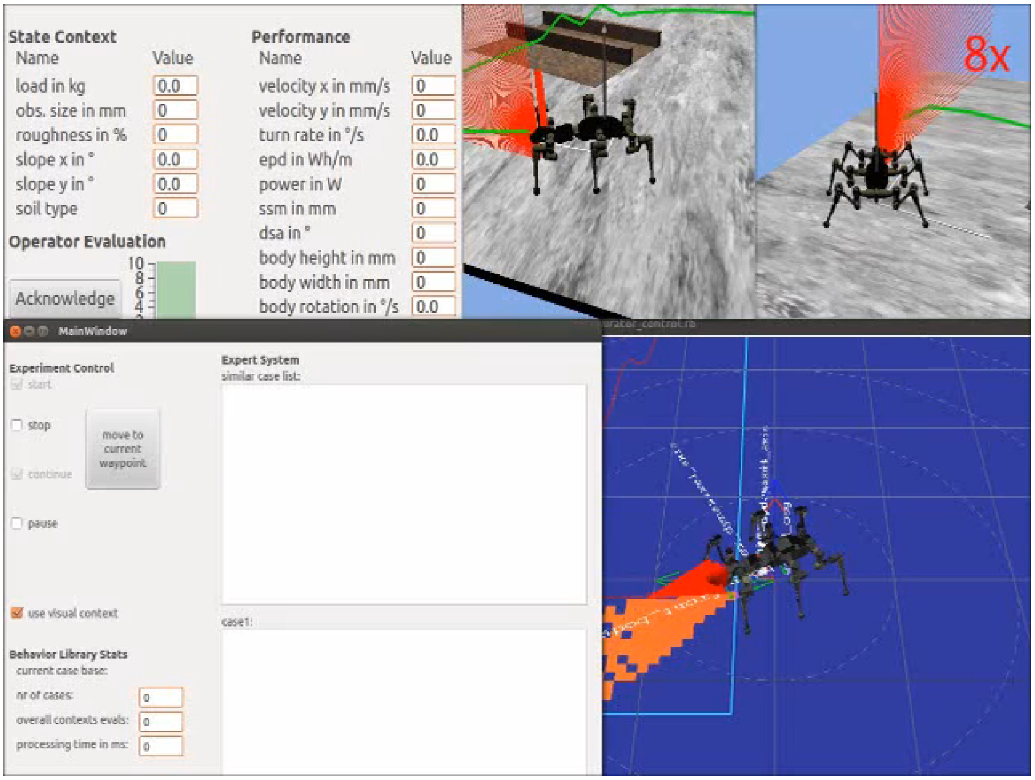
for each *behavior_eval* in *behavior_library* **do**
  for each *context_eval* in *behavior_eval* **do**
    $Sim_e^{State} = getStateContextSimilarity()$
  end for
  $Sim^{State} = getMaxStateSimilarity()$
  $e_{max} = getMostSimilarContextEvaluation()$
  $Sim^{Action} = getActionSimilarity()$
  $Sim = getBehaviorSimilarity()$
end for
$applyMostSimilarBehavior(blend\_time)$

Autonomous Control

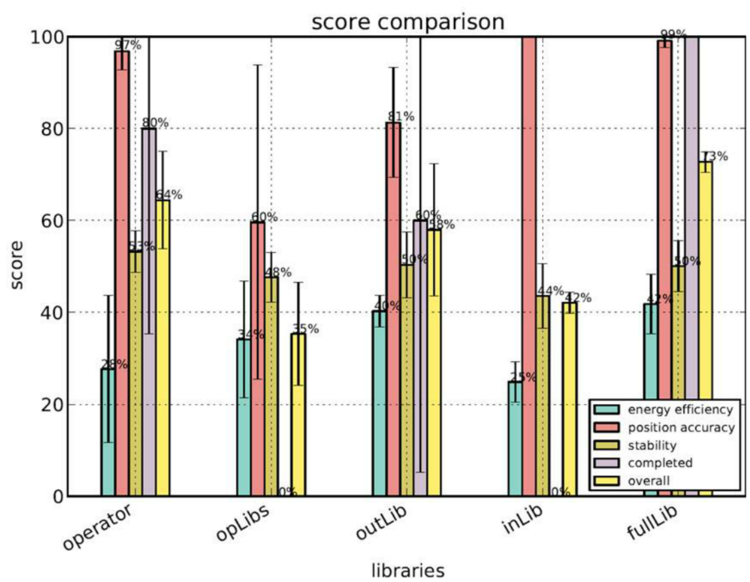
- Operator replaced by
  - Trajectory follower to generate motion commands
    - velocity x from 0 to 0.15 m/s
    - turn rate from -10°/s to 10°/s
    → *depending on orientation error*
  - Behavior configurator for autonomous behavior adaptation
    - 2 s blend time between behaviors

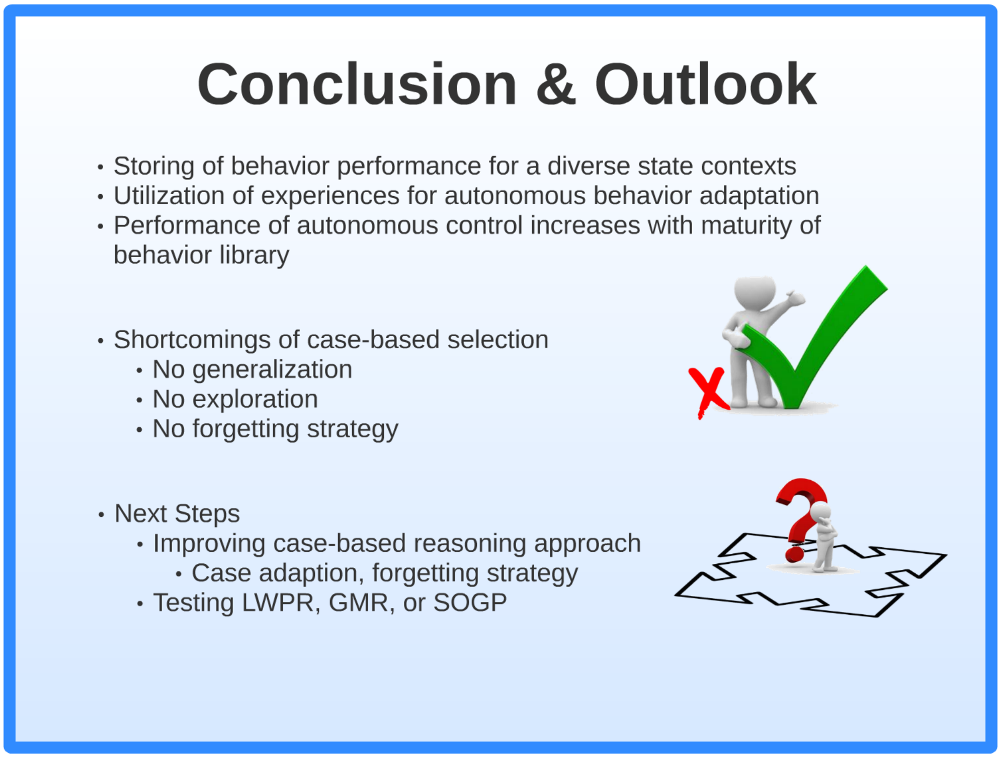
feature	weight
velocity x	0.8
velocity y	0.2
turn rate	1.0
body height	0.0
body width	0.0
ssm	0.0
dsa	0.1
power	0.0
epd	0.1
vibration	0.1

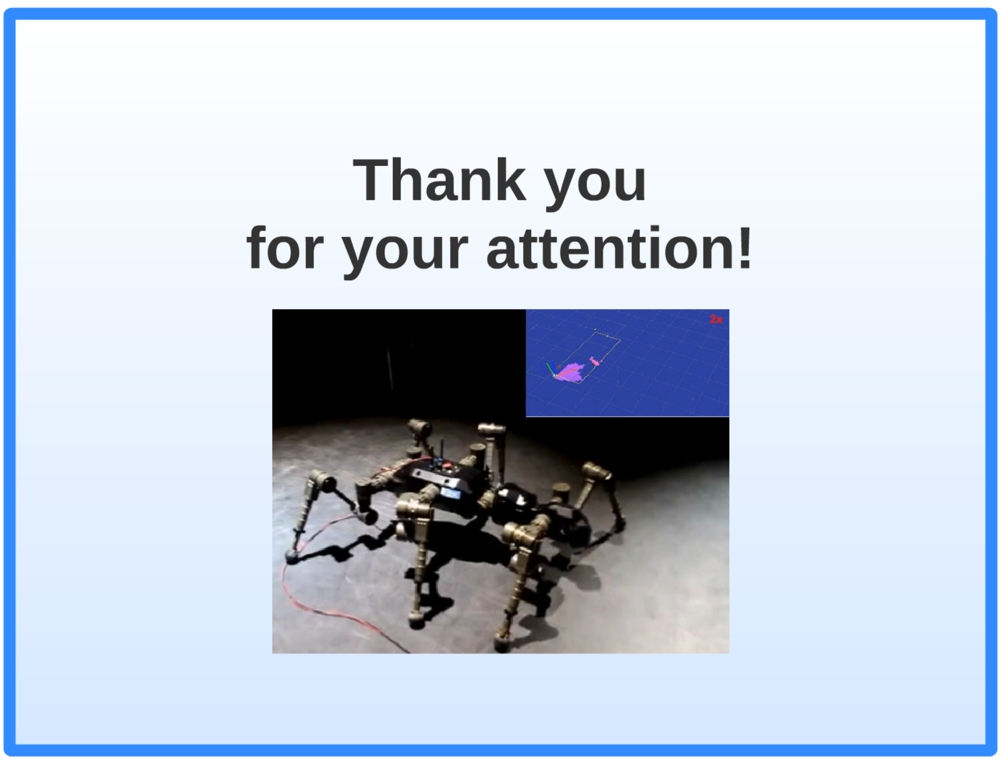


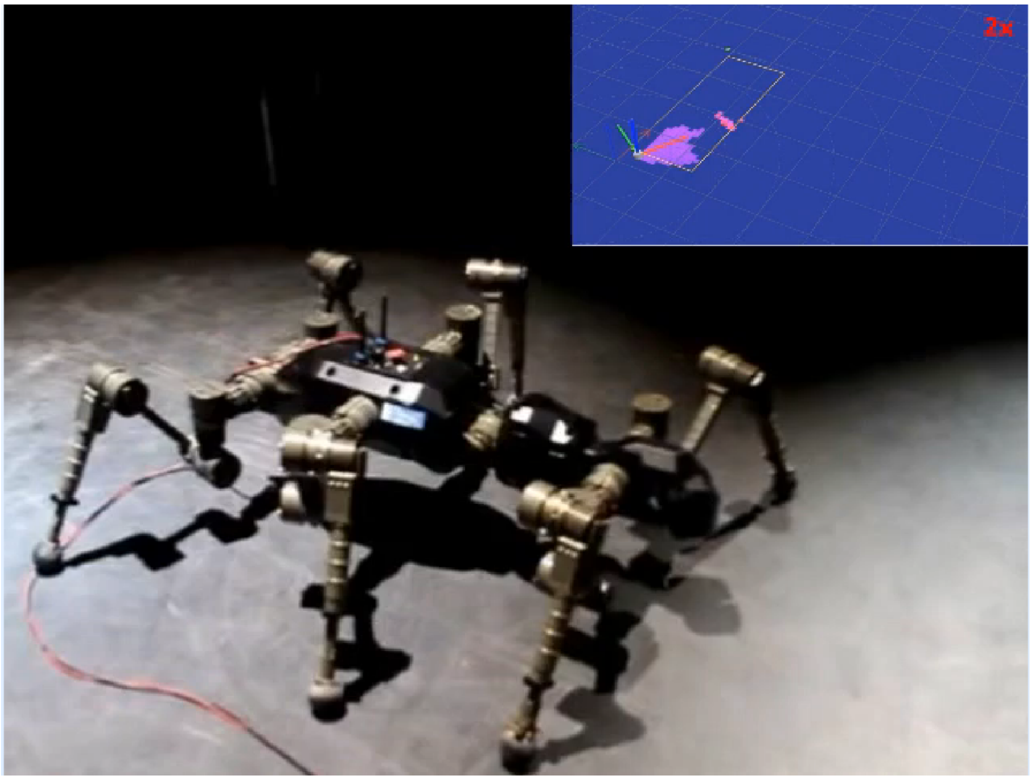


Results on Outdoor Obstacle Course




Conclusion & Outlook
Storing of behavior performance for a diverse state contexts
Utilization of experiences for autonomous behavior adaptation
Performance of autonomous control increases with maturity of behavior library
Shortcomings of case-based selection
No generalization
No exploration
No forgetting strategy
Next Steps
Improving case-based reasoning approach
Case adaption, forgetting strategy
Testing LWPR, GMR, or SOGP


Thank you
for your attention!


2x

3.3 ‘VaMEx - Vipe: Exploration in schwer zugaenglichem Terrain anhand visueller und propriozeptiver Daten im Valles Marineris’ (LM-T-03)

Daniel Kuehn [(1)]

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

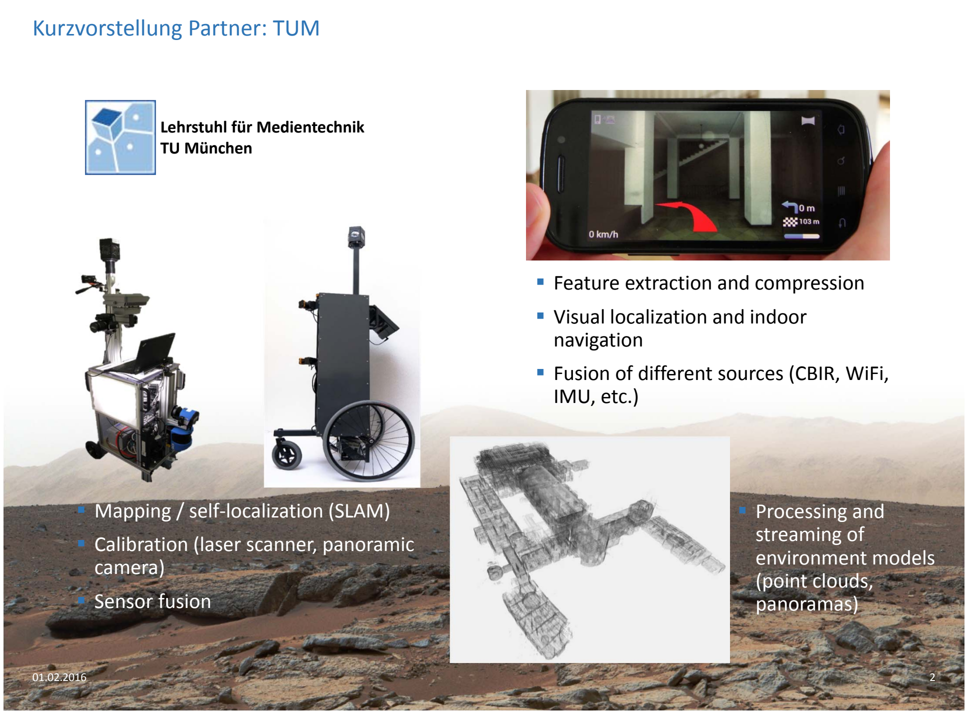
Contact: daniel.kuehn@dfki.de

Abstract

The presentation introduced the Vipe project, which is a part of the ”VaMEx - Valles Marineris Explorer” Initiative, started by the DLR Space Administration. The Initiatives aim to explore craters on Mars up to 7 km deep fully autonomous by a heterogeneous swarm of robots, including the hominid robot Charlie. The Valles Marineris, a jagged rift valley, places high demands on robotic exploration mission. This environment appears due to the earlier volcanic activity as well as the references to water resources extremely promising for a variety of scientific issues. To have a comprehensive picture of Valles Marineris and thus potential niches for extraterrestrial life, areas which are difficult to access have to be included in the exploration in particular.

Within the first VaMEx project, a swarm of heterogeneous robots (rovers and aerial robots) already allowed a significant application expansion of the exploration mission. Still, caves, steep slopes, and rugged rock formations continue to be a major challenge for the use of mobile robots. The aim of VIPE is to fill this gap within the newest swarm member Charlie, to increase the overall swarm locomotion and navigation abilities. Due to Charlies lightweight and highly integrated design, its agility, and integrated tactile sensors ideally suited to deal with difficult terrain. Furthermore, a novel visual positioning and mapping approach will be developed, featuring a 360° panoramic camera which allows a positioning with very low drift despite the above-mentioned, demanding conditions. This visual positioning is to be supplemented by a complementary proprioceptive approach based on tactile sensors to improve self-localization. This is a prerequisite for movement planning and reactive motion control to allow the robot to overcome obstacles autonomously.

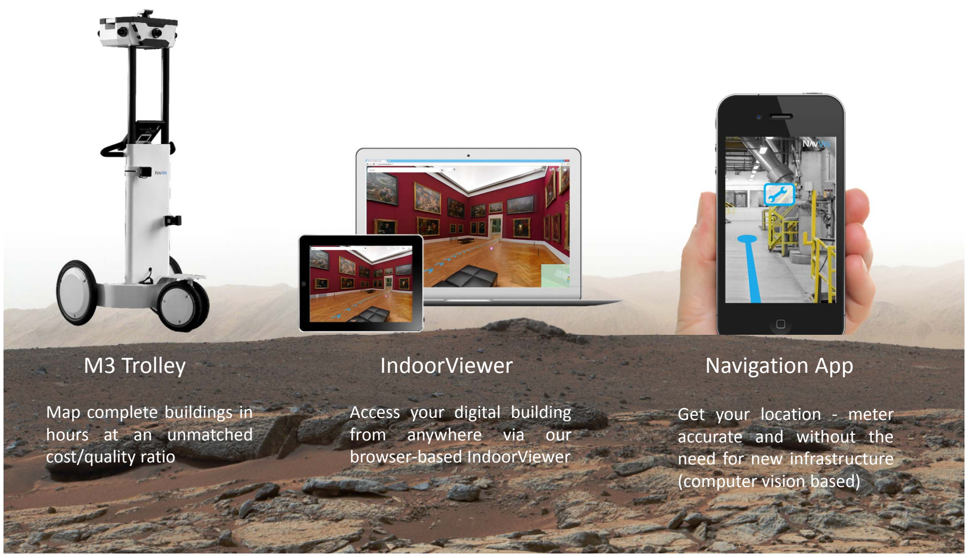

Gefördert durch:
Bundesministerium für Wirtschaft und Energie
aufgrund eines Beschlusses des Deutschen Bundestages
VaMEx-VIPE
Exploration in schwer zugänglichem Terrain anhand visueller und propriozeptiver Daten im Valles Marineris
Deutsches Zentrum für Luft- und Raumfahrt e.V. (DLR)
Raumfahrtmanagement | Navigation
Deutsches Forschungszentrum für Künstliche Intelligenz GmbH
Lehrstuhl für Medientechnik TU München
NAVVIS


Kurzvorstellung Partner: TUM
Lehrstuhl für Medientechnik TU München
Feature extraction and compression
Visual localization and indoor navigation
Fusion of different sources (CBIR, WiFi, IMU, etc.)
Mapping / self-localization (SLAM)
Calibration (laser scanner, panoramic camera)
Sensor fusion
Processing and streaming of environment models (point clouds, panoramas)
01.02.2016
2

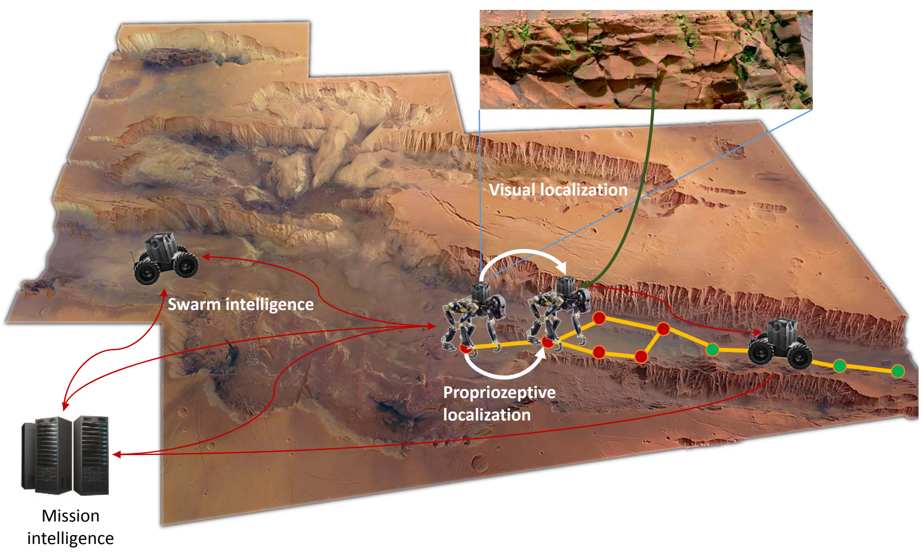
Kurzvorstellung Partner: Navvis GmbH

Located in Munich, Spin-off from TU Munich (2013)

NavVis



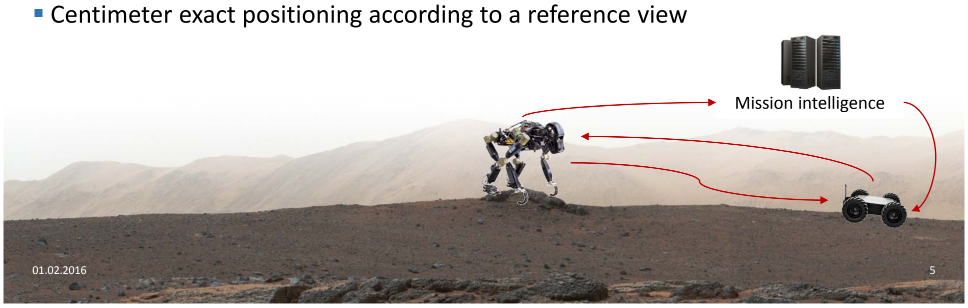
Motivation and Vision



01.02.2016 Bildnachweis: ESA/DLR/FU Berlin, CC BY-SA 3.0 IGO 4

Aims TUM and Navvis

- Development of two test platforms with 360° Camera, IMU and PC
- Analysis of existing features regarding their suitability for the scenario
- Visual redetection of places with respect to the circumstances of the Valles Marineris
- Exchange of visual information between the members and the Swarm mission intelligence
- Adaptation / continuous updating of a map with respect to certain changes
- Centimeter exact positioning according to a reference view



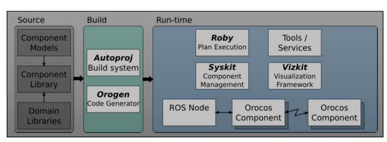
Aims DFKI

Hardware adaption Charlie v2

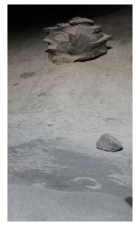
- Analysis of appropriate visual sensors
- Extension of the sensory concept
- Electronics: adaptation to newly added components
- Exchange / stiffening of various components
- Lightweight design still essential factor

Software adjustments Charlie v2

- Software adjustments due to the changes in the electro-mechanics
- Expansion: navigation or planning algorithms
- Embedded into the rock Framework

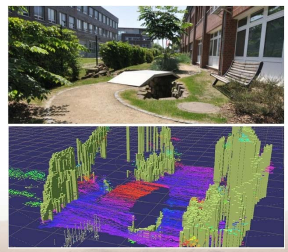


Aims DFKI



Motion Planning for overcoming known obstacles

- Feasibility analysis on overcoming obstacles
- Whole - Body - Control
- Contact Free overcoming vs. Inclusion of the obstacle
- Find and Plan of contact points

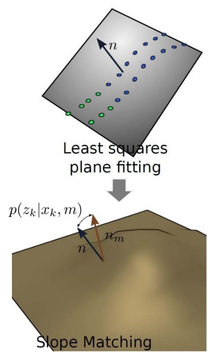


Reactive motion control to deal with inaccuracies in the environment model

- (Further) development of a reactive and fail-safe motion control
- Real-time capability
- Robust analysis of sensor information
- Interventions in cyclical motion by control loops or reflexes

01.02.2016 7

Aims DFKI



Positioning and navigation based on proprioceptive sensor data

- Soil information as an additional input to expand generated maps
- Secure Navigation, if no visual information is available
- eSLAM adaptation to Charlie
- Generalization of the existing approach

Exploration path planning for multiple exploration participants

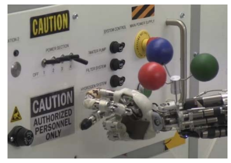
- Establishment of exploration strategies
- Path planning for exploration for multiple participants
- Adjustments of the exploration path planning from "Entern" to the capabilities of the robot Charlie
- Navigation to exploration target

01.02.2016 8

Aims DFKI

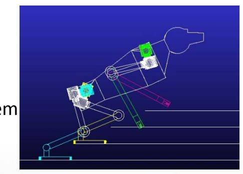
Motion planning to manipulate objects

- Development of basic manipulation strategies to improve locomotion capabilities
- Reactive methods while carrying out specific movements
- Development of methods for the simultaneous execution of multiple relevant sub-tasks on the robot
- The stability of the system is always taken into account



Overcoming obstacles typical in buildings

- Feasibility analysis
- The robot is placed in front of an obstacle
- Implementation of basic behavior to overcome an obstacle similar to staircases
- Conducting experiments to evaluate necessary adaptations of the locomotor system



01.02.2016 9

Thank you for your attention

01.02.2016 10

3.4 'Development of Legs for the Humanoid Robot ARMAR-IV' (LM-T-04)

Heiner Peters[(1)]

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

Contact: heiner.peters@dfki.de

Abstract

Humanoid robotics is an emerging research field including inspiring challenges regarding mechanical development and design. This talk gives an overview about the mechanical development of the humanoid robot ARMAR-IV at the Karlsruhe Institute of Technology. The mechanical setup was finished in 2012 with the main focus lying on the mechanical leg design. The design of an universal drive unit which is used for the actuation of each DOF in the legs, including absolute angular and torque measuring is described in detail. Moreover different approaches to increase the peak torque of hip-, knee- and ankle joints without the use of additional motor power are presented. The approaches in every single joint lead to a fully integrated leg design, fulfilling humanlike boundary conditions regarding construction space and weight as well as required torques and angular velocities.

Due to legal restrictions, the presentation is not included in this document

Development of Legs for the Humanoid Robot ARMAR-IV

(due to legal restrictions, the presentation is not included in this document)

Heiner Peters

3.5 'Introduction of SherpaTT – Adaptive Suspension and Locomotion Coordinate Systems' (LM-P-01)

Florian Cordes[(1)]

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

Contact: `florian.cordes@dfki.de`

Abstract

The poster presents the hybrid wheeled-leg rover SherpaTT, which is the successor of the rover Sherpa. The rover in its integration state as of September 2015 is presented and the main specifications of the system are provided. SherpaTT has in the current integration status a weight of approximately 115 kg and a square shaped foot print of roughly 1 m×1 m in its standard pose. Definitions of the three standard poses that maximize the motion range for adaptive processes are given. Furthermore, the main coordinate systems used for different tasks in the locomotion control are described.

Deutsches Forschungszentrum für Künstliche Intelligenz GmbH

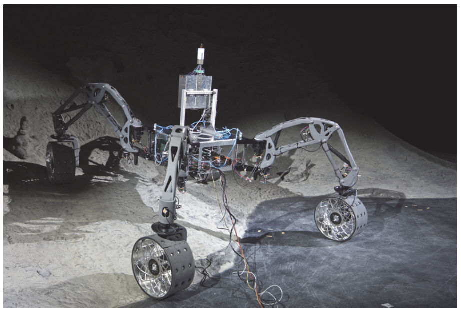
Introduction of SherpaTT

Adaptive Suspension and Locomotion Coordinate Systems

Florian Cordes

System Overview

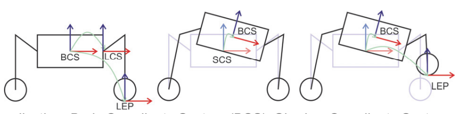
SherpaTT is a reconfigurable and versatile hybrid wheeled-leg robot. It features an active suspension system with four legs, each ending in a drivable and steerable wheel.
Three degrees of freedom (DoF) of each suspension unit are used for moving the leg end point (LEP) in the space around the robot.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



Photograph of integration study of SherpaTT without manipulator arm

SherpaTT Specification

- Weight: 115kg (without manipulator)
- Dimensions of footprint:
  - Min (stow position): 0.9m x 0.9m
  - Max: 2.2m x 2.2m
- Degrees of freedom:
  - Legs: 5 active DoF, planned is a 6th (passive) DoF by introducing flexible wheels for passive ground adaption
  - Arm: 6 active DoF
- On-board sensors:
  - Legs: Joint position (absolute and relative), speed, current consumption, supply voltage, and 4 x 6 degree of freedom force/torque sensor,
  - Body: Inertial Measurement Unit, battery voltage monitoring
  - Planned for navigation: Hokuyo UST-20LX + Basler Ace 25fps camera and a Velodyne rotating lidar.
- Power supply:
  - 44,4V / 10.0Ah (lithium polymer)
- Run-time:
  - approx: 150min
- Driving speed:
  - Currently limited to 0.16m/s
- Computational power:
  - Intel Core i7 Processor with 4x 2.2GHz (up to 3.20 GHz)



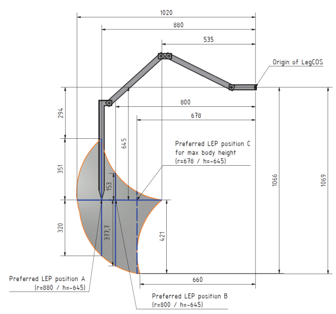
Visualization: Body Coordinate System (BCS), Shadow Coordinate System (SCS), Leg Coordinate System (LCS) and Leg End Point (LEP)

Movement Possibilities due to Active Suspension System

Using the active suspension it is possible to:

- Move single LEPs to conform to the terrain
- Coordinated movement of all LEPs to change the body's attitude
- Combine both possibilities to independently control the robot's attitude while driving in rough terrain

The Movement range of the LEPs 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 length. The volume of the movement range is spanned by rotating around the first joint of a leg (in total: 215°).



Range of motion of one leg in cut view (mock-up leg for dimensions is shown).

Locomotion Coordinate Systems (CS)

Different CS are needed for the realization of the full reconfiguration capabilities of the robot. The following CS are currently being used.

- Shadow Coordinate System (SCS)
  - Used for locomotion commands (i.e. forward, lateral and point turn)
  - Used for commanding the Body Posture
  - Transformation between SCS and BCS is the body posture
  - Coincides with BCS if BP = 0
    - BP defines: roll, pitch, yaw as well as x-lean, y-lean and body height
- Body Coordinate System (BCS)
  - Attached to the center of the robot body
  - Used for all internal kinematic calculations
- Shadow Leg Coordinate System (SLCS)
  - Used for manual foot print commands
  - Subset of SCS for convenience: Give LEP commands in cylindrical coordinates
- Leg Coordinate System (LCS)
  - Attached to body
  - Used in inverse kinematics

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

3.6 'An Experience-Based Interface for Abstracting the Motion Control of Kinematically Complex Robots' (LM-P-02)

Alexander Dettmann[(1)], Sebastian Bartsch[(2)], and Frank Kirchner[(1) (2)]

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

Contact: `alexander.dettmann@dfki.de`

Abstract

In order to provide higher mobility and to assist humans in building up infrastructure in future extraterrestrial space missions, kinematically complex robots are needed. One key challenge which needs to be addressed is to handle their complex motion control and to make use of their high potential. Utilizing the possibility to achieve various actions even in different ways by tuning manually numerous parameters of the motion control can be very demanding and even unmanageable when also taking communication delay into account.

Thus, the proposed experience-based interface is encapsulating the motion control of complex robots by autonomously mapping application-specific action parameters to robot-specific motion control parameters depending on the current context. Therefore, the robot is using experiences collected from previously executed behaviors. Apart from acquiring experiences during operation of the real robot, they can also be collected in simulation. The possibility to test in low gravity environments makes the latter a valuable tool for increasing the robot's knowledge base for space missions.

The experiments in this paper show that reconfiguring the motion control can be beneficial and that in simulation optimized behaviors can easily be integrated in the experience-based control interface to improve the performance of a robot. In addition, the transferability from simulation to the real system is shown.

Please note, that the corresponding paper is published in:
An experience-based interface for abstracting the motion control of kinematically complex robots; A. Dettmann, S. Bartsch, and F. Kirchner; In Proceedings of ASTRA 2015.

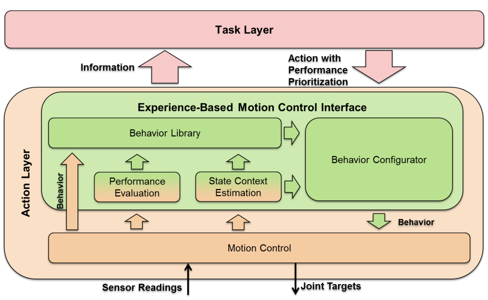
German Research Center for Artificial Intelligence

An Experience-Based Interface for Abstracting the Motion Control of Kinematically Complex Robots

Alexander Dettmann, Sebastian Bartsch, and Frank Kirchner

Introduction

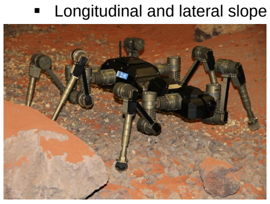
- Future space mission require higher mobility to reach locations of scientific or ecological interest
- Kinematically complex robots
  - Capable of realizing numerous tasks and adapting to varying contexts
  - Require sophisticated motion control which needs suitable parameterization to produce desired behavior
  - Same action can be realized by numerous behaviors with different behaviors
  - High control effort resulting in high operator load
- Autonomous mapping between scenario-specific action and robot-specific parameters needed which also incorporates current context



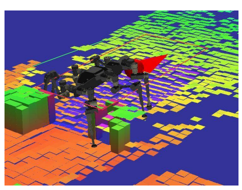
Experience-based motion control interface

Performance and State Context Features for Locomotion

- Performance features characterize robot's behavior
  - Action performance features characterize action execution
    - Longitudinal and lateral velocity
    - Turn Rate
  - Meta performance features characterize
    - Stability (static stability measure, dynamic stability angle)
    - Efficiency (power, energy per distance, body vibration)
- State context features characterize environment
  - Step Hazard
  - Roughness
  - Longitudinal and lateral slope



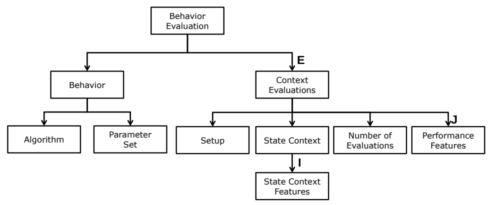
SpaceClimber in ESA's Mars Yard (ESTEC)



Generated map and region of interest for state context estimation

Behavior Library

- Behaviors (Algorithm + Parameterization)
- State Contexts
- Behavior Evaluations



Experiences stored in behavior evaluations

Behavior Configurator

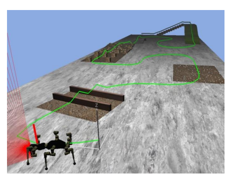
```
normalize(cur_state_context_features)
normalize(des_action_features)
for each behavior_eval in behavior_library do
   for each context_eval in behavior_eval do
      Sim_e^State = getStateContextSimilarity()
   end for
   Sim^State = getMaxStateSimilarity()
   e_max = getMostSimilarContextEvaluation()
   Sim^Action = getActionSimilarity()
   Sim = getBehaviorSimilarity()
end for
applyMostSimilarBehavior(blend_time)
```

$$Sim_e^{State} = 1 - \frac{\sum_{i=1}^{I}(s_i^{cur} - s_i^{ref,e})^2 \cdot w_i^S}{\sum_{i=1}^{I} w_i^S}$$

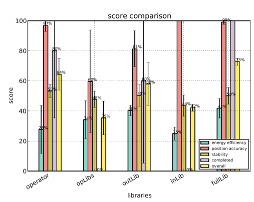
$$Sim^{State} = \max_{e \in E}(Sim_e^{State}) \quad e_{max} = \operatorname{argmax}_{e \in E}(Sim_e^{State})$$

$$Sim^{Action} = 1 - \frac{\sum_{j=1}^{J}(p_j^{cur} - p_j^{ref,e_{max}})^2 \cdot w_j^P}{\sum_{j=1}^{J} w_j^P}$$

$$Sim = Sim^{State} \cdot Sim^{Action}$$



Obstacle course to collect experiences



Score comparison between manual and autonomous control utilizing different behavior libraries

Conclusion

- Motion control abstracted
  - Action-specific instead of robot-specific interface
  - Performance prioritization possible
  - Autonomous configuration of control layer
- Constantly growing behavior library
  - Gaining confidence during operation
  - Incorporating system wearout
  - Storing and utilizing real and simulated experiences possible

Supported by:

DLR

The presented work was carried out in the project LIMES, a collaboration between the DFKI Robotics Innovation Center and the University of Bremen, funded by the German Space Agency (DLR, Grant numbers: 50RA1218, 50RA1219) with federal funds of the Federal Ministry of Economics and Technology (BMWi) in accordance with the parliamentary resolution of the German Parliament.

Universität Bremen

Contact:
DFKI Bremen & University of Bremen
Robotics Innovation Center

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

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 0

E-mail:
reports@dfki.de

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