SFB/TR 8 Spatial Cognition Final Colloquium: Poster Presentations

Thomas Barkowsky (Ed.)

SFB/TR 8 Report No. 039-09/2014
Report Series of the Transregional Collaborative Research Center SFB/TR 8 Spatial Cognition
Universität Bremen / Universität Freiburg

Contact Address:

Dr. Thomas Barkowsky
SFB/TR 8
Universität Bremen
P.O.Box 330 440
28334 Bremen, Germany

Tel +49-421-218-64233
Fax +49-421-218-64239
barkowsky@sfbtr8.uni-bremen.de
www.sfbtr8.uni-bremen.de

Table of Contents

R1-[ImageSpace]

Computational Modeling of Mental Spatial Knowledge Processing

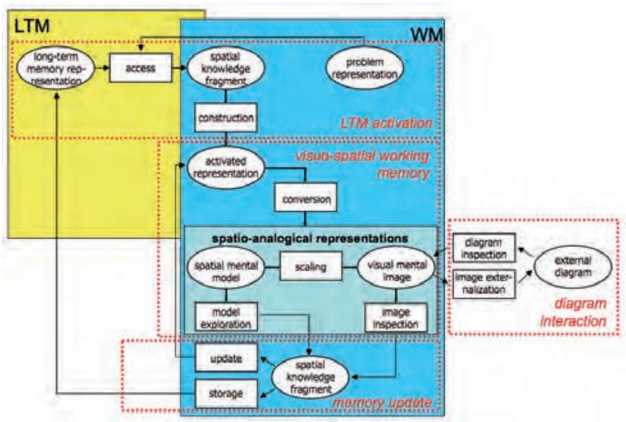
SPATIAL COGNITION
R1-[ImageSpace]

Thomas Barkowsky, Christian Freksa, Holger Schultheis,
Sandra Budde, Ana-Maria Olteteanu, Jan-Frederik Sima, Rasmus Wienemann

The Architecture

Core Assumptions

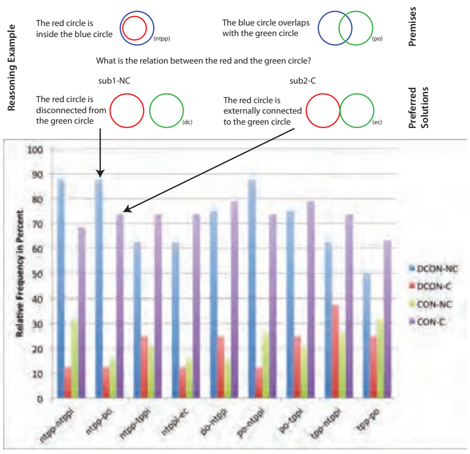
- Spatio-analogical representations
- Representations are scalable (knowledge type, type-specific rep., spatial-visual continuum)



Spatial Working Memory

Topological Reasoning

- Clear Preferences
- Large individual differences
- Variable Stability in preferences
- What gives rise to interindividual variation?



Mental Models vs. Images

- Subjects solved three-term series problems

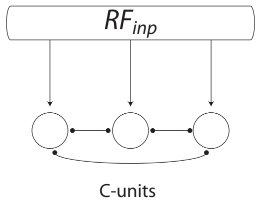
	Condition 1 (Mental Model)	Condition 2 (Mental Image)
Instructions	Only solve the task	„Imagine the letters as cities on a map“
Significant eye movements	1 out of 25 subjects	10 out of 23 subjects
Preferences	equidistance	Non-Eye: equidistance Eye: cardinal direction

Spatial Language

- Spatial terms (e.g., *above*) are used to specify the location of a target relative to a reference object
- Two crucial processes: *Reference frame selection* (RFS) and *computing goodness of fit* (GOF)

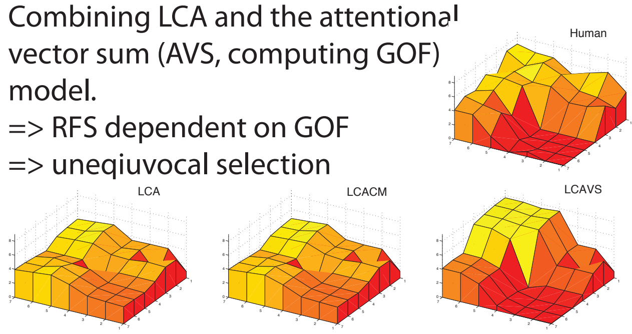
Reference Frame Selection

- 3 candidate models for RFS
- LCA provides the best account
  => importance of inhibition
  => selection on RF parameters



RFS <-> GOF

- Combining LCA and the attentional vector sum (AVS, computing GOF) model.
  => RFS dependent on GOF
  => uneqiuvocal selection



Function and GOF

- Talk by Thomas Kluth tomorrow

Affective States during Problem Solving

- New method for eliciting affective states
- Empirical study employing the method
- Two main results:
- 1) valence of feedback modulates affect only for good performers
- 2) no impact of motivation on affect

Strong Spatial Cognition

(see Talk and Publications)

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Computational Cognitive Modeling Methodology

SPATIAL COGNITION
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Holger Schultheis

Available Methodology

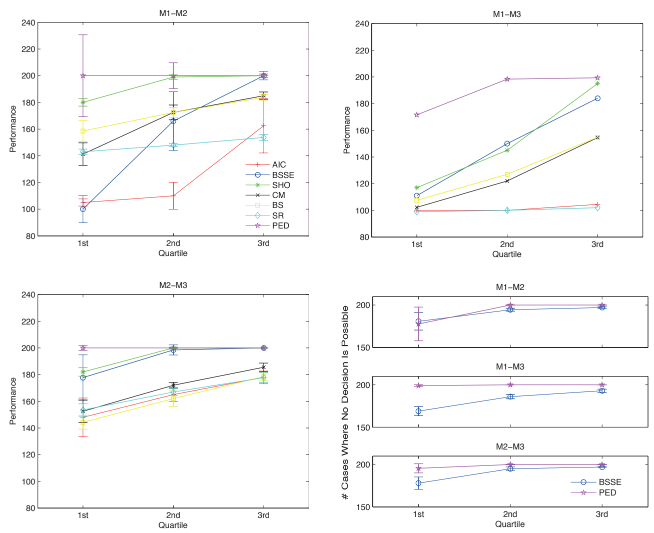
- Cognitive modeling can be methodologically challenging
- Surprisingly little guidance available on which methods to use in which situations
- Aim: Facilitate computational cognitive modeling by refining and extending existing methodology

Model Comparison and Selection

- Key criterion: How well models can account for human behavior
- Hard to measure due to overfitting
- Existing methods that avoid overfitting difficult: Properties unkown; no guidance on use

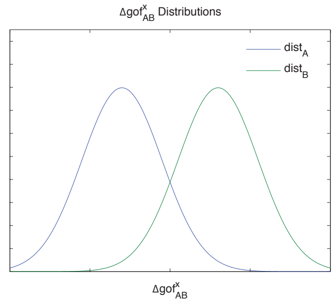
Comparing Comparison Methods

- 5 widely applicable candidate methods: SHO, BS, BSSE, PBCM, PED.
- Compared to each other and to two standard approaches (SR, AIC) on 3 pairs of memory models.



- PED has highest accuracy, but few decision. Can only be applied to pairs of models
- SHO accuracy close to PED, but none of its restrictions
- SHO technically simple -> easy to use -> facilitated use of sophisticated methodology

Cross-Fitting



Use two GOF difference distributions to judge which model provides the better explanation.

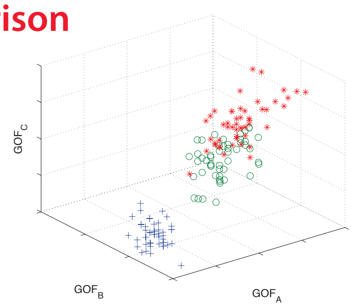
Two issue:

- Classification method?
- Multi-model comparison?

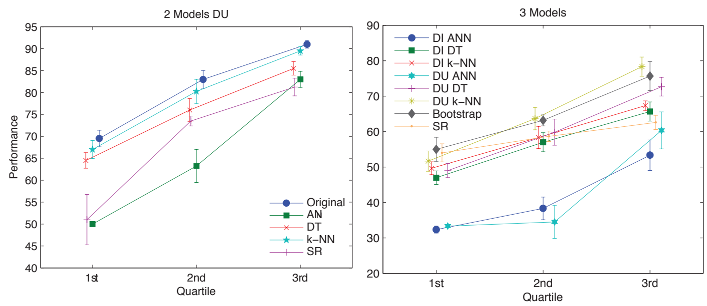
Classification

- Tested 8 easy-to-use classification methods: Binning, boundary search, k-NN, etc.
- 6 artificial distribution pairs + distributions arising from 7 pairs of actual cognitive models
- k-NN constitutes the best general method choice

Multi-Model Comparison



- Instead of GOF differences consider GOF vectors <GOF_1, GOF_2, ..., GOF_k> for k models
- k k-dimensional distributions
- Model recovery study corroborates validity of approach



Outlook

- How many times to run a stochastic model?
- More comprehensive evaluation of comparison methods
- Multi-model extension of comparison methods

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Mental Imagery: The Perceptual Instantiation Theory

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Jan Frederik Sima, Thomas Barkowsky

Phenomena of Mental Imagery

Mental Scanning

- time linearly correlated to distance
- time/distance relationship varies with circumstances

Mental Reinterpretation

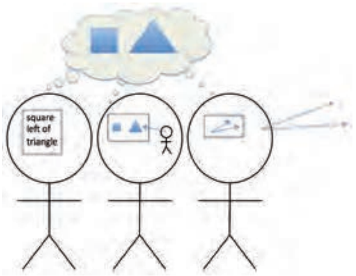
- easy and hard ambiguous stimuli
- reinterpretation aided by hints

Eye Movements

- correspond to processed information
- functional for information recall

Problem

- Imagery debate remains unsolved
- Contemporary theories lack formal description of core concepts
- Lack of formalization leads to lack of (mechanical) explanations and concrete predictions



Descripive theory (Pylyshyn), pictorial theory (Kosslyn), enactive theory (Thomas)

Solution

- Computational theory/model of mental imagery
- Implementing conceptions of grounded/embodied cognition (grounded symbols)
- Based on active and direct perception (building on enactive theory of Thomas, 1999)

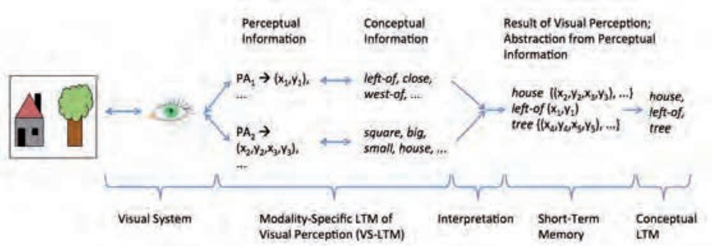
Result

- More concrete, in-depth explanations of phenomena
- Simpler and more parsimonious theory
- Explanations for phenomena not explained before

Visual Perception

(partly consistent with enactive theory)

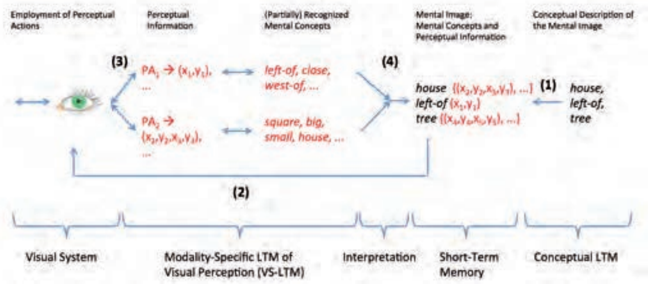
- **Active Perception**, is realized by perceptual actions
- **Object Recognition** is the successful application of respective perceptual actions
- Different perceptual actions employed top-down for hypothesis-testing to provide specific perceptual information
  - perceptual actions: e.g., saccades, covert attention shifts, adjusting lens, ...
  - perceptual information: e.g., coordinates in space, existance of edges, orientation of edges, distance, ...



- Perceptual information mapped onto mental concepts
  - mental concepts: e.g., spatial relations, shapes, objects, ...

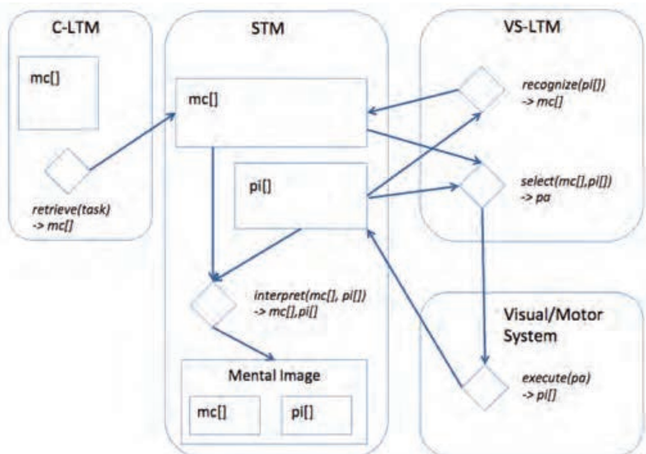
Visuo-Spatial Mental Imagery

- Memory of a scene stored as conceptual description, i.e., set of mental concepts
  - abstracted from perceptual information
- Mental concepts grounded in perceptual actions used for their recognition, e.g., left of <=> sets of saccades, covert attention shifts, hand movements, ...
- Mental concepts mapped onto one valid set of perceptual actions considering current context



Computational Model

- Perceptual actions (pa): attention shifts implemented as vectors
- Mental concepts (mc): spatial relations and shapes
- Perceptual information (pi): coordinates in space



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Human Use of Spatial information in Problem Solving

SPATIAL COGNITION
R1-[ImageSpace]

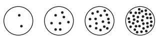
Rasmus Wienemann, Holger Schultheis

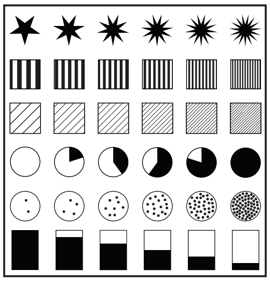
Problem

- What spatial information do humans represent when solving problems?

Analogies

- RQ: Do humans use implicit spatial information when solving Problems?
- Analogies from a spatial domain to an ordered but non-spatial domain.
- Three Term Series Problems: "B is west of P", "P is west of Y"
  Y : P : B :: ⁝ : ● : ?

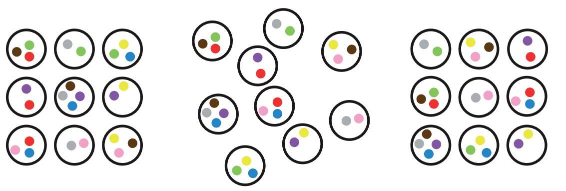




The Role of Spatial Structure in Problem Solving

- What is the Influence of the spatial representation of a problem have on human performance?

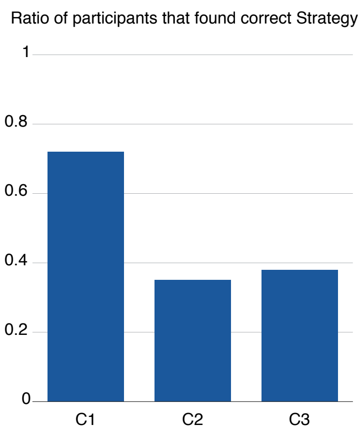
Tic-Tac-Toe Isomorph

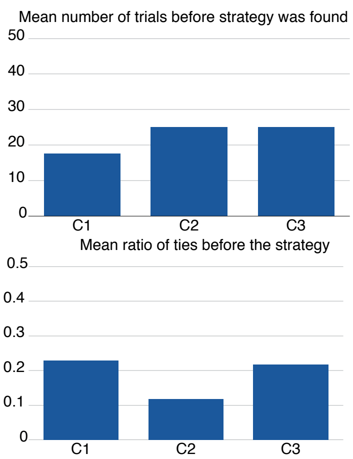


C1 Ordered   C2 Random   C3 Arranged Random

Results

- Ordered condition (C1) facilitates recognizing game's structure.

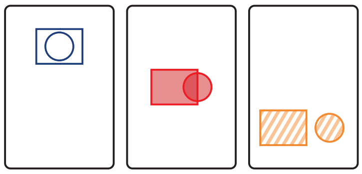




Future Work

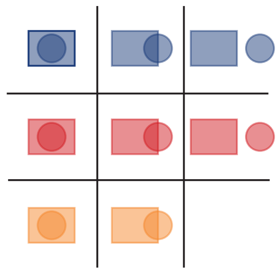
Prominence of Spatial Information

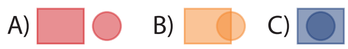
- RQ: What kind of information is used for classification of abstract stimuli?
- Free classification; spatial vs non-spatial classification
- Adapted Wisconsin Card Sorting Test



Ambiguous Progressive Matrices

- RQ: What information (spatial vs non-spatial) will be used in ambiguous problem solving?

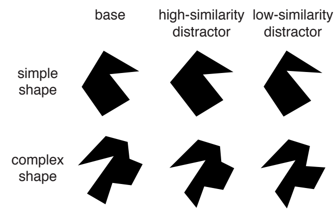


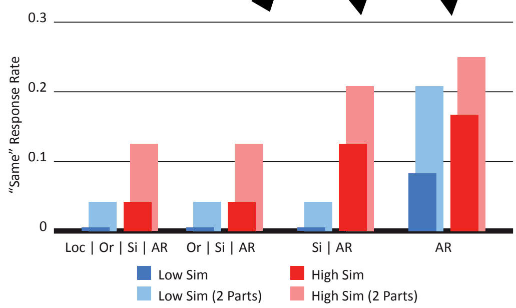


Spatial Abstraction during Mental Rotation

with Adrew Lovett, Northwestern University

- Development of a cognitive model investigating abstraction of spatial information during mental rotation





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Restructuring for Creative Problem-Solving

SPATIAL COGNITION

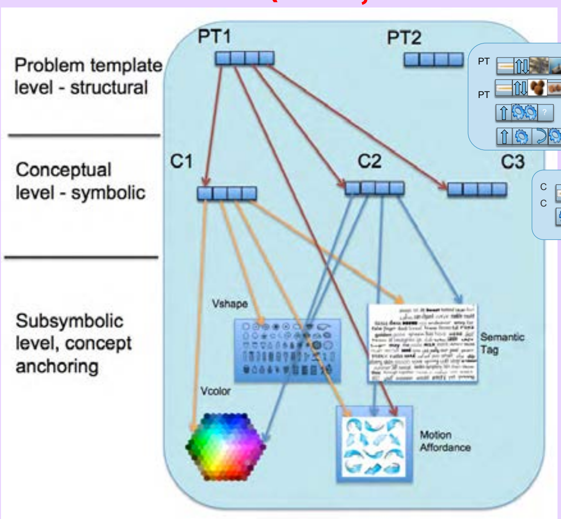
R1- [ImageSpace]

Ana-Maria Olteţeanu, Christian Freksa

Scope

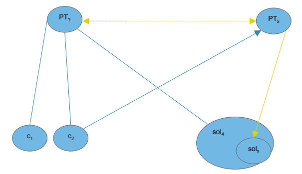
- Cognitively inspired creative problem-solving that integrates visuospatial ability and can be compared to human performance
- To enable the AI-human comparison and AI assistance with creative tasks
- To further elucidate the cognitive mechanisms for creative problem solving (and the role of the visuospatial apparatus)

The framework (Olteţeanu 2014)



- subsymbolic level provides grounding and enables search of objects with similar features as the ones given, on various dimensions
- structured representation provides re-representation and compositionality

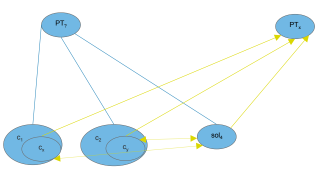
Example mechanisms



Given: $\{c_1, c_2, sol_4\}$

if $(\exists PT_x \supset c_1) \vee (\exists PT_x \supset c_2) | PT_x \cap sol_4 \neq \emptyset$

Try: $\{c_1, c_2, sol_4\} = PT_x$

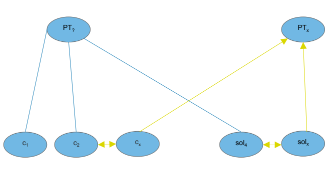


Given: $\{c_1, c_2, sol_4\}$

Decompose: $c_x = c_1 \cap sol_4$

Decompose: $c_y = c_2 \cap sol_4$

Reassemble problem template as: $\{c_x, c_y, sol_4\}$



Given: $\{c_1, c_2, sol_4\}$

if $\exists c_x \text{sim} c_1| \quad (a_x \subset c_x) \cap (sol_4 \vee \text{sim} sol_4) \neq \emptyset$

Try: $\{c_1, c_2, c_x, sol_4\}$ or $\{c_x, c_2, sol_4\}$

Compound Remote Associate Test Problem-solver

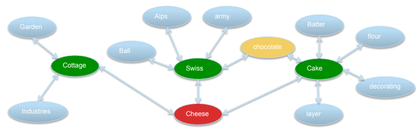
Remote Associate Test (Mednick 1971)

- 3-item problems

COTTAGE SWISS CAKE

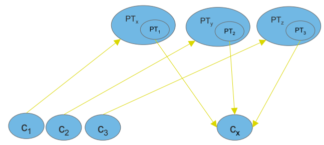
- Find a 4th item, common to all

CHEESE



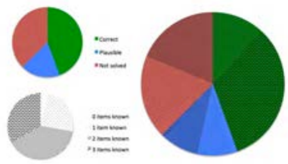
$$c_1 = falling, c_2 = Actor, c_3 = Dust$$
$$c_4 = ?, \text{so that}$$
$$\exists PT_1 = \{c_1, c_4\}, \exists PT_2 = \{c_2, c_4\}, \exists PT_3 = \{c_3, c_4\}$$

$$PT_1 = Falling\ Star, PT_2 = Star\ Actor, PT_3 = Star\ Dust$$
$$c_4 = Star$$



Accuracy

Answer /items known	0 items	1 item	2 items	3 items	Total
Correct	0	0	17	47	64
Plausible	2	11	12	1	26
Not solved	4	23	27	0	54
Total	6	34	56	48	
Accuracy			30.36%	97.92%	



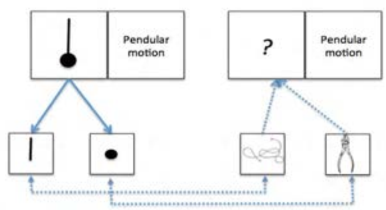
Plausible answers

RAT Query	Bowden Correct answer	New correct or plausible non-matching answer
French Car Shoe	HORN	COMPANY
Mill Tooth Dust	SAW	GOLD
Change Circuit Cake	SHORT	DESIGN
Cat Number Phone	CALL	HOUSE
Off Military First	BASE	PAY
Child Scan Wash	BRAIN	BODY
Home Sea Bed	SICK	WATER
Cry Front Ship	BATTLE	WAR

Object composition problems

Agent needs a certain object, but neither the object nor a direct replacement can be found in the environment

- Task: Compose object out of similar object parts
- Object part encoding and re-representation



Contact

amoodu@informatik.uni-bremen.de

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R3-[Q-Shape]

R3-[Q-Shape] Reasoning about Paths, Shapes, and Configurations

SPATIAL COGNITION
R3-[Q-Shape]

Phase I (2003-2006)

Foundations of QSR: Theoretical Background, Calculus Development, Reasoning Mechanisms

PIs : Christian Freksa, Reinhard Moratz
Researchers: F. Dylla, L. Frommberger, J.O. Wallgrün, D. Wolter

Cooperations
R4-[LogoSpace] I2-[MapSpace] I3-[SharC] I4-[SPIN]

Topics:
- Constraint-based inference engine (SparQ)
- Neighborhood-based reasoning
- Roadmap representations
- Hierarchical and structural representations of shape
- Spatial decomposition

Dissertations:
- D. Wolter (2004) : Spatial Representation and Reasoning for Robot Mapping – A Shape-Based Approach

Phase II (2007-2010)

Compact Task-Specific Representations and Reasoning Mechanisms for Cognitive Agents
Abstraction: Aspectualization, Coarsening, Conceptual Classification

PIs : Christian Freksa, Diedrich Wolter
Researchers: F. Dylla, L. Frommberger, J.O. Wallgrün

Cooperations
R4-[LogoSpace] I2-[MapSpace] R6-[ObjectSpace] I4-[SPIN] I1-[OntoSpace]

Topics:
- Conceptual neighborhood structures: automatic deduction, task adaptivity, complex configurations
- Maps: efficient place recognition, map-based communication, and map merging
- Autonomous learning by means of abstraction

Dissertations:
- J.O. Wallgrün (2008) : Hierarchical Route Graph Representations for Mobile Robots based on Generalized Voronoi Graphs
- F. Dylla (2008) : An Agent Control Perspective on Qualitative Spatial Reasoning
- L. Frommberger (2009) : Qualitative Spatial Abstraction for Reinforcement Learning

Phase III (2011-2014)

Reasoning for Intelligent Agents in Real-World Scenarios

PIs : Diedrich Wolter, Christian Freksa, Frank Dylla
Researchers: I. Colonius, L. Frommberger (Capacity Lab), J.H. Lee, A. Kreutzmann

Cooperations
R4-[LogoSpace] [DesignSpace] I2-[MapSpace] N1-[SocialSpace]

Topics:
- Realization, Real Algebraic Geometry for deciding consistency
- Behavior formalization (QLTL/CNL): representation, configuration-based planning, recognition, presentation

Dissertations:
- J.H. Lee (2013) : Qualitative Reasoning about Relative Directions: Computational Complexity and Practical Algorithm
- A. Kreutzmann (2014) : Qualitative Spatial and Temporal Reasoning based on And/Or Linear Programming (submitted)
- I. Colonius (2014) : Qualitative Process Analysis – A Case Study in the Naval Domain (in preparation)

SparQ: A Toolbox for Qualitative Spatial Reasoning in Applications (2003 - 2014)

- Reference implementations of calculi & methods
- Downloadable (v0.7.4, Linux/Mac)
- Applied worldwide
- Off-the-shelf integration (text based TCP/IP interface)
- Extendability / Calculus development

Reviewed Publications (Phase I / Phase II / Phase III):

Journals: (2 / 5 / ≥5); Conferences: (15 / 10 / ≥15); Book Contributions (2 / 6 / ≥3); Workshops & Symposia (8 / 8 / ≥13)

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Advancing Qualitative Spatial Reasoning Techniques

SPATIAL COGNITION
R3-[Q-Shape]

Dynamic QSR

From static to dynamic scenarios

Recognition

Presentation

QSR + Actions

High-level agent control based on Qualitative Spatial Reasoning

Reasoning about actions

I1-[OntoSpace]

Real Algebraic Geometry

New algorithms for consistency checking based on multivariate polynoms

H. Hong

QSR + DL

Not „fruitfull“ but productive discussions with T. Schneider and C. Lutz

I1-[OntoSpace] R. Möller

Model Checking

Sequences of CSPs

Conceptual Neighborhood

Recognition ✓

Combining Various Calculi

Actions need more than one spatial aspect

Combinations of calculi are basically a new calculus

R4-[LogoSpace]

Realization (Quantification)

Generate instances

RAG generates realizations

Double Exp. complexity

[DesignSpace]

Relative Directions

Real Algebraic Geometry can decide consistency

< 5 enitities

ER-complete (NP < ER)

Topological Mode Spaces

extends Conceptual Neighborhood

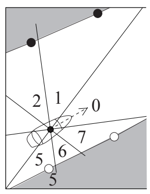
by A. Galton

Configuration-Based Control

Action + QSR worsen the qualification problem

Configurations can be transfered

Probabilistic planning

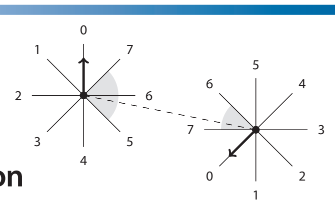


StarVars (Approximates Relative Directions)

Discretize global orientations

NP-complete

Calculates a realization



Linear Temporal Logic

Snapshot or qualitative change based

Scales to large number of states

And/Or Linear Programming

Combine calculi ✓

Realization ✓

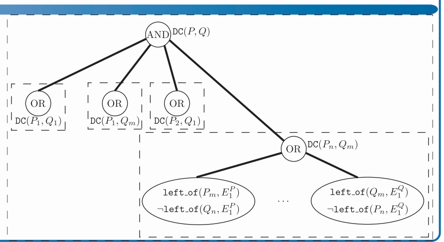
Partially grounded ✓

NP-complete ✓

Full QSR ✗

Unknown shapes ✗

Arbitrary orientations ✗



QLTL and CNL

Recognition ✓

Planning ✓

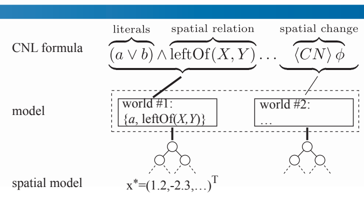
Rule analysis ✓

Supervision ✓

Visualization ✓

Knowledge Representation ✓

$$\phi^{1a}_{start} := \text{OVERLAP}(r, \text{social}(h)) \wedge \text{HEAD\_ON}(r, h)$$
$$\phi^{1a}_{effect} := \neg\text{PO}(r, \text{personal}(h)) \wedge \diamond(\text{ON\_LEFT}(h, r)\ R\ \text{BEHIND}(h, r))$$
$$\phi^{1a}_{end} := \text{BEHIND}(h, r)$$



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Applying Qualitative Spatial Reasoning Techniques

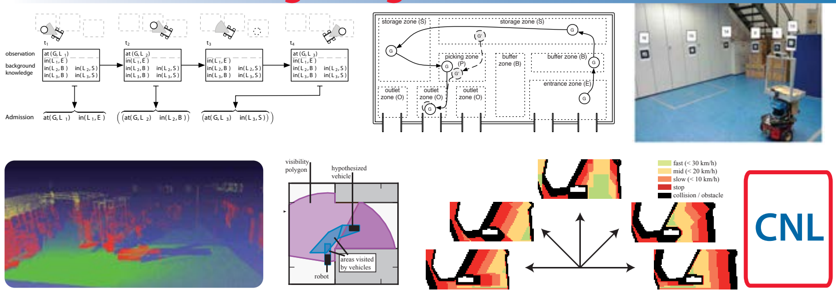
SPATIAL COGNITION
R3-[Q-Shape]

Diedrich Wolter, Christian Freksa, Frank Dylla
Immo Colonious, Jae Hee Lee, Lutz Frommberger, Arne Kreutzmann

Cooperations: [DesignSpace] · M. Eppe · BIBA · A7-[FreePerspective] · CoFriend

Recognition · Planning · Rule Analysis · Supervision · Externalization (Visualization) · Knowledge Representation

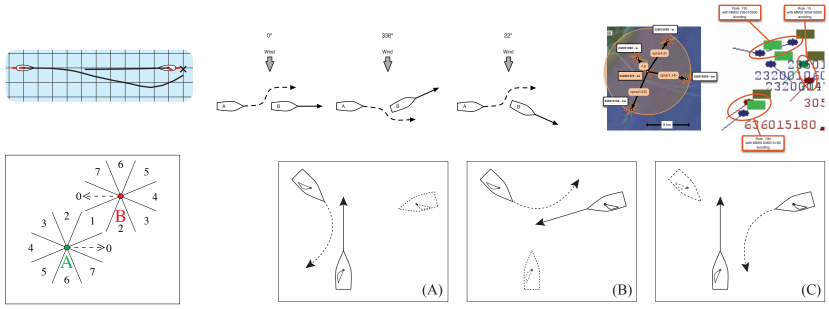
Industrial Settings (Logistics)



Processes

Traffic Rules

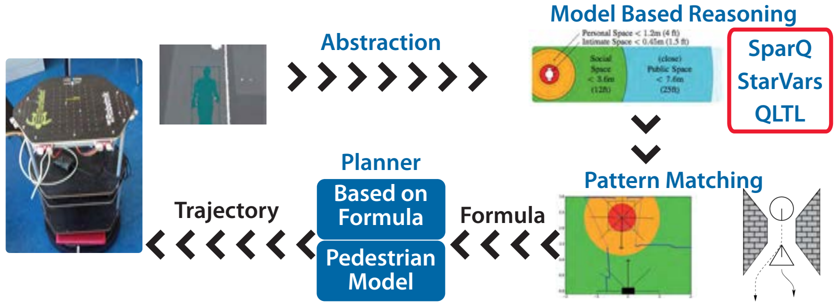
Sea Navigation



Traffic Rule Compliance

Rule Conflicts

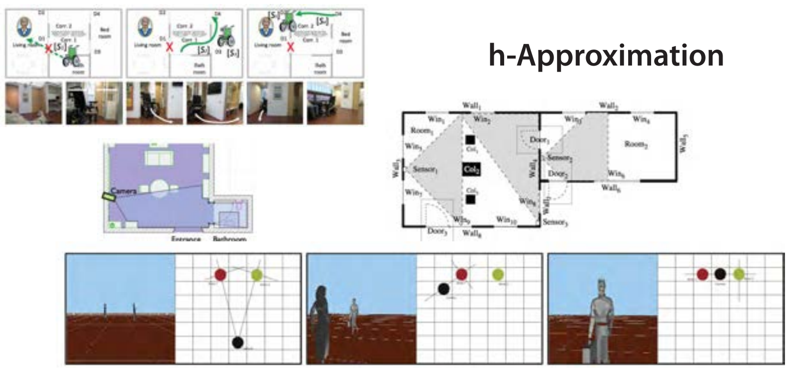
Social Robotics



Rule Representation

Robot

Design / Architecture / Ambient Assisted Living



Failure Diagnosis

Design Requirements

Narratives

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R4-[LogoSpace]

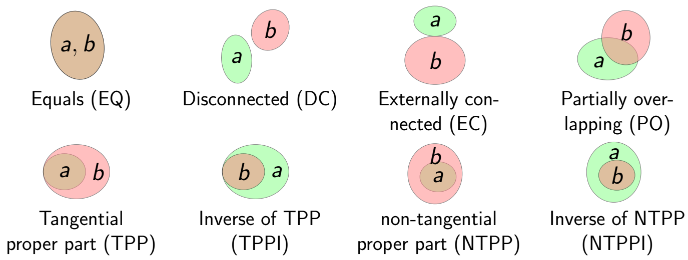
Project Overview

R4-[LogoSpace]

Bernhard Nebel, Till Mossakowski, Stefan Wölfl

Motivation

- In natural language qualitative spatial and/or temporal concepts are ubiquitous
- Qualitative representation: description of spatial or temporal configurations on a purely qualitative level, abstracts from numerical data
- Qualitative reasoning: reasoning methods tailored for the qualitative representation language
- Application domains: human-machine interaction, GIS (integrity rules, query answering), navigation systems (route descriptions), location-based services, etc.



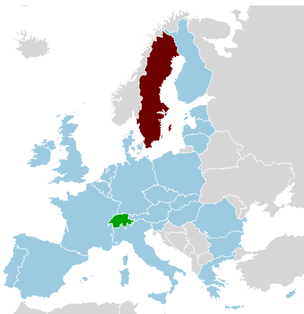
The RCC8 base relations

Qualitative Representation & Reasoning

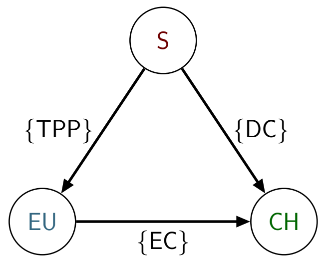
Define formalism for abstraction:
use set of relations as vocabulary, e.g., "is north of", "is south of", "is part of", "is left of", etc.

Reasoning about satisfiability:

- rule sets
- constraint satisfaction techniques
- usable in established reasoning paradigms, e.g., Datalog, ASP, SAT, CP, SMT, etc.

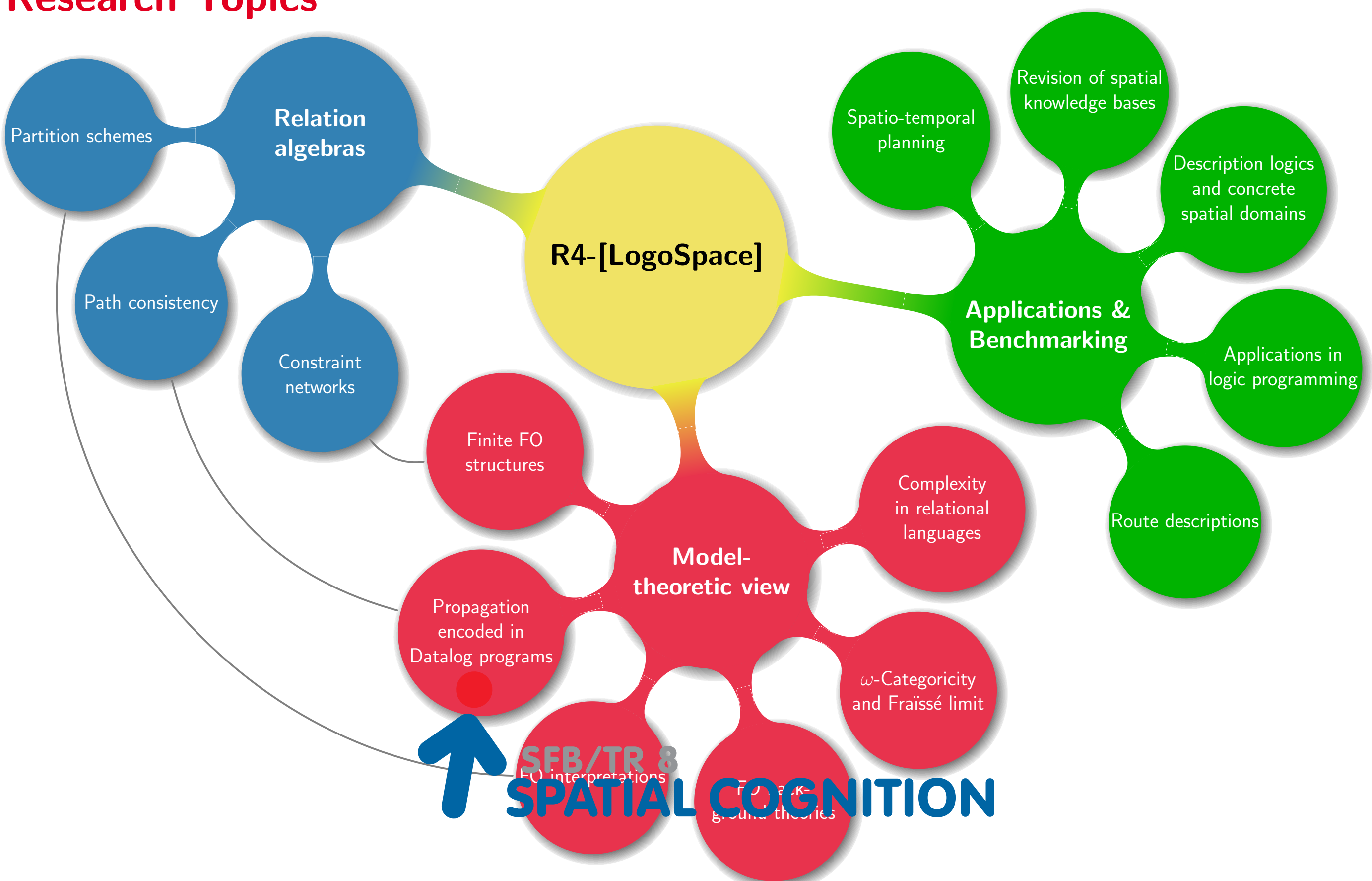


Spatial configuration



Qualitative description represented as constraint network

Research Topics



Project Highlights

SPATIAL COGNITION

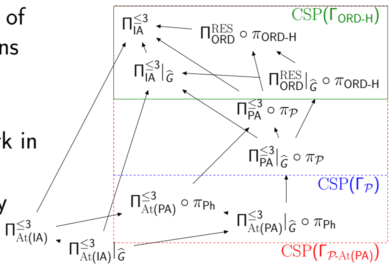
R4-[LogoSpace]

Bernhard Nebel, Till Mossakowski, Stefan Wölfl

Applying Qualitative Reasoning in Logic Programming

Inference encoded by Datalog programs. Usable in ASP, SAT, etc.

- Automatic minimization of qualitative representations and rules
- Study and comparison
- Superior to previous work in SAT, ASP
- Novel RCC8 Horn theory
- FOL based

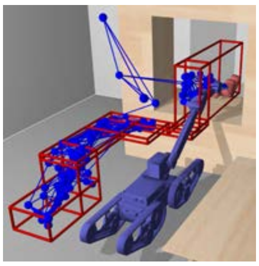


Publications

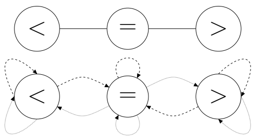
- Manuel Bodirsky and Stefan Wölfl. *RCC8 is Polynomial on Networks of Bounded Treewidth.* IJCAI 2011.
- Julien Hué, Matthias Westphal and Stefan Wölfl. *An Automatic Decomposition Method for Qualitative Spatial and Temporal Reasoning.* ICTAI 2012.
- Matthias Westphal, Julien Hué and Stefan Wölfl. *On the Propagation Strength of SAT Encodings for Qualitative Temporal Reasoning.* ICTAI 2013.
- Matthias Westphal and Julien Hué. *A Concise Horn Theory for RCC8.* ECAI 2014.
- Matthias Westphal, Julien Hué and Stefan Wölfl. *On the Scope of Qualitative Constraint Calculi.* KI 2014.

Qualitative Planning

Reduce search space by qualitative spatio-temporal abstraction.



- New spatio-temporal relational languages and sequential CSPs
- Non-trivial problems are NP-complete



Publications

- Matthias Westphal, Christian Dornhege, Stefan Wölfl, Marc Gissler and Bernhard Nebel. *Guiding the Generation of Manipulation Plans by Qualitative Spatial Reasoning.* Spatial Cognition & Computation: An Interdisciplinary Journal 2011.
- Matthias Westphal, Julien Hué, Stefan Wölfl and Bernhard Nebel. *Transition Constraints: A Study on the Computational Complexity of Qualitative Change.* IJCAI 2013.

Qualitative Route Descriptions

Generate, evaluate, and optimize route descriptions based on distinct, non-deterministic agent models.

- Problems become NP-hard if agents detect cycles
- Certain evaluation tasks are coNP-hard
- MDP-like extensions for modeling probabilistic agents

⟨*left*, *left*, *right*⟩

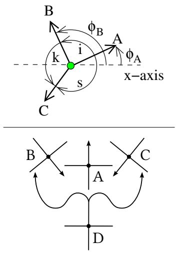
Publications

- Jochen Renz and Stefan Wölfl. *A Qualitative Representation of Route Networks.* ECAI 2010.
- Matthias Westphal, Stefan Wölfl, Bernhard Nebel and Jochen Renz. *On Qualitative Route Descriptions: Representation and Computational Complexity.* IJCAI 2011.
- Matthias Westphal and Jochen Renz. *Evaluating and Minimizing Ambiguities in Qualitative Route Instructions.* ACM-GIS 2011.
- Matthias Westphal, Stefan Wölfl, Bernhard Nebel and Jochen Renz. *On Qualitative Route Descriptions: Representation, Agent Models, and Computational Complexity.* To appear in "Special Issue of the Journal of Philosophical Logic on KR&R".

Relative Directions

Develop and compare reasoning approaches based on a-closure, linear programming, SMT, combinatorial geometry, oriented matroid theory.

- Combinatorial geometrical methods allow to derive composition tables for the Dipole Calculi
- SMT-based reasoning about sectors around oriented points improves on composition tables
- Benchmarks of efficiency and effectiveness of different approaches to this $\exists\mathbb{R}$ hard problem
- Explore interdependency functions between relative directions and mereotopology



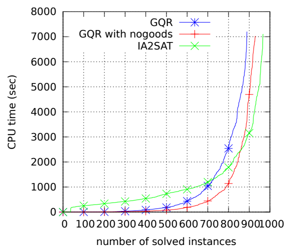
Publications

- Reinhard Moratz, Dominik Lücke, Till Mossakowski. *A Condensed Semantics for Qualitative Spatial Reasoning About Oriented Straight Line Segments.* AIJ, 2011.
- Till Mossakowski, Reinhard Moratz. *Qualitative Reasoning about Relative Direction of Oriented Points.* AIJ 2012.
- André van Delden and Till Mossakowsi. *Mastering Left and Right – Different Approaches to a Problem That is Not Straight Forward.* KI 2013.
- André van Delden. *Quality in Quantity – Relative Direction Constraints using Sector Sets around Oriented Points.* ECAI 2014.
- André van Delden and Reinhard Moratz. *Crossing the Boundary — Two Benchmarks for Qualitative Spatial Reasoning bridging Relative Directions and Mereotopology.* SC 2014.

Applications and Benchmarking

GQR — the state-of-the-art implementation of path consistency.

- Improvements based on nogood techniques from CP
- Used for spatio-temporal planning with qualitative representations
- Used to implement belief revision of qualitative representations
- Theoretical study of revision operations in the context of qualitative reasoning



Publications

- Matthias Westphal, Stefan Wölfl and Jason Jingshi Li. *Restarts and Nogood Recording in Qualitative Constraint-based Reasoning.* ECAI 2010.
- Anthony G. Cohn, Jochen Renz and Stefan Wölfl (eds.). Proceedings of IJCAI-2011 Workshop on Benchmarks and Applications of Spatial Reasoning.
- Mehul Bhatt, Hans Guesgen, Stefan Wölfl and Shyamanta Hazarika. *Qualitative Spatial and Temporal Reasoning: Emerging Applications, Trends, and Directions.* Spatial Cognition & Computation: An Interdisciplinary Journal 2011.
- Julien Hué and Matthias Westphal. *Revising Qualitative Constraint Networks: Definition and Implementation.* ICTAI 2012.
- Matthias Westphal and Julien Hué. *Nogoods in Qualitative Constraint-based Reasoning.* KI 2012.
- Frank Dylla, Till Mossakowski, Thomas Schneider, Diedrich Wolter. *Algebraic Properties of Qualitative Spatio-Temporal Calculi.* COSIT 2013.

Future Work

Planned activities in the near future.

- Relative directions: Explore adaptive grid methods combining Genetic Programming, Ant Colony Optimization and Q-Trees
- Integrating qualitative constraint languages and Possibilistic Logic into ASP
- Description Logic and qualitative constraint languages

Publications

- Julien Hué, Matthias Westphal and Stefan Wölfl. *Towards a new Semantics for Possibilistic Answer Sets.* KI 2014.

Presented at
IJCAI'11

RCC8 is Polynomial on Networks of Bounded Treewidth

Manuel Bodirsky[1] and Stefan Wölfl[2]

[1] LIX, CNRS UMR 6171, France [2] University of Freiburg, Germany

SPATIAL COGNITION
R4-[LogoSpace]

Motivation

- RCC8: a popular constraint formalism in Qualitative Spatial Reasoning
- . . . good for representation of topological information between extended spatial objects (regions)
- The general network consistency problem (*"decide whether an RCC8 constraint network is satisfiable"*) is NP-complete,
- . . . but tractable for several classes of (disjunctive) constraint relations (tractable subclasses)
- Is the network consistency problem also tractable when networks have a particular structure (e.g., bounded treewidth)?

Main idea:

Apply model-theoretic methods/results

- Show that all solutions of any RCC8 constraint network can be embedded into a single ω-categorical RCC8 model
- The CSP of this model is known to be tractable for constraint networks of bounded treewidth

Outline of the Proof

Lemma
The class of finite RCC8 models has the amalgamation property.

Theorem
A countable class $\mathcal{C}$ of finite relational structures with amalgamation property is the age of a countable homogeneous (and hence ω-categorical) structure (Fraïssé limit).

Corollary
RCC8 has a representation by a countably infinite, ω-categorical structure $\mathfrak{R}$.

Theorem (B./Dalmau, 2008)
The CSP of an ω-categorical structure is tractable when restricted to networks with constraint graphs of bounded treewidth.

Theorem
The network consistency problem for RCC8 restricted to networks of bounded treewidth can be solved in polynomial time.

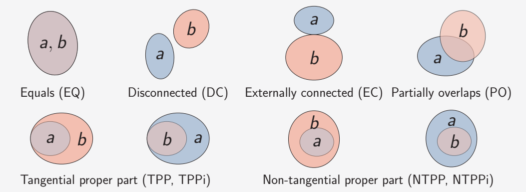
Outlook

- So far no empiric evaluation:
  What are the benefits for reasoning (cp. Li, et al, 2009)?

Selected References:

- M. Bodirsky and V. Dalmau. Datalog and constraint satisfaction with infinite temp[illegible] In: *STACS'06*, 2006; full version: *arXiv*, 2008.
- J.J. Li, T. Kowalski, J. Renz, and S. Li. Combining binary constraint networks i[illegible]tive reasoning. In: *ECAI*, 2008.
- J.J. Li, J. Huang, and J. Renz. A divide-and-conquer approach for solving interva[illegible]gebra networks. In: *IJCAI*, 2009.
- C. Lutz and M. Miličić. A tableau algorithm for DLs with concrete domains and GCIs. In: Journal of Automated Reasoning 38, 2007.
- D.A. Randell, A.G. Cohn, and Z. Cui. Computing transivity tables: A challenge for automated theorem provers. In: *CADE*, 1992.

RCC8 relations



RCC8 composition table

$\circ^{RCC8}$	DC	EC	PO	TPP	NTPP
DC	1	DC, EC, PO, TPP, NTPP	DC, EC, PO, TPP, NTPP	DC, EC, PO, TPP, NTPP	DC, EC, PO, TPP, NTPP
EC	DC, EC, PO, TPPi, NTPPi	DC, EC, PO, TPP, TPPi, EQ	DC, EC, PO, TPP, NTPP	EC, PO, TPP, NTPP	PO, TPP, NTPP
PO	DC, EC, PO, TPPi, NTPPi	DC, EC, PO, TPPi, NTPPi	1	PO, TPP, NTPP	PO, TPP, NTPP
TPP	DC	DC, EC	DC, EC, PO, TPP, NTPP	TPP, NTPP	NTPP
NTPP	DC	DC	DC, EC, PO, TPP, NTPP	NTPP	NTPP
			. . .		

Simplification of composition rules

$$\begin{aligned}
DC(x,y) \wedge Pi(y,z) &\Rightarrow DC(x,z)\\
EC(x,y) \wedge P(y,z) &\Rightarrow EC(x,z) \vee PO(x,z) \vee PP(x,z)\\
EC(x,y) \wedge Pi(y,z) &\Rightarrow DC(x,z) \vee EC(x,z)\\
EC(x,y) \wedge NTPPi(y,z) &\Rightarrow DC(x,z)\\
PO(x,y) \wedge P(y,z) &\Rightarrow PO(x,z) \vee PP(x,z)\\
NTPP(x,y) \wedge P(y,z) &\Rightarrow NTPP(x,z)\\
P(x,y) \wedge NTPP(y,z) &\Rightarrow NTPP(x,z)\\
PP(x,y) \wedge PP(y,z) &\Rightarrow PP(x,z)\\
Pi(x,y) \wedge P(y,z) &\Rightarrow \neg DC(x,z)
\end{aligned}$$

Model-theoretic notions

$\mathfrak{A} = \langle A, DC^{\mathfrak{A}}, \dots \rangle$ and $\mathfrak{B} = \langle B, DC^{\mathfrak{B}}, \dots \rangle$: RCC8 models

$\mathfrak{A}$ substructure of $\mathfrak{B}$: $A \subseteq B$ and $R^{\mathfrak{A}} = R^{\mathfrak{B}} \cap (A \times A)$ for each $R \in \{DC, EC, \dots\}$

Isomorphism between $\mathfrak{A}$ in $\mathfrak{B}$: a bijective mapping $f : A \to B$ such that f and f^{-1} preserve all relations

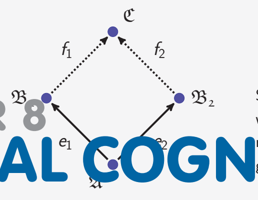
Automorphism of $\mathfrak{A}$: an isomorphism $f : \mathfrak{A} \to \mathfrak{A}$

Embedding of $\mathfrak{A}$ in $\mathfrak{B}$: a mapping $f : A \to B$ that is an isomorphism between $\mathfrak{A}$ and $\mathfrak{B}[f(A)]$

Age of $\mathfrak{A}$: the set of finite structures that can be embedded into $\mathfrak{A}$

Homogeneous $\mathfrak{A}$: every isomorphism between finite substructures of $\mathfrak{A}$ can be extended to an automorphism of $\mathfrak{A}$

Amalgamation property



Scenarios S_1, S_2 of constraint networks $N_1 = \langle V, \dots \rangle$, $N_2 = \langle V_2, \dots \rangle$, r[illegible] $S_1|_{V_1 \cap V_2} = S_2|_{V_1 \cap V_2}$ can be g[illegible] together

SFB/TR 8 SPATIAL COGNITION

Support by: Universität Bremen DFG Deutsche Forschungsgemeinschaft UNI FREIBURG

Presented at ECAI'14

A Concise Horn Theory for RCC8

Matthias Westphal and Julien Hué

Department of Computer Science, University of Freiburg, Germany

SPATIAL COGNITION

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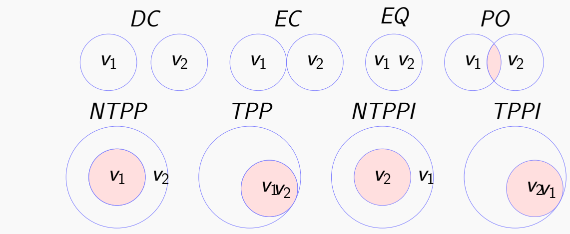
Region Connection Calculus (8 Atoms)

RCC8 is a Constraint Language for describing regions of space with 8 atomic relations:



- Γ_{RCC8A} the FO structure defining these 8 *atomic* relations
- Γ_{RCC8} the FO structure with 256 relations defined by disjunctions on two variables, e.g. $EQ(x,y) \vee PO(x,y)$

Consider FO formulas of the form
$\psi = \exists v_1, \ldots, v_n\, R(v_i, v_j) \wedge \cdots \wedge S(v_k, v_l)$ over Γ_{RCC8}.

CSP(Γ) is the decision problem: $\Gamma \overset{?}{\models} \psi$.

- CSP(Γ_{RCC8}) is NP-complete
- $\Gamma_{\widehat{\mathcal{H}}_8}$ is the largest reduct of Γ_{RCC8} which expands Γ_{RCC8A} such that CSP($\Gamma_{\widehat{\mathcal{H}}_8}$) is in P; these are 148 relations
  Proof by Horn SAT encoding with size $O(n^4)$

Example

Description of Central Park, Manhattan, and New York:

$\psi_{\mathrm{Ex}} := \exists \mathrm{CP}, \mathrm{M}, \mathrm{NY}\; NTPP(\mathrm{CP}, \mathrm{M}) \wedge TPP(\mathrm{M}, \mathrm{NY}) \wedge (NTPP \vee TPP \vee EQ)(\mathrm{NY}, \mathrm{CP})$

Syntactic interpretations of Γ_{RCC8}

- Natural interpretation in Γ_{RCC8A} by disjunction
- We propose another syntactic interpretation π_{RCC4}
- ... in a reduct of Γ_{RCC8} named Γ_{RCC4}

Γ_{RCC4} has the 4 symbols $\{C, O, P, NTP\}$ defined in Γ_{RCC8}:

- $NTP(x,y) := NTPP(x,y)$,
- $C(x,y) := \neg DC(x,y)$,
- $O(x,y) := \neg(DC(x,y) \vee EC(x,y))$,
- $P(x,y) := TPP(x,y) \vee NTPP(x,y) \vee EQ(x,y)$

- 42 RCC8 relations are definable in Γ_{RCC4} using only conjunction and negation
- All 148 relations of $\Gamma_{\widehat{\mathcal{H}}_8}$ are Horn definable in Γ_{RCC4}

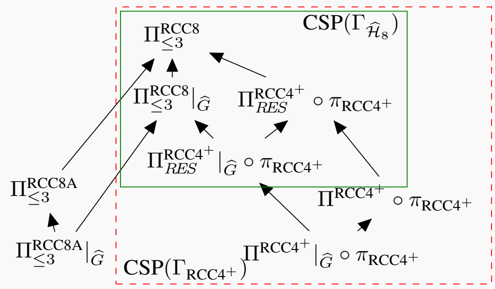
Example continued

Using these syntactic interpretations:

$$\varphi_{\pi_{\mathrm{RCC8A}}}(\psi_{\mathrm{Ex}}) := \exists \mathrm{CP}, \mathrm{M}, \mathrm{NY}\; NTPP(\mathrm{CP}, \mathrm{M}) \wedge TPP(\mathrm{M}, \mathrm{NY}) \wedge (NTPP(\mathrm{NY}, \mathrm{CP}) \vee TPP(\mathrm{NY}, \mathrm{CP}) \vee EQ(\mathrm{NY}, \mathrm{CP}))$$

$$\varphi_{\pi_{\mathrm{RCC4}}}(\psi_{\mathrm{Ex}}) := \exists \mathrm{CP}, \mathrm{M}, \mathrm{NY}\; NTP(\mathrm{CP}, \mathrm{M}) \wedge P(\mathrm{M}, \mathrm{NY}) \wedge \neg P(\mathrm{NY}, \mathrm{M}) \wedge \neg NTP(\mathrm{M}, \mathrm{NY}) \wedge P(\mathrm{NY}, \mathrm{CP})$$

Propagation by Datalog programs



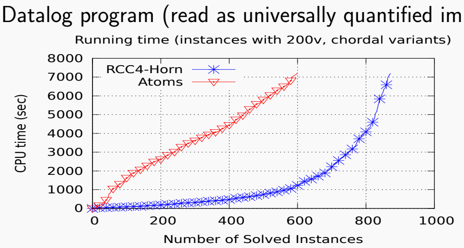
- Strong 3-consistency $\Pi^{\mathrm{RCC8}}_{\leq 3} \approx 131\,000$ rules
- ... 68 rules when restricted to bodies on atoms $\Pi^{\mathrm{RCC8A}}_{\leq 3}$
- We propose Π^{RCC4^+} with 18 rules:

$P(x,x)$	$\overline{NTP}(x,x)$
$C(x,y) :- O(x,y)$	$O(x,y) :- P(x,y)$
$P(x,y) :- NTP(x,y)$	$\mathrm{false} :- P(y,x), NTP(x,y)$
$O(x,y) :- O(y,x)$	$C(x,y) :- C(y,x)$
$\mathrm{false} :- C(x,y), \overline{C}(x,y)$	$\mathrm{false} :- NTP(x,y), \overline{NTP}(x,y)$
$\mathrm{false} :- O(x,y), \overline{O}(x,y)$	$\mathrm{false} :- P(x,y), \overline{P}(x,y)$
$P(x,y) :- P(x,z), P(z,y)$	$C(x,y) :- C(x,z), P(z,y)$
$O(x,y) :- C(x,z), NTP(z,y)$	$O(x,y) :- O(x,z), P(z,y)$
$NTP(x,y) :- P(x,z), NTP(z,y)$	$NTP(x,y) :- NTP(x,z), P(z,y)$

Propositional SAT encodings

Simply consider the Herbrand expansion of the (interpreted) input formula and the Datalog program (read as universally quantified implications). How good is unit propagation (UP) on the resulting formula?

- Size in $O(n^3)$ (three distinct variables in programs)
- UP emulates (at least) Datalog semantics
- Previously encoding of $\Pi^{\mathrm{RCC8A}}_{\leq 3}$ considered
- ... but *UP does not even solve CSP(Γ_{RCC8A})*
- Instead, in $\Pi^{RCC4^+}|_{\widehat{G}}$ *UP solves CSP($\Gamma_{\widehat{\mathcal{H}}_8}$)*



- Π^{RCC4^+} is smaller and better than $\Pi^{\mathrm{RCC8A}}_{\leq 3}$
- Novel interpretation and program enables propositional CNF superior to previous "support" encoding: smaller and better for UP
- Future work: Π^{RCC4^+} for Constraint Programming — avoid Herbrand expansion

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References

- D.A. Randell, Z. Cui, A. G. Cohn, 'A spatial logic based on regions and connection', KR, 1992
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Presented at IJCAI'13

On the Computational Complexity of Qualitative Change

M. Westphal, J. Hué, S. Wölfl, and B. Nebel
Department of Computer Science, University of Freiburg, Germany

SPATIAL COGNITION
R4-[LogoSpace]

Qualitative Spatial Reasoning in a Nutshell

- Constraint languages on infinite domains $\mathcal{D}$
  $$\Gamma = \langle \mathcal{D}; R_1^{\mathcal{D}}, \dots, R_n^{\mathcal{D}} \rangle$$
- Knowledge as primitive positive formulas:
  $$\varphi = \exists x_1 \dots x_m : \bigwedge_j R_j\, x_{j_1} \dots x_{j_l}$$
- Complexity of the satisfiability problem depends on Γ; **P**, **NP**, ..., undecidable

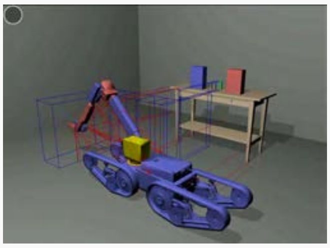
Example: Point Algebra

- base algebra $(\mathbb{Q}, <)$
- full algebra $(\mathbb{Q}, <, \leq, \neq)$

Interpret $<$ spatially (in front/behind) and in multiple dimensions

PA is central

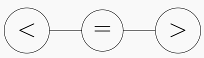
Interval Algebra, Cardinal Directions, Block Algebra, Rectangle Algebra can be expressed by PA



Towards Spatio-Temporal Semantics

- Characterize motion qualitatively
- Handle time by snapshots of the world (states) (as opposed to domains as "object-histories")
- Instance of CSP(Γ): primitive positive formulas without free variables
- Instance of SeqCSP(Γ): $\mathcal{S} = \langle V, (Q^1, \dots, Q^d) \rangle$ where the Q^i are instance of CSP(Γ)
- Qualitative descriptions should handle (immediate) continuity in motion: $x < y \overset{?}{\longleftrightarrow} x > y$
- Associated with neighborhood graphs [Freksa, 1991]
- Represent continuity as $2 \cdot n$-ary relations: $T_2 / T_4 \subseteq \mathcal{D}^{2 \cdot n}$
  $x_1, \dots, x_n$ can immediately transform into $x_{n+1}, \dots, x_{2 \cdot n}$
- Neighborhood graphs provide merely binary projection of T_2 / T_4

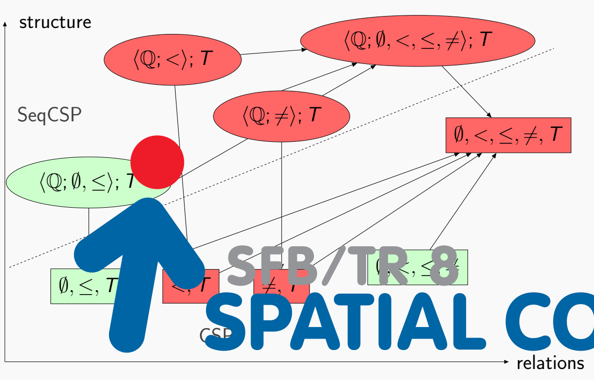
Definition of Transitions



- T_2-solution of SeqCSP(Γ):
  $$\alpha^t(v_i) < \alpha^t(v_j) \Longrightarrow \alpha^{t+1}(v_i) \leq \alpha^{t+1}(v_j).$$

- T_4-solution of SeqCSP(Γ): T_2-solution such that
  $$\alpha^t(v_i) \neq \alpha^t(v_j) \wedge \alpha^t(v_k) = \alpha^t(v_l) \Longrightarrow \neg(\alpha^{t+1}(v_i) = \alpha^{t+1}(v_j) \wedge \alpha^{t+1}(v_k) \neq \alpha^{t+1}(v_l))$$
- It does not allow point-to-interval and interval-to-point transitions at the same time.

The Complexity of Continuity



P, **NP-complete**

Unrestricted relational languages

Annotate variables with time points
→ allows relations between variables at different times

- x moves right towards y is now expressible as a relation
  $$R_{\text{move\_right}}(x^0, y^0, x^1, y^1) := (x^0 < y^0) \wedge (x^1 \leq y^1) \wedge (x^0 < x^1)$$
- Entities can be restricted to not change
  In state spaces relations are restricted to not change
- Existing P/NP-completeness dichotomy result for constraint languages built on $<$ [BK, 2010]
- Languages interesting for theoretical study
  → proper semantics for (qualitative) transition systems
- T_2 and T_4 relations can be generalized between any tuple of variables

Where to go from Here?

- Analyzing continuity in non point-based formalims (RCC, OCC, etc.)
- Investigating state space approach is close to AI planning, e.g., PDDL
- Integrating continuity constraints into SAT/CP

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Support by:
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Reasoning about Relative Direction Constraints using Sector Sets around Oriented Points

Presented at ECAI'14

André van Delden
Department of Computer Science, University of Bremen, Germany

R4 - [LogoSpace]

Initial Objective

- Improve on the $\mathcal{OPRA}$ calculus in order to make spatial reasoning about relative directions more versatile.
- Allow for qualitative abstractions. Provide a superset of the $\mathcal{OPRA}$ relations.
- Stay computationally useful!

Introduction

In applications dealing with spatial properties, often these properties are not given or useful as precise metric data but in terms of qualitative notions such as *inside*, *left* or *bigger*. For spatial reasoning about qualitative, relative directions, the $\mathcal{OPRA}$ calculus [1] is a prominent candidate that is based on oriented points and fits into the relation algebraic approach to Qualitative Spatial Reasoning.
However, this calculus has some important limitations:

- Relations of different granularity can not easily be used at the same time.
- Higher granularities result in very big composition tables (e.g. 16 GB), which make reasoning infeasible.
- It only includes even, equiangular partitions of the real plane,
- The *front* and *back* relations are unidimensional.
- Integrating quantitative information is not directly possible.

Using a modern SMT-solver, these problems can be avoided. Deploying the angular constraints that are used to compute the composition tables of the $\mathcal{OPRA}$ calculi directly to a given constraint network allows for more flexible and effective reasoning that can even be faster than relying on the algebraic closure (AC) procedure from the relation algebraic approach.

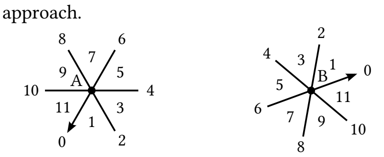


Figure 1: The $\mathcal{OPRA}_3$ base relation denoted by $A\ {}_3\angle_4^5\ B$.

The $\mathcal{OPUS}$ Relation Set

The $\mathcal{OPUS}$ (Oriented Points Using Sectors) relation set allows to describe relative directions of oriented points in the plane by means of sets of sectors around those oriented points. $\mathcal{OPUS}$ relations are binary relations defined by

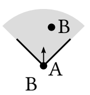
$$Opus(I_1, I_2) \stackrel{\text{def}}{\equiv} \{(x,y) \in \mathbb{O}^2 \mid \dot{x} \neq \dot{y} \ \wedge\ \angle\vec{x}(\dot{y} - \dot{x}) \in \bigcup I_1 \ \vee\ \dot{x} = \dot{y} \ \wedge\ \angle\vec{x}\vec{y} \in \bigcup I_2\},$$

where $\mathbb{O}$ denotes the set of oriented points in the real plane, $\vec{x}$ denotes the orientation of x, $\dot{x}$ denotes the location of x and I_1, I_2 are finite sets of real intervals. For notational convenience we define

$$Opus_{AB} I_1 I_2 \stackrel{\text{def}}{\equiv} (A, B) \in Opus(I_1, I_2)\ .$$

The language combining such $\mathcal{OPUS}$ constraints by conjunction and disjunction is simply called *the* $\mathcal{OPUS}$.

Example: We write $Opus_{AB}\{[0, \frac{\pi}{4}], [\frac{7}{4}\pi, 2\pi)\}\{[\pi, \pi]\}$ to denote that B, as seen from oriented point A, lies either in the front quadrant including the boundary or exactly at A but oriented backwards. Since the $\mathcal{OPUS}$ distinguishes between the directions *left* and *right* by the relations $Opus(\{(0, \pi)\}, \emptyset)$ and $Opus(\{(\pi, 2\pi)\}, \emptyset)$, deciding realizability of a spatial description using $\mathcal{OPUS}$ relations is as hard as deciding satisfiability in the existential theory of the reals, which is NP-hard [2].



Triangle Consistency

- Express an $\mathcal{OPUS}$ sentence in QF_LRA, the quantifier free first order theory of linear inequalities over the reals.
- Add angular dependencies: e.g. the sum of interior angles in an triangle equals π.
- Use an SMT-solver to decide the satisfiability of these angular constraints.

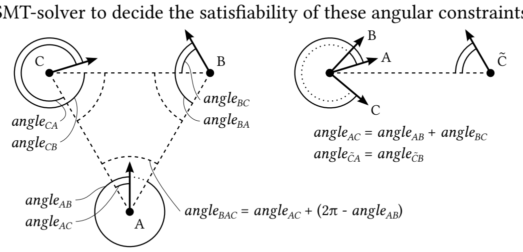


Figure 2: Proper and degenerated oriented point triangles.

Basic Formulas

- Each $\mathcal{OPUS}$ constraint $Opus_{AB} I_1 I_2$ can be directly translated into the following QF_LRA formula:

$$\text{OPair}_{AB} I_1 I_2 \stackrel{\text{def}}{\equiv} \left(\begin{array}{l} \neg same_{AB} \wedge \bigvee_{i \in I_1} \inf i \lesssim angle_{AB} \lesssim \sup i \\ \vee\ same_{AB} \wedge \bigvee_{i \in I_2} \inf i \lesssim angle_{AB} \lesssim \sup i \end{array} \right)$$

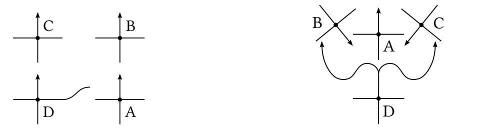
where $\lesssim$ is either strict or not depending on whether the interval is open or closed at the respective end.
- Add triangle constraint formulas that depend on whether some oriented points lie on each other or not.
- For each triple of oriented points, use a case-by-case analysis over the variables $same_{AB}$, $same_{AC}$ and $same_{BC}$:

$$\textcircled{?}ABC \stackrel{\text{def}}{\equiv} \left(\begin{array}{l} \neg same_{AB} \wedge \left(\begin{array}{l} \neg same_{AC} \wedge \left(\begin{array}{l} \neg same_{BC} \wedge \textcircled{\cdot}ABC \\ \vee\ same_{BC} \wedge \textcircled{\cdot}BCA \end{array} \right) \\ \vee\ same_{AC} \wedge \left(\begin{array}{l} \neg same_{BC} \wedge \textcircled{\cdot}ACB \\ \vee\ same_{BC} \wedge \text{False} \end{array} \right) \end{array} \right) \\ \vee\ same_{AB} \wedge \cdots \end{array} \right)$$

The formula $\triangle S$ expressing the triangle consistency (TC) of an $\mathcal{OPUS}$ description S is given by translating each constraint $Opus_{AB} I_1 I_2$ in S into the corresponding $\text{OPair}_{AB} I_1 I_2$ formula, restricting the angles of all pairs not occurring in S to lie in $[0, 2\pi]$ and conjuncting the formula $\textcircled{?}ABC$ for every unordered triple ABC.

Two Interesting Scenarios

These scenarios can be interpreted as robotic sensor deviation and human left-right confusion.



Fourth Corner Problem
$A\ {}_2\angle_0^4\ B,\quad A\ {}_2\angle_2^5\ D,$
$B\ {}_2\angle_2^6\ C,\quad C\ {}_2\angle_4^0\ D.$

Left Right Confusion Problem
$A\ {}_2\angle_1^1\ B,\quad A\ {}_2\angle_7^7\ C,$
$B\ {}_2\angle_7^7\ D,\quad C\ {}_2\angle_1^1\ D.$

Figure 3: Two algebraically closed $\mathcal{OPRA}_2$ scenarios that are triangle inconsistent.

Results of a Benchmark on $\mathcal{OPRA}_8$ networks

These are some results of a self-regulating randomized benchmark on $\mathcal{OPRA}_8$ constraint networks using a timeout of 20 seconds.

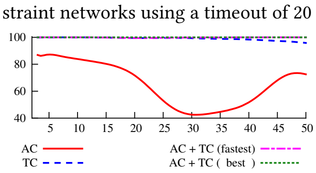


Figure 4: Percentage of inconsistent networks discovered by each method; per network size.

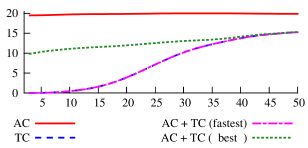


Figure 5: Average runtime in seconds of each method; per network size.

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Contact Information

- Email: andre.van.delden@uni-bremen.de
- Phone: +49 421 218 64265
- Project: SFB/TR 8/R4-[LogoSpace] funded by the DFG.

Support by: Deutsche Forschungsgemeinschaft · Universität Bremen

Mastering *Left* and *Right*

Different Approaches to a Problem That is Not Straightforward

Presented at KI'13

André van Delden and Till Mossakowski

Department of Computer Science, University of Bremen, Germany

SPATIAL COGNITION

R4 - [LogoSpace]

Initial Objective

- Implement or interface all proposed $\mathcal{LR}$ semi-decision procedures in a Haskell library.
- Implement a self-regulating randomized relative benchmark procedure that is applicable to any qualitative spatial calculus.
- Compare the $\mathcal{LR}$ semi-decision procedures through this benchmark procedure.

Introduction

Reasoning over spatial descriptions involving relations that can be described as *left*, *right* and *inline* has been studied extensively during the last two decades. While the fundamental nature of these relations makes reasoning about them applicable to a number of interesting problems, it also makes reasoning about them computationally hard. The key question of whether a spatial scene that is described using these relations can be realized is as hard as deciding satisfiability in the existential theory of the reals. We summarize the semi-decision procedures proposed so far and present the results of a self-regulating randomized benchmark illustrating the relative effectiveness and efficiency of these procedures.

The $\mathcal{LR}$ Calculus

The $\mathcal{LR}$ calculus [1] is a relative orientation calculus in which three points are related, two of which determine a vector serving as frame of reference. The third point can then be either to the left (l) or right (r) of this vector or in front (f), in the back (b) or inside (between the points) (i) of it. It can also coincide with the start point (s) or the end point (e) of the vector. As special cases, there are two more relations, one denoting that the first two points coincide but are distinct from the third (*dou*) and the other denoting that all points coincide (*tri*). These base relations partition the $(\mathbb{R}^2)^3$ and can be combined to general relations through disjunction.

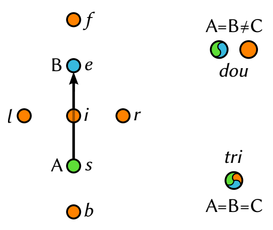

Figure 1
The $\mathcal{LR}$ base relations.

The Semi-Decision Procedures

- The *algebraic closure* algorithm is essentially the common path consistency algorithm modified to be based on the binary (BAC) or ternary (TAC) composition of relations. Several polynomial time algorithms computing this fixed-point are discussed in [2].

- In the *algebraic geometric reasoning* (AR) approach integrated into the SparQ [3] toolbox an n-ary qualitative relation R over a domain $\mathcal{D}$ is modeled as the zero set of a set of multivariate polynomials F_R over real-valued variables $y_1, \ldots, y_k$:
$$\forall x_1, \ldots, x_n \in \mathcal{D} \colon R(x_1, \ldots, x_n) \iff \exists y_1, \ldots, y_k \in \mathcal{R} \colon \forall f \in F_R \colon f(y_1, \ldots, y_k) = 0$$
Thus, a constraint network is expressed as a system of polynomial inequalities which can be solved using Gröbner bases and sets of polynomial transformation rules.

- Any n point solution of an $\mathcal{LR}$ constraint network induces $n \cdot (n-1)/2$ undirected lines connecting all the points. The connecting lines between three arbitrary points form a (possibly degenerated) triangle. The *triangle consistency* (TC) approach of [4] uses simple properties of the angles of these triangles, like the sum of the three angles always adding up to π, and expresses them as a system of equalities and inequalities over the angles of triangles. Triangle consistency can be verified in polynomial time by using an algorithm for solving systems of linear inequalities.

- Interpreting the nodes of $\mathcal{LR}$ networks as vectors in $\mathbb{R}^3$ any consistent $\mathcal{LR}$ scenario is necessarily an acyclic chirotope of rank 3, where *acyclic* means that all vectors lie in an open half-space [5, 6]. This alone gives a feasible semi-decision procedure for the consistency of $\mathcal{LR}$ constraint networks. Furthermore an $\mathcal{LR}$ scenario is consistent iff its associated acyclic chirotope is realizable. Since every rank 3 chirotope with up to 8 points is realizable [6], only verifing the axioms of an acyclic chirotope provides a complete polynomial time decision procedure for $\mathcal{LR}$ constraint networks with up to 8 points. Chirotopes are one form of appearance of *oriented matroids* (OM) for which *biquadratic final polynomials* (BFP) provide a tried-and-tested polynomial time semi-decision procedure, which is based on Grassmann-Plücker relations [7].

A Self-Regulating Random Benchmark Procedure

Problems

- Huge and unknown number of possible $\mathcal{LR}$ constraint networks of a given size.
- Lack of a big database of real world constraint networks.
- Naïvely randomly generated scenarios are mostly trivially inconsistent.

Possible Solution

- Adjust network parameters that are independent from the calculus and methods.
- This parameters should have a phase transition, i.e. a small range of values in which the transition from mostly consistent to mostly inconsistent networks happens.
- A simple yet interesting parameter is the *network density*, i.e. the ratio of elements related to each other to the total number of elements.

Our program takes the arguments *rels*, d, t, n, m, M, *methods* and generates n networks for each size between m and M allowing only relations from *rels* and giving each method in *methods* a time of t seconds to decide the consistency of a network. Starting with the smallest size m and the initial density d it generates one random connected network at a time, collects the results of the methods and adjusts the density of the next network according to the following rule: Let d and s be the density and size of the latest generated network and let d' and s' be the density and size of the network to be generated next. If $s' = s + 1$ then d' is set to the multiple of $\binom{s'}{3}^{-1}$ that is closest to d. If $s' = s$ then the new density is calculated depending on the results collected so far: Let Δ be the difference between the number of networks of size s and density d that have been shown to be inconsistent – by any method in *methods* – and those that have not been detected as inconsistent. Then the new density is set to

$$d' := \min\left(1,\ \max\left(\frac{6}{s(s-1)},\ d - \operatorname{sgn}(\Delta)\binom{s}{3}^{-1}\right)\right).$$

This way we find the common phase transition of the combined methods regarding the density of the networks and can be sure to generate mostly non-trivial networks.

Results of a Benchmark on $\mathcal{LR}$ networks

These are some results of a benchmark on $\mathcal{LR}$ networks using a timeout of 20 seconds.

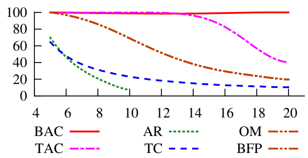

Figure 2: Percentage of inconsistent networks discovered by each method; per network size.

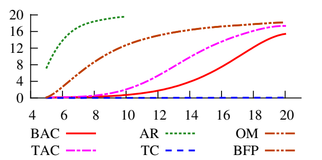

Figure 3: Average runtime in seconds of each method; per network size.

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Contact Information

- Email: andre.van.delden@uni-bremen.de
- Phone: +49 421 218 64265
- Project: SFB/TR 8/R4-[LogoSpace] funded by the DFG.

Support by: DFG Deutsche Forschungsgemeinschaft Universität Bremen

Presented at IJCAI'11

On Qualitative Route Descriptions

M. Westphal[1], S. Wölfl[1], B. Nebel[1], J. Renz[2]

[1] University of Freiburg, Germany [2] ANU Canberra, Australia

SPATIAL COGNITION R4-[LogoSpace]

Motivation

- Route navigation is a widely used application of spatial data
- Navigation systems are good at guiding users at decision points . . .
- . . . but are bad at generating "good" route descriptions

"Good" route descriptions?

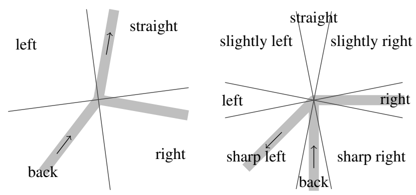
- Compact representation
- Easy to remember and process
- Minimize potential user errors
- Enables reasoning
- Applicable to user generated maps
- Automatic generation

Representation of Decisions

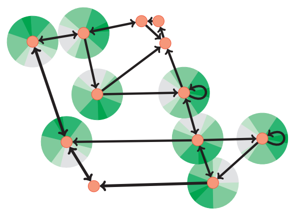
Use egocentric variants of STAR calculi

- mathematically well-defined partition schemes
- relations directly usable as qualitative turn labels
- allow for defining directions of arbitrary granularity

- Route description: sequence of qualitative turn labels



Two different qualitative schemes to define turn actions



Turn actions at decision nodes in the map

From Maps to Decision Frames

Starting point: a map-like graph (as, e.g., in OpenStreetMap):

For navigation tasks one only needs information about when and where to turn along a route.

- Intersections: decision points for navigation
- Contour nodes: relevant points between intersections to extract directional information
- Path arcs: connections between decision nodes, i.e., the possible decisions for each agent

Idea: use qualitative direction relations to describe turns at intersections, such as, "turn sharp left", "turn right", "turn around", or "go straight"

Abstract from the metric data:
Convert map into a decision frame that contains only the intersection nodes but also includes qualitative information about turn directions
To this end, introduce one state for each incoming arc of an intersection node
Qualitative direction relations are calculated wrt. to the first and last contour node of path arcs

Agent Models

Distinguish different execution models for agents:

- a^s strict processing of turn instructions
- a^d agent proceeds in straight direction if next instruction is not executable
- a^g agent recognizes goal states
- a^l agent learns visited states

Reasoning task	a^s	a^{dg}	a^{sgl}	a^{dgl}
Check existence of a conformant path to a destination	P	P	NP-complete	NP-complete
Determine set of final states	P	P	BH_2-complete	BH_2-complete
Check existence of a description with bounded length	P	P	P	NP-complete

Brief evaluation

Compute and evaluate shortest route descriptions for a part of Canberra (≈ 20 km^2) based on 10, 000 random pairs of start/destination states.

Given are the average success probabilities (in [0, 1]) for reaching the destination (rows optimized for, column evaluated on)

$STAR_2^r$

Opt.\Eval.	a^s	a^{dg}	a^{dgl}
a^s	0.41 (0.38)	0.41 (0.38)	0.41 (0.38)
a^{dg}	0.01 (0.11)	0.25 (0.33)	0.24 (0.33)
a^{dgl}	0.02 (0.12)	0.29 (0.35)	0.29 (0.35)

$STAR_4^r$

Opt.\Eval.	a^s	a^{dg}	a^{dgl}
a^s	0.62 (0.36)	0.62 (0.36)	0.62 (0.36)
a^{dg}	0.01 (0.11)	0.56 (0.39)	0.56 (0.39)
a^{dgl}	0.01 (0.11)	0.61 (0.38)	0.61 (0.38)

Outlook

- Optimize reliability of route descriptions
  - Optimal algorithms (exponential time expected)
  - Approximation algorithms
- Balance different criteria: reliability, metric length, . . .
- Integrate landmarks and spatial chunking

SFB/TR 8 SPATIAL COGNITION

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Support by: Universität Bremen, ANU, DFG Deutsche Forschungsgemeinschaft, Australian Government Australian Research Council, DAAD, GROUP OF EIGHT

R6-[SpaceGuide]

Human and Robot Navigation in Structured Environments

R6-[SpaceGuide]

Christoph Hölscher, Wolfram Burgard, Gerhard Strube

Quantifying Spatial Ambiguity

Motivation

- Unreliable localization in ambiguous environments
- Utilize artificial (but indistinguishable) landmarks to reduce the ambiguity

Goals

- Determine positions for artificial landmarks to support localization of robots and humans
- Develop a tool for architects to identify potentially ambiguous places in buildings

Pose Uniqueness

- Measure of how distinguishable a pose is from the other poses
- Based on the potential observations of the robot in the map

$$\mathcal{U}(x,m) = \frac{1}{\int_{\tilde{x}\in\mathcal{X}} \underbrace{p(z^{x*} \mid \tilde{x}, m)}_{\text{Sensor model}} \, d\tilde{x}}$$

where

$$z^{x*} = \text{argmax}_z \, p(z \mid x, m)$$

Experimental Evaluation

Robot Navigation

- Occupancy grid, candidate locations: occupied cells
- Sensor: laser range scanner, landmarks: reflective tape
- Detection based on remission values

Transfer to Human Navigation

- Candidate location for human landmarks: free cells
- Algorithm chooses from a set of 100 randomly sampled landmark positions
- Comparison experiment: humans are asked to mark most ambiguous locations for landmark placement

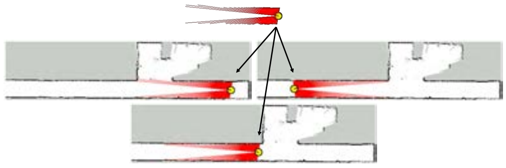
Conclusion

- Approach to reduce perception ambiguity in the environment by placing indistinguishable landmarks
- Provides locations and number of landmarks

Publication

- D. Meyer-Delius, M. Beinhofer, A. Kleiner, W. Burgard. **Using Artificial Landmarks to Reduce the Ambiguity in the Environment of a Mobile Robot**. In *Proc. of the Int. Conf. on Robotics and Automation (ICRA)*, Shanghai, China, 2011.

Aisle 14 Aisle 15 Aisle 16 Aisle 17



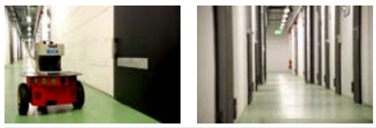
Robot poses cannot be distinguished based on sensor data

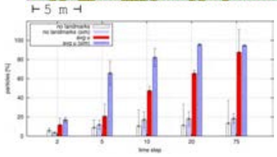
Landmark Placement

- Choose landmark that maximizes the average uniqueness in the environment
- Select the locations $m \subseteq \mathcal{V}$ out of the candidate locations $\mathcal{V}$ that **maximize the average uniqueness**

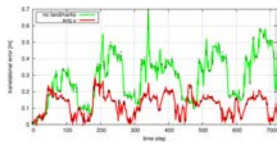
$$m^* = \underset{m\subseteq\mathcal{V}}{\text{argmax}} \left(\frac{1}{||\mathcal{X}||} \int_{x\in\mathcal{X}} \mathcal{U}(x,m) dx \right)$$

- Approximate Solution
- Incrementally select maximizing location

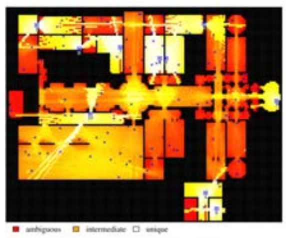




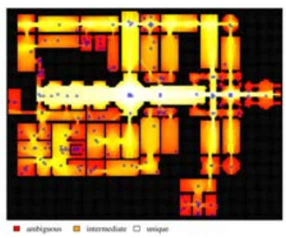
Faster global localization convergence



Improved position tracking performance



Landmarks selected by our approach



Landmarks selected by humans

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Human and Robot Navigation in Structured Environments

R6-[SpaceGuide]

Christoph Hölscher, Wolfram Burgard, Gerhard Strube

Efficient Landmark Placement

Motivation

Achieve robust mobile robot navigation

- In assembly halls or storage facilities
- In ambiguous or dynamic environments
- If the same trajectory is executed many times
  - ⇨ Place artificial landmarks to achieve robustness

Problem Formulation

Optimize the localization performance of a robot on a given trajectory by

- Placing artificial landmarks that the sensors of the robot can observe
- Finding near-optimal locations for these landmarks

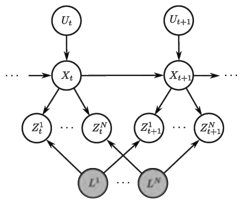
We assume a

- Motion model of the robot
- Landmark observation model
- Desired trajectory
- Control policy

Finding the optimal landmark locations is NP-hard

State Estimation

- Apply a Hidden Markov Model to estimate the state of the robot



Dynamic Bayes Network

At time t:

X_t: state of the robot

Z_t^i: observation of i-th landmark

L^i: position of i-the landmark

U_t: control command

Placing Landmarks

- Defined as an optimization problem
- Objective function: conditional mutual information

$$F(\mathcal{A}) = I(X_{1:T}; Z^{\mathcal{A}}_{1:T} | U_{1:T}, L_{1:N})$$
$$= h(X_{1:T} | U_{1:T}, L_{1:N}) - h(X_{1:T} | Z^{\mathcal{A}}_{1:T}, U_{1:T}, L_{1:N})$$

- Given the properties of the system, find the set $\mathcal{A}^*$ of landmarks with

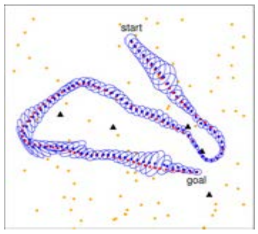
$$\mathcal{A}^* = \underset{\mathcal{A} \subseteq \mathcal{V}; |\mathcal{A}| \leq n}{\operatorname{argmax}} F(\mathcal{A})$$

- Approximate the solution using a greedy selection scheme

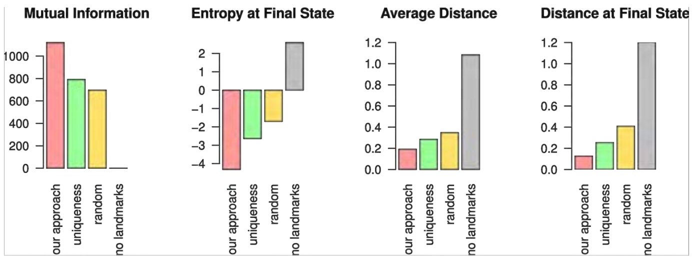
Experimental Results

Simulation

- 20 different randomly sampled tasks, each consisting of
  - Set $\mathcal{V}$ of possible landmark positions
  - Desired trajectory
- Autonomous controls
- Evaluation of four different goodness criteria

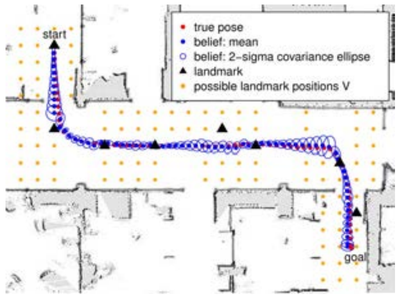


One of the randomly selected tasks



Real Robot

- Evaluation of selected landmark positions using an autonomous mobile robot equipped with a web cam pointing upwards and visual markers as landmarks



Landmarks selected by our method and one trajectory of a robot using these landmarks for localization

Conclusions

- More accurate localization using fewer landmarks
- No assumptions about linearity of the system or about the structure of the set of possible landmark locations
- Effective, approximate solution to an NP-hard problem

Publication

- M. Beinhofer, J. Mueller, W. Burgard. **Near –Optimal Landmark Selection for Mobile Robot Navigation.** In *Proc. of the Int. Conf. on Robotics and Automation (ICRA)*, Shanghai, China, 2011.

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Human and Robot Navigation in Structured Environments

SPATIAL COGNITION
R6-[SpaceGuide]

V. Langenfeld, S. Kuliga, R. Stülpnagel, C. Hölscher

Ambiguity

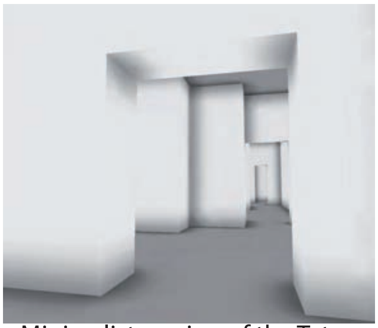
- Indistinguishability of locations without additional information (e.g. movement history)
- Robot: caused by isovist equality
- Human: assumably similar visual appearance, but the 360° experiment suggests the influence of other factors such as expectation and overall complexity.

Research Question

- Strategies of human landmark placement for disambiguation?
- Robot performance with landmarks placed by humans?

360° Experiment

- Tate Gallery with many of different spatial arrangements e.g.: long/short line of sight, columns, ...
- 100 locations chosen by minima/maxima of: integration, connectivity, jaggedness, U_{robot}.
- Presentation of locations from the egocentric perspective, recall of the location in layout view.
- Landmark placement from allocentric view to simplifiy the self relocalisation task.



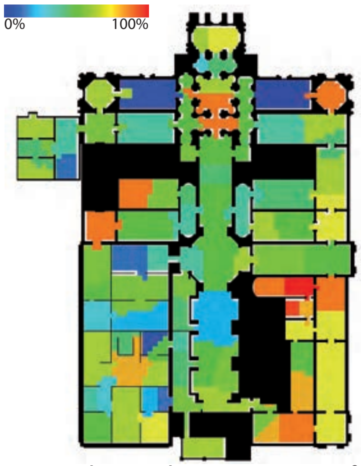
Minimalist version of the Tate Gallery during presentation.

Results

- Landmarks placed by humans are at significantly more integrated locations (U = 41641.0, n1 = 3050, n2 = 51, p = .000) and at significantly more connected (U = 30699.0, n1 = 3050, n2 = 51, p = .000) than by chance.
- Task is in its form uncommon, placement heuristics are based on navigation rather than on self localisation. Only 40% of the participants explained that they intentionally used landmarks for disambiguation rather than to mark places they would most likely navigate to. But calculation of the optimal solution on U_{human} yields a subset of the chosen locations.
- Humans are able to evaluate the correctness of their self localisation (r = .626, p = .000).

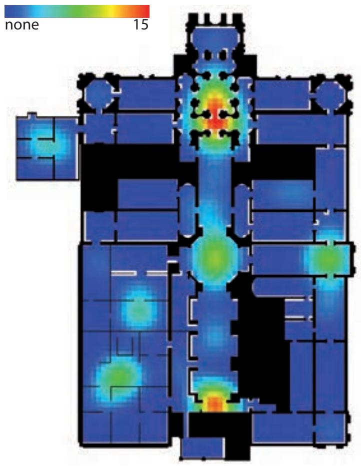
Robot using Landmarks placed by Humans

- Landmarks set by humans at more unique places than by chance (avg U_{robot} = .727, avg U_{lm} = .946, U = 26874, n1 = 3050, n2 = 51, p = .000).

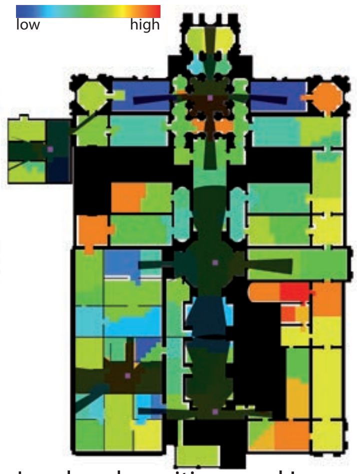


U_{human} being the percentage of correct self localisations.

U_{robot} as calculated.



Heatmap of human landmark placement.



Landmark positions and Isovists maximizing U_{human}.

- The best human solution places three landmarks in highly unique areas, two at U_{robot} improving positions.

The best human landmark placement by means of maximizing U_{robot}. Even this solution uses three landmarks to disambiguate places that have far above the average uniqueness of the building.

Discussion & Conclusion

- Humans place landmarks at useful positions for humans. However, this effect may be dependent on the building.
- For robot navigation there are far more useful solutions than the landmarks placed by humans.

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Human Navigation in Structured Indoor Environments

SPATIAL COGNITION
R6-[SpaceGuide]

Wayfinding in the Seattle Public Central Library

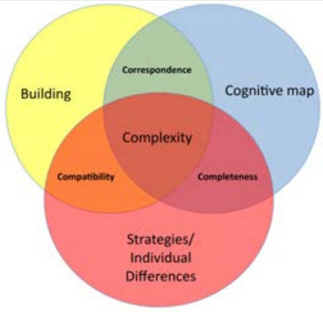
Saskia Kuliga, Ben Nelligan, Steven Marchette, Laura Carlson, Ruth Conroy Dalton, Amy Shelton and Christoph Hölscher.

Background

- Built in 2004 by Rem Koolhaas (OMA) / LMN. 38,300 m^2 on 11 floors
- High praise for being a showcase of modern architecture
- Sharp criticism that visitors get lost during navigation

→As part of a post-occupancy evaluation, we conducted a wayfinding study to understand:

Which factors account for library visitors' navigation and orientation difficulties?



Framework by Carlson, et al. (2010), Getting Lost in Buildings, Current Directions in Psychological Science

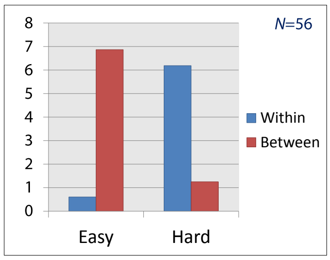
Methods

- Based on spatial analyses: predefinition of expected "easy" and "difficult" navigation tasks
- *Peoplewatcher* app to track participants' wayfinding behavior (paths & "events")
- Standardized questionnaires to assess individual spatial skills (MRT, SOT, SBSOD, SAT, QSR) and user experience in building

Screenshot of Peoplewatcher app (Dalton & Dalton)

	(Expected) "Easy Task"	(two tasks not analyzed here)	(Expected) "Hard Task"
Within Floors	Childrens' Restrooms **1.25** Expectations	Aviation Room* (4.37)	Sherlock Holmes Book **3.05** Non-Spatial Influences
Across Floors	Non-Fiction DVDs **2.38** Think Global	Music Practice Rooms* (3.25)	Meeting Room #6 **3.27** Spatial Reasoning

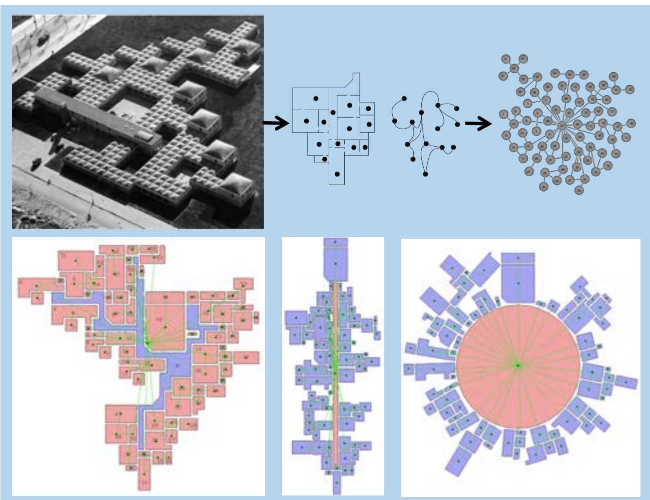
Expected and Mean Perceived Difficulty of Wayfinding Tasks (table) and potential underlying strategy (orange tags) Scale :easy(1)-difficult (4, 6)



Percentage of Deviation from Shortest Ideal Path and Perceived Difficulty

Discussion & Conclusions

- Perceived, subjective task difficulty does *not* fully match a-priori expected task difficulty based on space syntax analyses.
- High scores on spatial skills do not necessarily mean overall successful performance. No overall classification of "good" or "bad" navigators. Wayfinding tasks require adaptive strategies.
- **Planned continuation:** Investigate user wayfinding behavior in a systematically redesigned virtual model of this library.



Amsterdam Municipal Orphanage: translation to boundary graph (above) and transformation to final layouts (with network, linear, and circular circulation)

	Visual intelligibility	Expected subjective difficulty
'Network' circulation	R^2=.45	64% rated as the most difficult
'Linear' circulation	R^2=.63	79% rated as the easiest
'Concentric' circulation	R^2=.32	48% rated as intermediate

Linking building circulation typology and human wayfinding

Saskia Kuliga, Asya Natapov, Christoph Hölscher

Aims

Understanding the relationship between architectural configuration and human wayfinding performance.

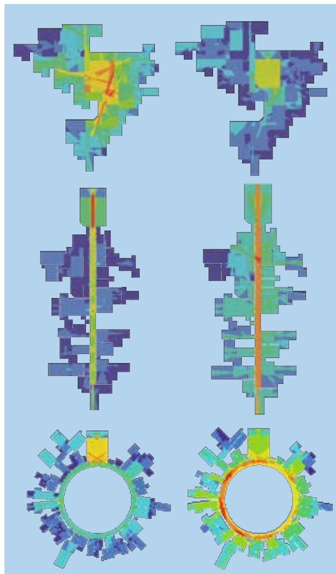
→ How to systematically redesign buildings (e.g. for empirical studies or pre-occupancy evaluation)?

Methods

Systematic graph-based circulation redesign of the existing building.

Planned Continuation

→ Investigate user wayfinding behavior in these three VR models.



Space Syntax VGA Connectivity (left) and VGA Integration Measures

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R7-[PlanSpace]

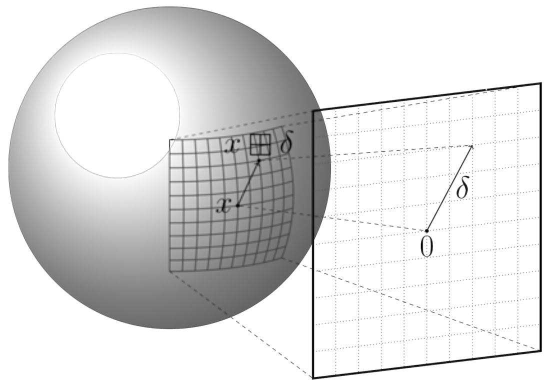
Sparse Least Squares on Manifolds

A7-[FreePerspective]

Christoph Hertzberg, Udo Frese, Thomas Röfer

[+]-Manifolds

- Integration of manifolds into least-squares estimators
- By encapsulating their structure in a [+] operator
- Flexible definition of various state spaces
- Mathematical theory and software framework



Axioms of a [+]-Manifold S

$x \boxplus \delta$ smooth in δ and $y \boxminus x$ smooth in y.

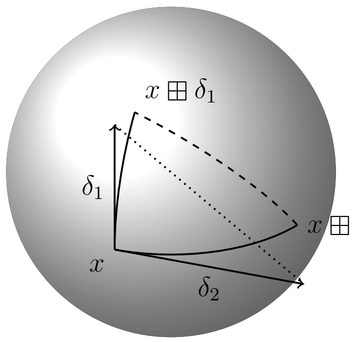
range of unique values $0 \in V \subset \mathbb{R}^n$

$$x \boxplus 0 = x$$

$$\forall y \in \mathcal{S}: \quad x \boxplus (y \boxminus x) = y$$

$$\forall \delta \in V: \quad (x \boxplus \delta) \boxminus x = \delta$$

$$\forall \delta_1, \delta_2 \in \mathbb{R}^n: \|(x \boxplus \delta_1) \boxminus (x \boxplus \delta_2)\| \leq \|\delta_1 - \delta_2\|$$



Probababilistic Concepts on a [+]-Manifold

$$\mathcal{N}(\mu, \Sigma) := \mu \boxplus \mathcal{N}(0, \Sigma),\ \mu \in \mathcal{S},\ \Sigma \in \mathbb{R}^{n \times n}$$

$$X \sim \mathcal{N}(\mu, \Sigma) = \mu \boxplus \mathcal{N}(0, \Sigma) \overset{*}{\Leftrightarrow} X \boxminus \mu \sim \mathcal{N}(0, \Sigma)$$

$$\operatorname{E} X = \operatorname{argmin}_{x \in \mathcal{S}} \operatorname{E}(\|X \boxminus x\|^2)$$

$$\operatorname{Cov} X = \operatorname{E}\left((X \boxminus \operatorname{E} X)(X \boxminus \operatorname{E} X)^\top\right)$$

Gauss-Newton on a [+]-Manifold

$$f(X) - z \sim \mathcal{N}(0, \Sigma) \qquad\qquad f(X) \boxminus z \sim \mathcal{N}(0, \Sigma)$$

$$J_{\bullet k} := \frac{f(x_i + \varepsilon e_k) - f(x_i - \varepsilon e_k)}{2\varepsilon} \qquad J_{\bullet k} := \frac{(f(x_i \boxplus \varepsilon e_k) \boxminus z) - (f(x_i \boxplus -\varepsilon e_k) \boxminus z)}{2\varepsilon}$$

$$x_{i+1} := x_i - (J^\top \Sigma^{-1} J)^{-1} J^\top \Sigma^{-1} (f(x_i) - z) \qquad x_{i+1} := x_i \boxplus -(J^\top \Sigma^{-1} J)^{-1} J^\top \Sigma^{-1} (f(x_i) \boxminus z)$$

Example: Stereo-Camera Calibration in <50 Lines of Code

```
typedef MTK::vect<2> vec2;                // 2D vector
typedef pair<vec2, vec2> vec2pair;        // Measurement pair
typedef MTK::vect<3> vec3;                // 3D vector
typedef MTK::SO3< > SO3;                  // 3D Orientation
typedef MTK::trafo<SO3> trafo;            // 3D Transformation
typedef MTK::vect<9> CamIntrinsics;       // Camera intrinsics

class Camera : public CamIntrinsics {
    vec2 sensor2image(const vec3& point) const;};

MTK_BUILD_MANIFOLD(StereoCamera,
    ((Camera, left))
    ((Camera, right))
    ((trafo, left2right))
)

SLOM_BUILD_MEASUREMENT(StereoMeasurement, 4,
    ((StereoCamera, K)) ((trafo, left2world)),
    ((vec3, p_world)) ((vec2pair, z_ti)))

SLOM_IMPLEMENT_MEASUREMENT(StereoMeasurement, ret){
    vec3 p_left = left2world->inverse() * p_world;
    vec3 p_right = K->left2right * p_left;
    ret << K->left.sensor2image(p_left)   - z_ti.first,
           K->right.sensor2image(p_right) - z_ti.second;
}
```

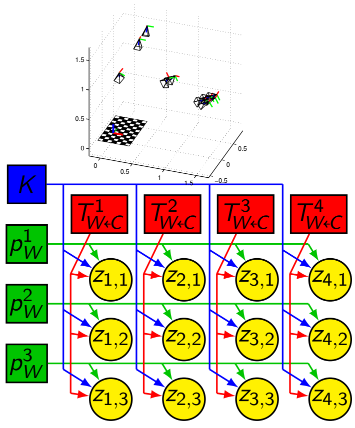
```
vector<vec3> pts_world;   // calibration point positions

Estimator est;                      // Optimizer class
// Camera parameters (shared by all measurements):
VarID<StereoCamera> K = est.insertRV(StereoCamera());

for(int t=0; t<num_images; ++t){
    // collect data, get initial guess for left camera
    vector<vec2pair> z_t;
    trafo left2world_init;
    find_checkerboard(left2world_init, z_t, pts_world);

    VarID<trafo> left2world = // local ID left2world
          est.insertRV(left2world_init);
    for(int i=0; i<num_points; ++i)
        est.insertMeasurement (StereoMeasurement(
              K, left2world,
              pts_world[i], z_t[i]));
}

for(int i=0; i<100; ++i) est.optimizeStep();
cout << "Camera intrinsics " << *K << "\n";
```



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Detailed Modeling and Calibration of a Time-of-Flight Camera

SPATIAL COGNITION

A7-[FreePerspective]

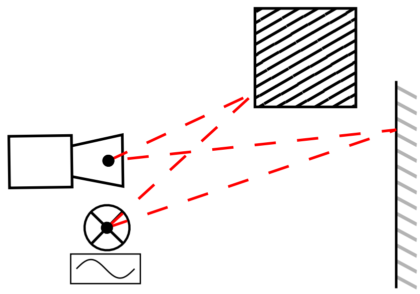
Christoph Hertzberg, Udo Frese, Thomas Röfer

Idealistic Model

- $\psi(t) = a\sin(2\pi\nu t) + c_O$
- $z(t) = \alpha \cdot \psi(t - \Delta t) + c_B$
- $s^{[k]} = \int_{\frac{k}{4\nu}}^{\frac{k+2}{4\nu}} z(t)\,\mathrm{d}t = c_2 + \frac{A}{2}\cos\left(\frac{\pi}{2}k - 2\pi\nu\Delta t\right)$

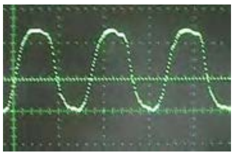
- $A = \sqrt{\left(s^{[0]} - s^{[2]}\right)^2 + \left(s^{[1]} - s^{[3]}\right)^2}$
- $\Delta t = \frac{1}{2\pi\nu}\,\mathrm{atan2}(s^{[1]} - s^{[3]}, s^{[0]} - s^{[2]})$

- $Z = (s^{[0]} - s^{[2]}) + (s^{[1]} - s^{[3]})\mathbf{i}$
- $A = |Z|$
- $\Delta t = \frac{1}{2\pi\nu}\arg Z$



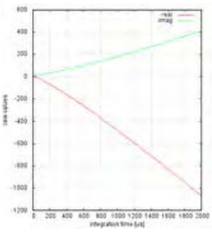
Irregularities

Lens Distortion
Vignetting

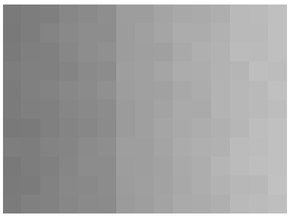


https://www.cayim.com/forum/uploads/monthly_04_2013/post-199-0-71702000-1366139588.jpg

Non sinusoidal light



Non-Linearities



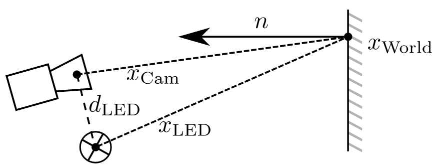
Fixed Pattern Noise

Lens Scattering

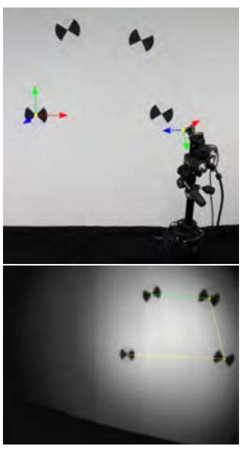
Model

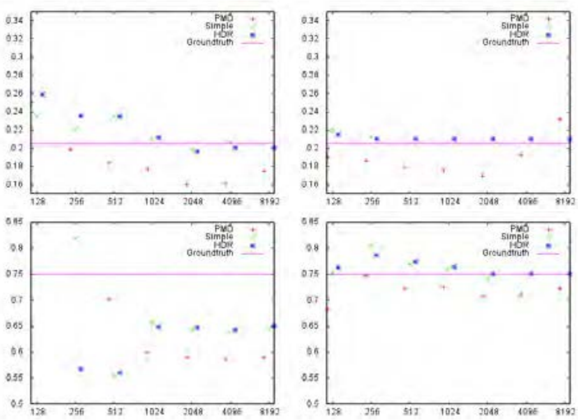
- Vignetting: $\ell_L(x_{\mathrm{LED}})$
- Emitted light: $\psi(t)$ modelled by piece-wise polynomials
  - $\Psi_P(\Delta t) = \int_{\Delta t}^{\Delta t + 0.5} \psi(t)\,\mathrm{d}t$
- Sensor non-linearities g_G using rational polynomials
- Fixed Pattern Noise: Complex factor h_p per pixel

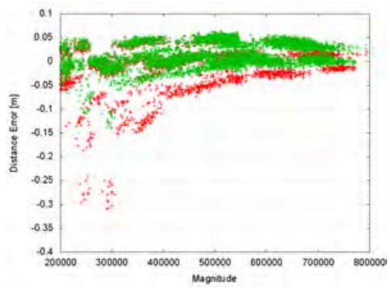
- $A = t_I \cdot \alpha \cdot \ell_L(x_{\mathrm{LED}}) \cdot \frac{\langle x_{\mathrm{LED}}, n\rangle}{\|x_{\mathrm{LED}}\|^3}$
- $\Delta t = \frac{\|x_{\mathrm{LED}}\| + \|x_{\mathrm{Cam}}\|}{\lambda}$
- $Z = h_p \cdot g_G(A \cdot (\Psi_P(\Delta t) + \mathbf{i}\Psi_P(\Delta t + \frac{1}{4})))$
- Unknowns: α, L, $H = (h_p)_{p \in I}$, G, P



Experiments







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R8-[CSpace]

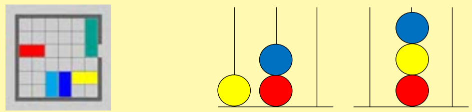
Planning Complexity

PI: Marco Ragni Associates: Rebecca Albrecht, Stefano Bennati, Sven Brüssow, Felix Steffenhagen

Research Question

- Human planning complexity is only investigated empirically.
- Computational Complexity measures don't take human psychological factors into account (e.g. Boolean circuit complexity).
- **Can we find a computational complexity measure that predicts empirical complexity?**

Problem Instances

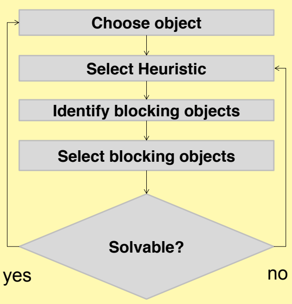


Rush Hour Tower of London

Approach

- Systematic formal investigation of **structural properties** of planning problems represented by **dependency graphs** and **state spaces**.
- Systematic analysis of **representational factors** (e.g. Gestalt Laws).
- Empirical studies of selected problems.
- Analysis of deviations from optimal solutions.
- Analysis of eye-movement patterns.
- Definition of **complexity measure** wrt. Structural and representational factors.
- Statistical analysis of the complexity measure as a predictor for empirical complexity.

Means-End Analysis



Steffenhagen et al. (2014), Albrecht et al. (2011)

Induces

Representational Factors

- Law of Common Fate
- Law of Continuity
- Law of Good Gestalt
- Law of Good Past Experience

Bennati et al. (2014), Albrecht et al. (2014)

Reduce

Dependency Graph (DG)

- **Directed, cyclic graph** (g)
- **Nodes** N**:** Game Objects
- **Edges** $E \subset N \times N$**:** Blocking Structure

Ragni et al. (2011)

Computa-tional

Structural Factors (SF)

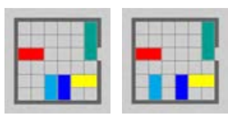
- Cycles
- Branching Factor
- Depth
- DG reconstructions

Ragni et al. (2011)

Results

- **Computational cognitive models** for Rush Hour (Bennati et al. 2013) and Tower of London (Albrecht et al. 2011; 2014).
- Human planning performance depends on
  - **representational complexity** e.g. clusters (Bennati et al. 2014)

Cluster?	Correct (%)	Optimal (%)
Yes	85.4	31.3
No	80.6	77.0

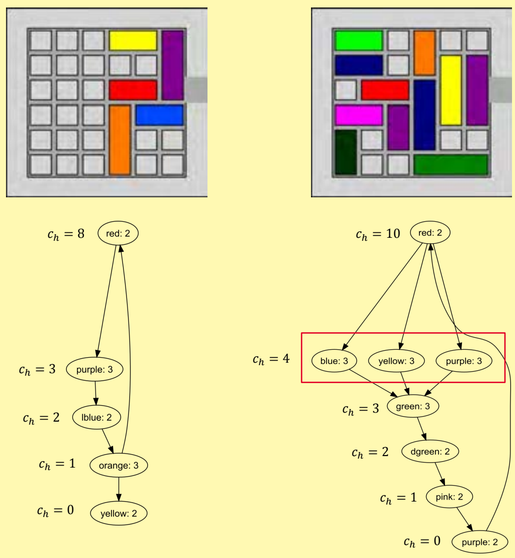


  - **structural complexity** e.g. cycles (Ragni et al. 2011) predictor ($r = .77,\ p < .001$):

$$c_H(n) = \sum_{s \in succ(n)} [c(s) + 1] + \sum_{b \in cycles(n)} depth(b)$$

$$c_H(g) = \sum_{n \in N} c_H(n); \quad c_H(p) = \sum_{g \in sol(p)} c_H(g)$$

Examples



$c_H(g) = 14$ $c_H(g) = 20$

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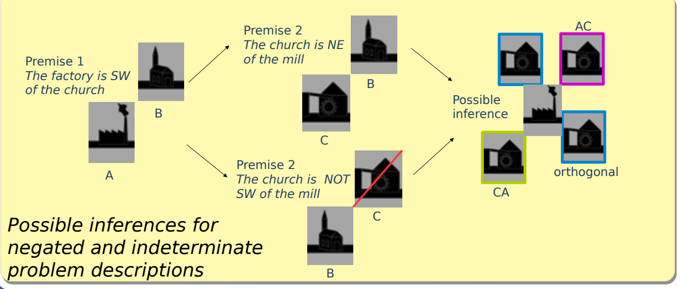
Processing of indeterminacy and negation in reasoning with cardinal directions an fMRI study

R8-[CSpace]

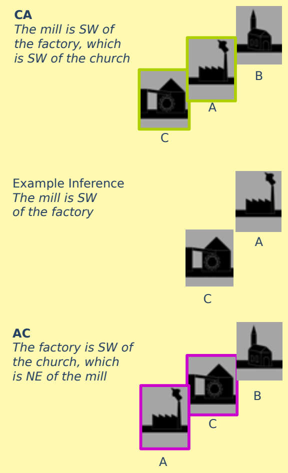
PI: Marco Ragni Associates: Simon Maier & Imke Franzmeier

Neural correlates of indeterminate and negated spatial relations

How are negated and indeterminate relations processed?
Which brain areas are involved in reasoning about indeterminate and negated spatial arrangements in cardinal directions?
Reasoning about determinate descriptions (allowing only one spatial arrangement) recruits mainly the superior parietal lobe (SPL) and the medial frontal gyrus (MFG) [Fangmeier 2006; Prado 2011]. In every day life spatial descriptions are often **indeterminate** [Ragni 2013] (i.e. allowing more than one spatial arrangement).



Possible inferences for negated and indeterminate problem descriptions



***Construction* phase**: In indeterminate cases reasoners tend to build a **preferred mental model** [**PMM**; Ragni & Knauff 2013] of the order **CA** keeping the order of the first premise unchanged (factory SW church) and integrating the third stimulus (mill) northeast of the factory. *This study addresses, whether **CA** is also the PMM for negated descriptions.*

Validation phase: Participants have to decide whether a presented **inference** is consistent given the two previous premises. In indeterminate and negated problems several inferences could be possible.

Model variation: When an inference deviates from the **PMM** reasoners have to vary the model and build an **alternative mental model** [**AMM**; Ragni 2013]. In indeterminate problems the **AC** order is a possible **AMM**. This **variation** is cognitively demanding [Ragni 2007] and involves higher superior parietal lobe (SPL) functioning as **validating** a **PMM**.
*Does the variation of a **PMM** recruit the SPL when solving (negated) problems in **cardinal directions**?*

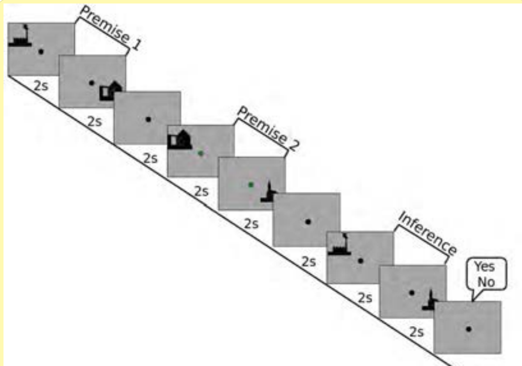
Methods: Testing negated and indeterminate relations

Procedure
- 3 buildings (mill, church, factory) were presented in determinate, indeterminate and negated 3 term reasoning problems (2 premises).
- Premises in four cardinal directions, SW, SE, NE, and NW
- Negated relation were indicated with a red fixation dot
- Subsequently, an inference with stimulus A and C was presented
- In indeterminate and negated problems some inferences were in line with the PMM and some required model variation to build an AMM
- Task: Subjects responded by yes/no button press whether an inference was valid given the 2 premises

MR parameters
- EPI: TR 2 seconds, 38 slices, 3x3x3mm
- Trial duration: 16s
- Variable inter trial interval

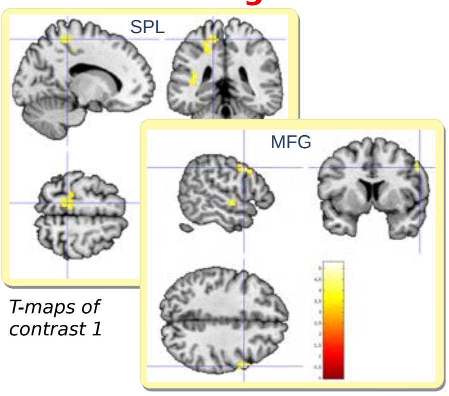
Participants
- 17 right-handed subjects

Data analysis
- Finite Impulse Response (FIR)
- 14 time bins
- Conclusion in time bin 11
- Full factorial mode



Time course of a determinate problem

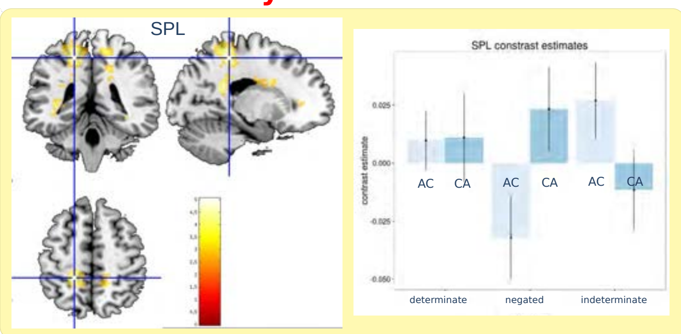
Results: Do negated and indeterminate relations differ functionally?



T-maps of contrast 1

Contrast 1: Which areas are active during model variation?
AC > CA in indeterminate problems:
- *SPL: -15,-42,63; T=4.26; p_{FWE}=0.277; p_{FWE}cluster=0.033**
- *MFG: 57,3,42; T=5.27; p_{FWE}=0.008*; p_{FWE}cluster=0.153*

Contrast 2: Do negated and indeterminate problems differ?
Interaction: problem X inference:
- *SPL: -18,-39,54; T=5.05; p_{FWE}=0.019; p_{FWE}cluster<0.001**



T-maps of contrast 2 with contrast estimates of the SPL peak voxel

Do negated relations result in determinate mental models?

Model variation in indeterminate spatial relational problems involve the SPL and MFG activation
- Increase in late time bins, probably attributable to variation / validation processes
- The SPL might hold spatial relational information [Ragni 2014]
- The MFG might process the application of constraints or rules during model variation
- Reasoning in cardinal directions (large-scale space) involves the same areas as reported for relational reasoning in small-scale spaces
- Higher SPL activation during **CA** in negated problems suggests model variation in this conclusion type
- Reasoners might build a **PMM** of the order **ABC** (instead of **CAB**) in negated problems
- Reasoners might build a determinate **PMM** (ABC) which is then labeled as being "wrong"
- Hence, preferred and alternative mental models in reasoning recruit brain areas that might hold and manipulate the spatial relations of these models

References

Fangmeier T (2006): FMRI evidence for a three-stage model of deductive reasoning. Journal of Cognitive Neuroscience 18:320–334.
Prado J (2011): The brain network for deductive reasoning: a quantitative meta-analysis of 28 neuro-imaging studies. Journal of Cognitive Neuroscience 23:3483–3497.
Ragni M (2007): Preferred Mental Models: How and Why They Are So Important in Human Reasoning with Spatial Relations.
Ragni M, Knauff M (2013): A Theory and a Computational Model of Spatial Reasoning With Preferred. Mental Models. Psychological Review.
Ragni M, Franzmeier I, Maier S (2014): The role of the posterior parietal cortex in relational reasoning. Cognitive Processing.

An exclusively behavioral study on this topic is under revision and the functional study was invited for publication frontiers in neurology

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Exploring the anatomical basis of deductive reasoning with transcranial magnetic stimulation

SPATIAL COGNITION

R8-[CSpace]

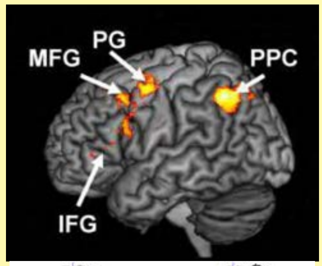
PI: Marco Ragni

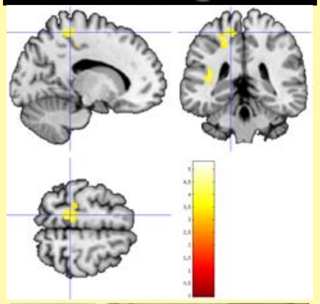
Associates: Imke Franzmeier, Simon Maier

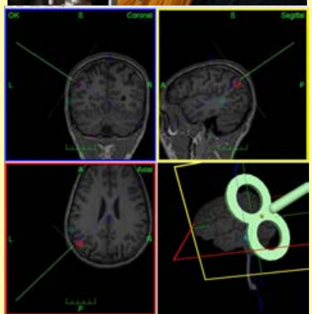
This study is currently under review at the Journal of Cog Neuroscience

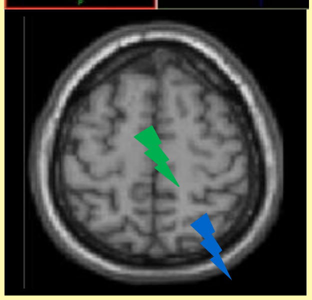
The neuroanatomy of deductive reasoning

- ➢ **The aim of this study was to use transcranial magnetic stimulation (TMS) to explore the role of the parietal lobe in deductive reasoning** (Franzmeier et al., 2014)**.**
- Deductive reasoning consistently activates the bilateral PPC (i.e. the **right SPL** and precunes (BA 7); and the left AG (BA 39) (as shown by the meta-analysis of Prado et al., 2011 and our review, Ragni et al. 2014)
- What is the causal role of the PPC, specifically the SPL, in the construction and manipulation of mental models? → Exploration by **Transcranial Magnetic Stimulation (TMS)**
  - transient & focal disruption of neural processes (Walsh & Pascual-Leone, 2003)
  - compromising performance even on cognitively complex behavioural tasks (e.g. reaction times are slowed ; Franzmeier, 2013)









Is the right SPL involved in mental model processing?

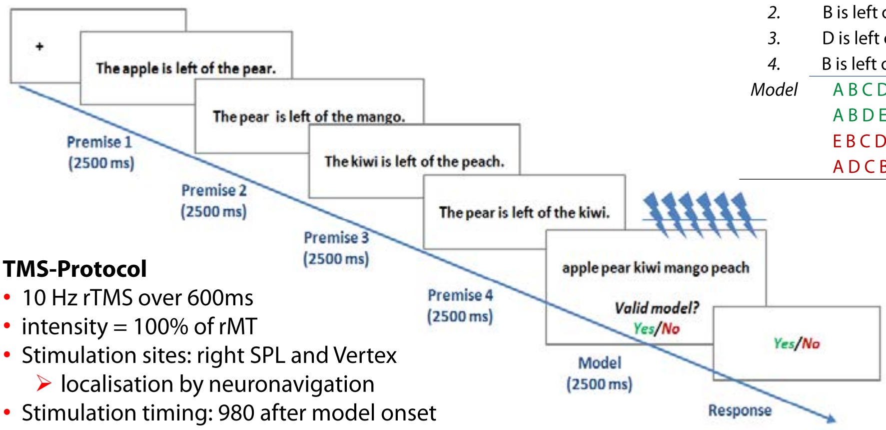
Materials: 72 indeterminate reasoning problems with four different models

Design: 2 × 3

➢ 2 stimulation sites × 3 model types (preferred, alternative, incorrect)

Procedure: 2 subsequent sessions with 36 problems each

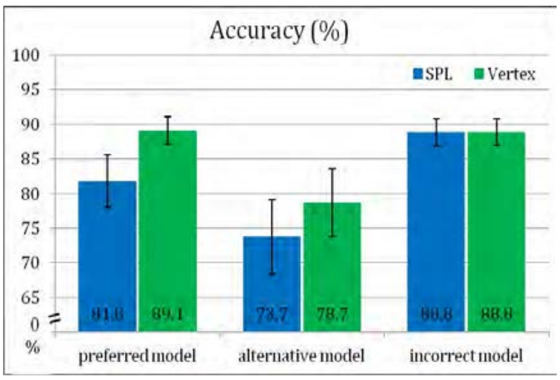
	Presented Stimuli	Model Type
1.	A is left of B	
2.	B is left of C	
3.	D is left of E	
4.	B is left of D	
Model	A B C D E	Preferred mental model
	A B D E C	Alternative model
	E B C D A	Incorrect model (far)
	A D C B E	Incorrect model (middle)



TMS-Protocol

- 10 Hz rTMS over 600ms
- intensity = 100% of rMT
- Stimulation sites: right SPL and Vertex
  - ➢ localisation by neuronavigation
- Stimulation timing: 980 after model onset

Effects of right SPL stimulation on relational reasoning



Participants: 24 right-handed students

Analysis: 2×3 repeated measures ANOVA: stimulation site × model type

Results:

- Effect of stimulation site:
  Vertex > SPL stimulation
- Effect of model type:
  incorrect > correct models
  preferred > alternative models

➢ SPL Stimulation of correct models affected the accuracy, while incorrect models remained unaffected.

Right SPL stimulation affected mental model processing

This experiment provides evidence for the causal role of the SPL in deductive reasoning

- ➢ The validation of correct models depends on mechanisms in the right SPL
- ➢ TMS, which has not been used before for a spatial reasoning paradigm , can be used successfully to investigate complex cognitive processes such as reasoning.

Ongoing work: The same paradigm has been tested in an fMRI study (N=28) and is currently analysed

References

Franzmeier, I. (2013). Neurowissenschaftliche Studien zur semantischen Verarbeitung im Satzkontext. Dissertation. University of Freiburg.

Franzmeier, I., Maier, S. J., Ferstl, E. C. & Ragni, M. (2014). The role of the posterior parietal cortex in deductive reasoning: A TMS study. In OHMB 2014. Human Brain Mapping Conference, Hamburg.

Prado et al. (2011). The brain network for deductive reasoning: a quantitative meta-analysis of 28 neuroimaging studies. *JoCogNeu*, 23(11), 3483–3497.

Ragni, M., Franzmeier, I., Wenczel, F., & Maier, S. (2014). The role of the posterior parietal cortex in relational reasoning. Cognitive Processing.

Walsh & Pascual-Leone, (2003). Transcranial magnetic stimulation: A neurochronometrics of the mind. Cambridge, MA: MIT Press.

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Levels of Spatial Reasoning

SPATIAL COGNITION
R8-[CSpace]

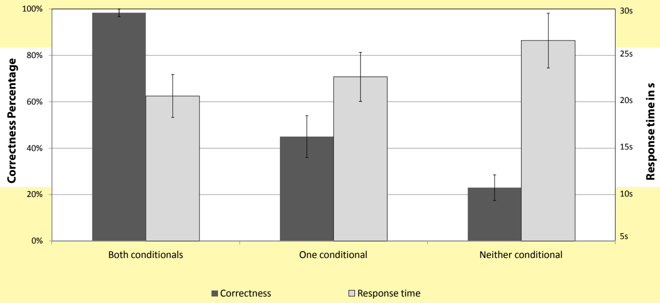
PIs: Marco Ragni, Lars Konieczny

Research Questions

- Why do humans draw specific conclusions and neglect others?
- Where are the associated brain regions for spatial relational reasoning located? Can we distinguish reasoning phases on this level?
- How can reasoning difficulty be modeled?

Behavioral Level

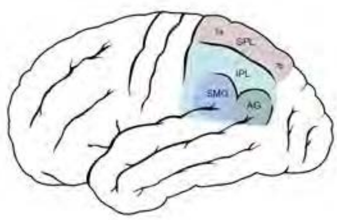
Conflict Detection:



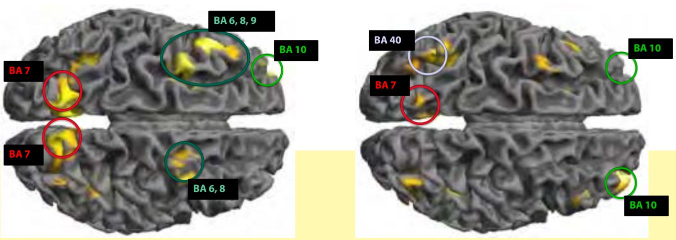
(Ragni, Sonntag, Johnson-Laird, subm.)

Neuronal Level

Our **meta-study** identified the SPL as activated region, assumed to be essential for the construction and manipulation of mental models (Ragni et al., 2014); this was further supported by our TMS- and fMRI-studies (Franzmeier et al., 2014; Maier et al., 2014).



Information Integration (Premise 3) **Information Retrieval** (Conclusion)



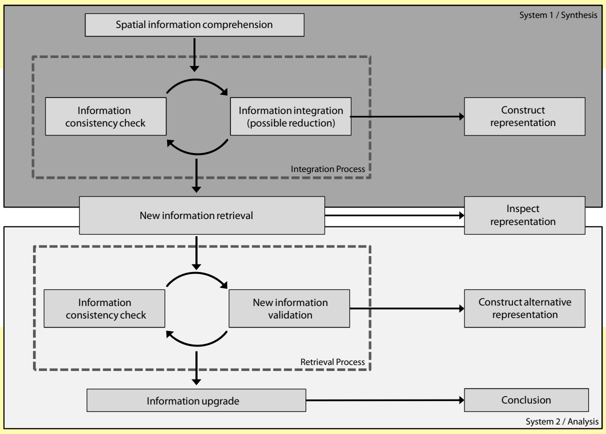
posterior anterior

(e.g., Fangmeier, in prep.)

Future Directions

- Changes in the reasoning process during aging
- Spatial abilities a key factor for general cognitive abilities?
  - → Relevance for education

Information Processing



Methods & Results

Behavioral Level

All phases of the reasoning process investigated

- human processing for conflicting information in ***classical, conditional,* and *quantified* relational reasoning**
  - → **Construction** of specific mental representations
  - → Identification of **conflict resolution** processes in Systems 1 and 2
- combinations of different domains
- accordance with eye movement patterns

Neuronal Level

- Meta-Analysis to identify associated brain regions in relational reasoning (Ragni et al., 2014)
- Findings supported by 3 TMS-Studies (Franzmeier et al., 2014); Visual Impedance Effect in cooperation with M. Knauff
- 3 fMRI-Studies analyzing the processing of indeterminate information and small/large scale space
  - → **SPL** relevant for the manipulation of mental models
  - → **Interplay between different brain regions** supports theory

Computational Level (Cognitive Modeling)

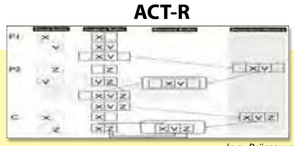
- Mind-Brain-Mapping Analysis of the ACT-R function analyzed
- ACT-R Models and Neural Network Models for relational reasoning
  - → Predicting **reasoning differences**
- Webmodel of PRISM with an extensive data collection

Computational Level

PRISM

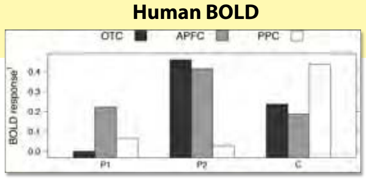
(e.g., Ragni & Knauff, 2013)

ACT-R

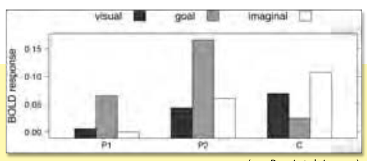


(e.g., Brüssow et al., 2013)

Human BOLD



Predicted BOLD



(e.g., Ragni et al., in prep.)

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New path: Cognitive Robotics

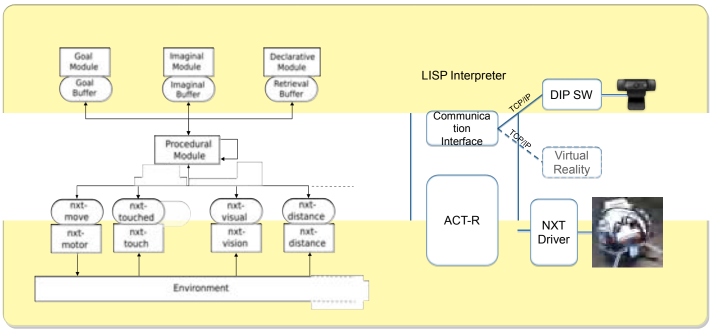
SPATIAL COGNITION
R8-[CSpace]

PI: Marco Ragni Associates: Enrico Rizzardi, Stefano Bennati

Spatial reasoning takes place in an **environment**,
hence understanding spatial complexity depends on the **embodiment** as well

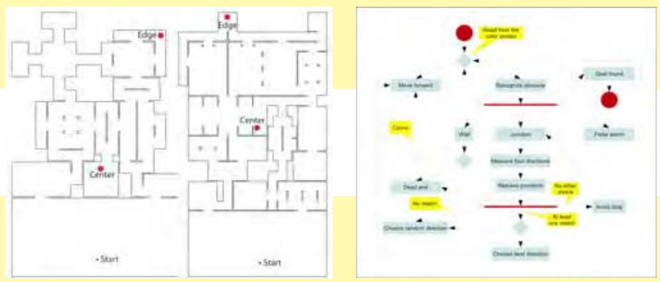
Research Questions

- Humans can **navigate** into an environment, can Cognitive Robots too? How?
- Which **perceptions** are sufficient to perform a navigation task?
- Can a Cognitive Robot show human-like behavior while navigating and searching for a goal?
- Which **platform** can be used to achieve that goal?
- Which are the **advantages** of cognitive robotics over classical robotics?



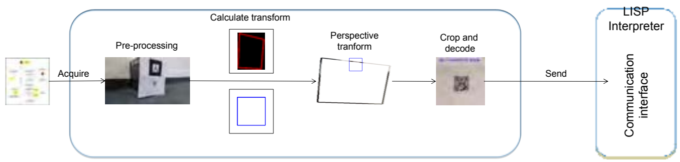
Methods

- **Mind-R**[1,2] as new inexpensive platform for Cognitive Robotics
- A LEGO Mindstorms robot controlled by the cognitive architecture ACT-R
- Navigation can be achieved with very **basic perceptions**
- Interactions with basic sensors and actuators for navigation tasks
- More advanced perception through **visual landmarks**



Results

- **Embodied cognition** by connecting ACT-R with a Cognitive Robot Mind-R
- Extended **ACT-R** with **new modules** to interact with the environment
- The robot simulates the human behavior and **learning strategies**[3] in a labyrinth navigation task
- Cognitive Robotics **used for teaching** purposes, successfully applied in the course "Formal Methods and Programming" WS 2012



Future Directions

- **Communicating Robots**: route description that a second robot has to understand
- Taking **forgetting** into account
- Connecting Mind-R for **spatial relational reasoning models**

1. **Mind-R Website**: http://webexperiment.iig.uni-freiburg.de/mind-r/index.html
2. "How to bouild an inexpensive cognitive robot: Mind-R" Authors E.Rizzardi, S.Bennati, M.Ragni. *Cognitive processing*, CogSci 2014, Tübingen 2014.
3. "Cognitive Robotics: Analysis of Preconditions and Implementation of a Cognitive Robotic System for Navigation Tasks" Authors S.Bennati, M.Ragni. *In Proceedings of the 11th International Conference on Cognitive Modeling*. Universitaetsverlag der TU Berlin, 2012.

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A2-[ThreeDSpace]

Three-Dimensional Map Construction

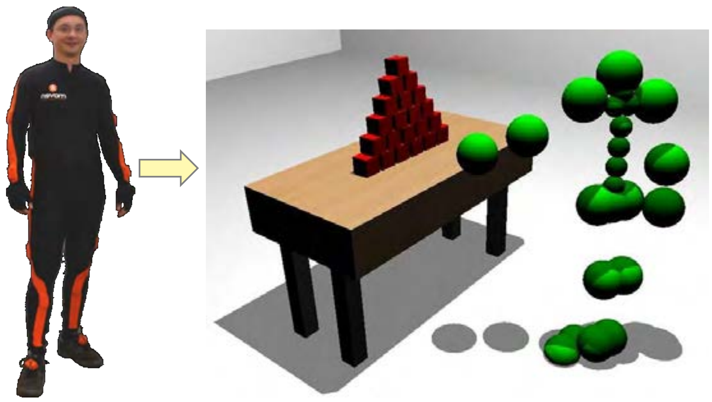
SPATIAL COGNITION
A2-[3D-Space]

Wolfram Burgard, Matthias Teschner

Motivation

- Which objects are relevant for humans?
- How do humans handle objects?

Goal: Reconstruction of 3D environment models from human motion and activity



Key Tasks and Work Packages

Activity Recognition
- static and dynamic gestures

Object representation
- Data structures for reconstruction and interactivity

Environment reconstruction
- Feature extraction
- Data association
- Optimization

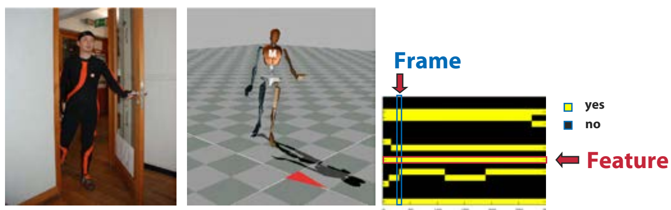
- Activity Recognition (WP 15)
- Reconstruction of Objects (WP 16)
- Data Structures (WP 17)
- Symmetries and Similarities (WP 18)
- Multi-Floor Mapping (WP 19)
- User Interaction (WP 20)
- Enhanced Reconstruction (WP 21)
- Evaluation and Integration (WP 22)

Activity Recognition

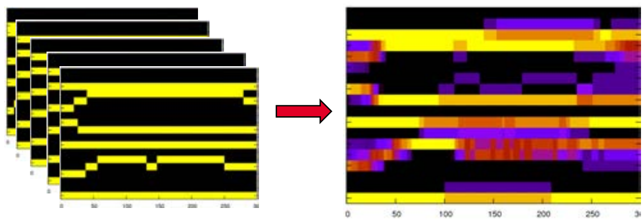
Consider different activities as landmarks describing the environment
- e.g., opening / closing doors, climbing stairs, sitting down, painting along edges, surfaces

Motion Templates for activity recognition:
- Each frame is described by a set of Boolean features (e.g., left foot in front of right foot…)
- Each activity consists of a sequence of frames
- Goal: learn a general motion template from a set of n training examples

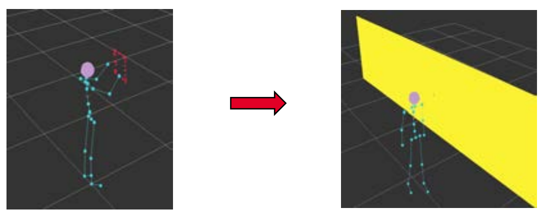
Other activities
- Neural networks for detecting stair climbing
- Painting objects
  left hand on hip, right hand moves along the surface to extract walls, tables, …



Opening a door : person, model, and activity pattern



Motion template generation: dynamic time warping + merge



Activity: paint rectangle   Wall landmark: plane

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Three-Dimensional Map Construction

Wolfram Burgard, Matthias Teschner

A2-[3D-Space]

Reconstruction of Objects

High-quality surface reconstruction from 3D data

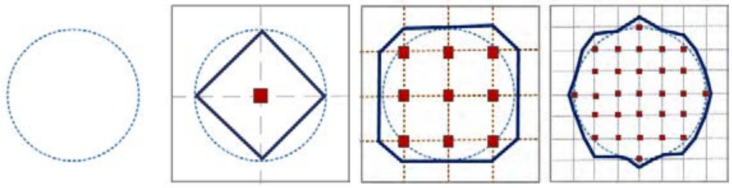
- Scalar field is reconstructed in a narrow band around the surface
  complexity and memory consumption scale with surface instead of volume
- Efficiency is improved by using marching cubes

Efficient post-processing steps

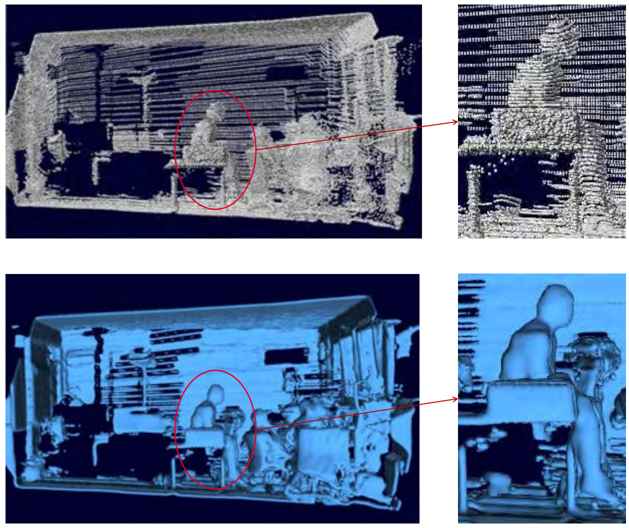
- Surface decimation: alleviates particle-alignment related bumpiness, reduces the number of required triangles in flat regions
- Subdivision: surface smoothing

Results

- Comparison to state of the art
- 15 - 20 x speedup
- 80% less memory required



Implicit representation based on a distance function on a voxel grid



Highly detailed surface mesh reconstructed from 3d point cloud data

Data Structures

Support of efficient insertion, deletion, and update operations

Requirements:

- details and smoothness,
- small memory consumption and computation time

Adaptive instead of uniform grids

- Detail varies in high curvature and flat regions
- 3-level grid structure adapts cells according to curvature of the surface
- Seamless stitching of mesh blocks from cells of different resolution: closing cracks with new triangles

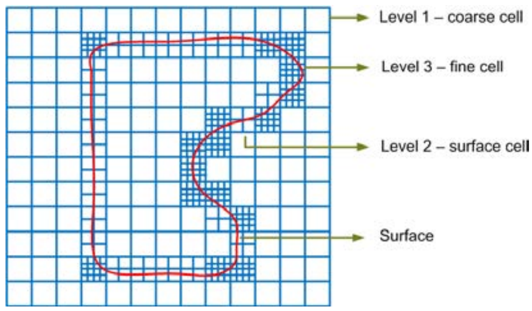
Results

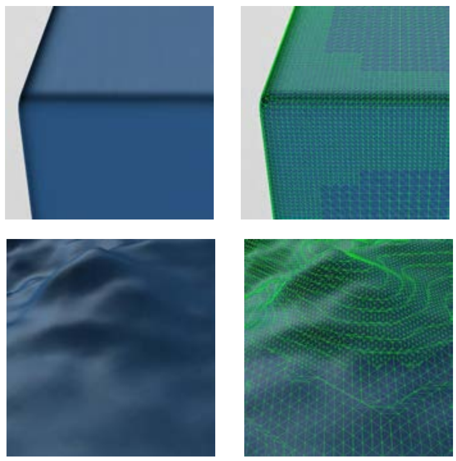
Comparison to single level low-resolution uniform grid:

- Reconstruction of fine details
- Comparable performance (memory, computation time)

Comparison to single level high-resolution uniform grids:

- similar quality,
- up to 4 x less memory, up to 60%faster





Reconstructed surfaces and underlying grid structures

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Three-Dimensional Map Construction

SPATIAL COGNITION

A2-[3D-Space]

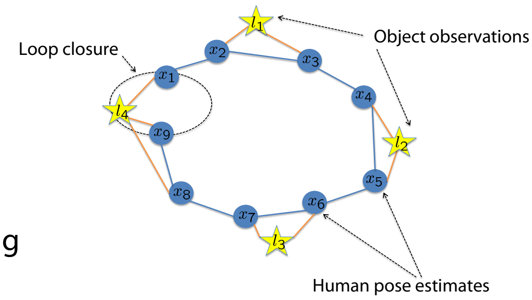
Wolfram Burgard, Matthias Teschner

Environment Reconstruction

Correct for drifts in the suit

Approach

- Landmark detection: doors, chairs, lines, planes
- Nearest neighbor data association
- Optimization: minimize the overall error of the graph using constraints between poses and objects
- Constraints: (co-) planarity, perpendicularity,…

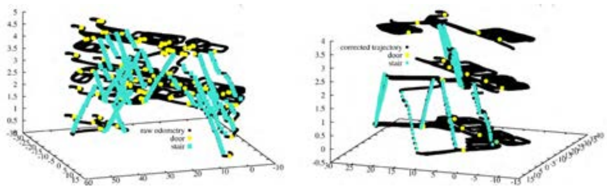


Formulation as graph-based optimization problem

Experimental Evaluation

Multi-Floor Mapping

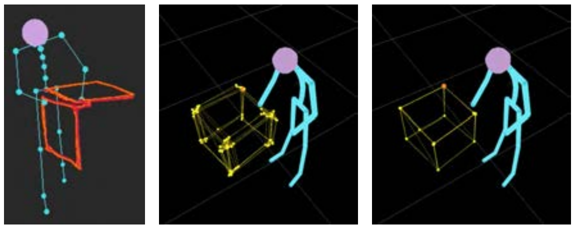
- University building with several floors
- Trajectory length 2.85km
- Door detection: 175 (178) TP, 1FP, average error:1 m±0.41 m
- Stair detection: 411 (473)TP, 0 FP
- Reconstruction matches the floor plans and corrects for drifts in the odometry



Raw odometry and reconstructed environment

Cube 3D

- Extraction of lines and detection of corners along the edges of 0.4x0.4m cube
- Optimization of the corner positions



3D reconstruction: detected corners before and after optimization

Key Publications

- G. Akinci, M. Ihmsen, N. Akinci, M. Teschner. **Parallel Surface Reconstruction for Particle-based Fluids**, *Computer Graphics Forum*, 31 (6), pp. 1797-1809, 2012.
- G. Akinci, N. Akinci, E. Oswald, M. Teschner. **Adaptive Surface Reconstruction for SPH Using 3-level Uniform Grids.** In *Proc. WSCG*, pp. 195-204, June 2013.
- N. Akinci, J. Cornelis, G. Akinci, M. Teschner. **Coupling Elastic Solids with Smoothed Particle Hydrodynamics Fluids.** *Journal of Computer Animation and Virtual Worlds (CAVW)*, 24(3-4), pp. 195-203, CASA 2013 Special Issue, 2013.
- B. Frank, C. Stachniss, R. Schmedding, M. Teschner, W. Burgard. **Learning Object Deformation Models for Robot Motion Planning.** In *Robotics and Autonomous Systems*, 24(8), pp. 1153-1174, 2014.
- S. Grzonka, A. Karwath, F. Dijoux, W. Burgard. **Activity-based Estimation of Human Trajectories.** *IEEE Transactions on Robotics (T-RO)*, 8(1), pp. 234-245, 2012.
- J. Sturm, C. Stachniss, W. Burgard. **A Probabilistic Framework for Learning Kinematic Models of Articulated Objects.** *Journal of Artificial Intelligence Research (JAIR)*, 41, pp. 477-526, 2011.

Collaborations

- A3: Human-motion tracking, building consistent maps, probabilistic models for articulated objects
- R7: Algorithms for parallel architectures, deformable object-fluid interaction, surface reconstructions
- BAALL: Interaction with futuristic environment, evaluation of mapping algorithm

Reasoning	Action	Interaction
R1-[ImageSpace]	**A2-[ThreeDSpace]**	I1-[OntoSpace]
R3-[Q-Shape]	**A3-[Multibot]**	I2-[MapSpace]
R4-[LogoSpace]	A5-[ActionSpace]	I3-[SharC]
R6-[SpaceGuide]	A7-[FreePerspective]	I5-[DiaSpace]
R7-[PlanSpace]	A8-[HumanoidSpace]	I6-[NavTalk]
R8-[CSpace]		

external cooperation (BAALL)

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A3-[Multibot]

Cooperative Human-Robot Exploration

A3-[Multibot]

Cyrill Stachniss, Wolfram Burgard

Objective

- Develop tools to explore unknown areas in cooperative mixed human-robot teams

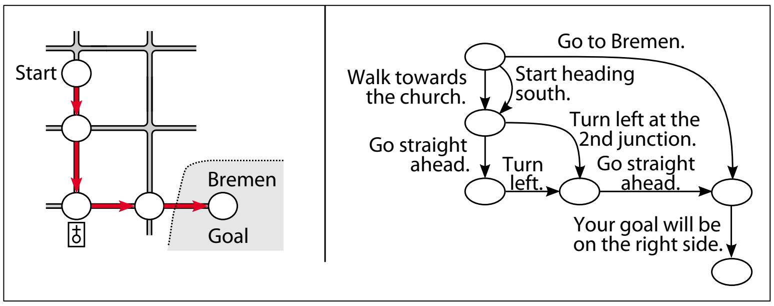
Build Semantic Maps

- Learn semantic maps that combine detected objects with laser and odometry information
- Representation as pose graph allows to propagate pose uncertainties and pose updates
- Build maps by observing human motions, in cooperation with A2-[ThreeDSpace]

Map of an office environment annotated with detected objects

Learn How to Describe Routes from Human Demonstrations

- Learn how to generate natural and intuitive route directions from human demonstrations
- Use inverse reinforcement learning to imitate style and cultural preferences of humans
- A user study suggests that the directions generated by our approach are perceived as highly human-like



Route on a map and corresponding Markov Decision Process representing different ways to describe the given route

Autonomous Robot Exploration

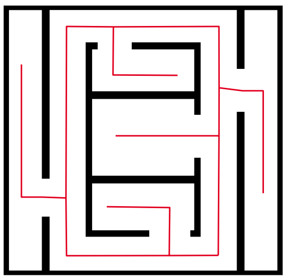
- Temporal symbolic planning for coordinating heterogeneous teams of robots
- Approach that allows robots to autonomously deploy artificial landmarks

} in cooperation with R7-[PlanSpace]

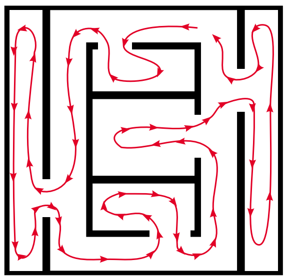
- Approach to quantify spatial ambiguity and to efficiently place landmarks for mobile robot navigation, in cooperation with R6-[SpaceGuide]

Exploration with Human-Provided Background Knowledge

- Exploit human-provided background knowledge for more efficient exploration
- Guide autonomous exploration by drawing a graph of the exploration region



Topologic graph provided by the user



Exploration strategy

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A5-[ActionSpace]

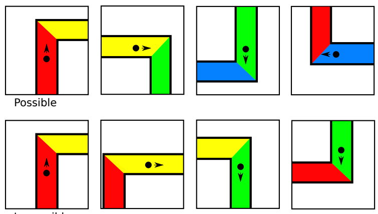
Overview A5-[ActionSpace]: Empirical Results and Experiments

SPATIAL COGNITION
A5-[ActionSpace]

Kerstin Schill

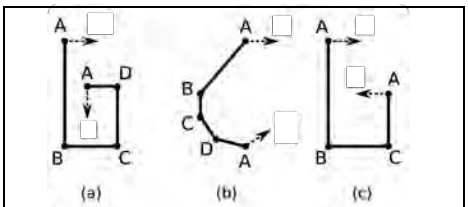
Impossible Worlds

We conducted a series of behavioral studies to investigate the nature of the spatial representation in humans. The experimental paradigm features the use of 'impossible' virtual environments (VE), which include severe violations of Euclidean geometry. The experiments were run with an omnidirectional locomotion input device, the "Virtu-sphere," which is a rotatable 10-foot hollow sphere that allows a subject inside to walk in any direction for any distance, while immersed in a virtual environment.

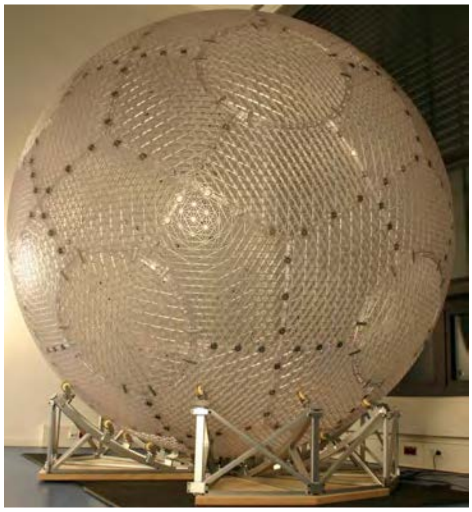


Impossible and possible virtual environments

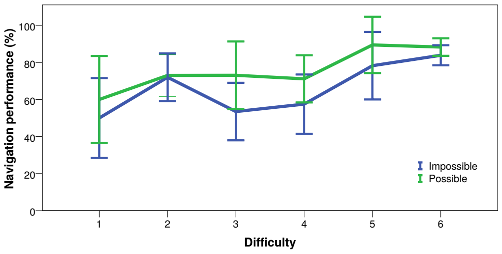
Study 1:
Do spatial violations affect navigation performance?
Study 2:
Which cognitive resources are required when exploring and building mental representations?
Study 3:
Is auditory space included in an integrated mental representation?
Study 4:
Are there differences of the exploration process in impossible VEs compared to possible VEs (in collaboration with i6-[Nav-Talk]?



Impossible Environments


Omnidirectional Input Device "Virtusphere"

Subjects are able to navigate in impossible VEs
The new results resemble our former ones, which have been obtained in a traditional VR-setup without sensorimotor feedback, in basic aspects.

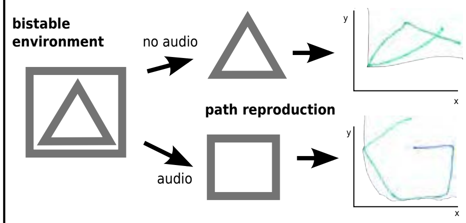


Study 1 navigation performance for impossible and possible worlds, respectively, organized by difficulty of the task.

Indication of a sensorimotor representation of space
Navigation in impossible VEs cannot rely on a map-like spatial representation. A map-like mechanism would be reflected in a breakdown of navigation performance in impossible VEs, because these VEs cannot be represented in a geometrically correct way.
The results indicate that motor/proprioceptive information may be combined with vision to a sensorimotor representation.

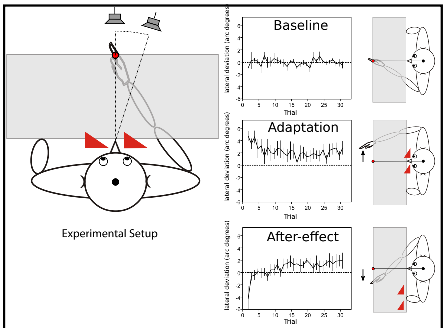
Cognitive Load
The Virtusphere as locomotion interface requires cognitive ressources for the novice users and may thus interfere with judgements about the environments. Nevertheless it remains remarkable how normal subjects behave in the impossible environments, in spite of the associated inconsistencies between vision and sensorimotor information.

Evidence for auditory influences on the representation of mid-scale spatial structures
There is an effect of auditory stimuli on path reproduction results, which applies particularly on VEs that bear a distinct ambiguous or 'bistable' nature. Other VEs are less systematically affected by auditory stimuli.

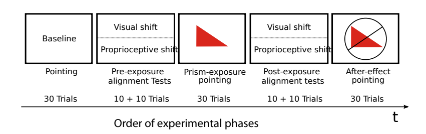


Study 3 Plots of the path reproduction outside of the learning environment are examples.

Multisensorimotor Spatial Alignment of the Senses



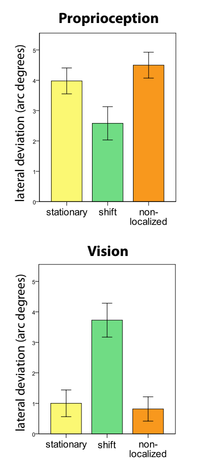
Pointing Task: typical results in baseline, prism-exposure, after-effect phases (example: stationary condition)



Multisensory contributions the sensorimotor calibration
Sensory modalities are usually appropriately aligned in space. audition, vision, and proprioception each direct actions to the same spatial coordinates. Subjects wearing prism glasses that shift the visual input first miss the target in a pointing task, but quickly adapt to the new sensorimotor configuration. This adaptation may take place in (1) the visual or (2) the proprioceptive pathway. Usually, the proprioceptive component is affected, probably due to the often observed dominance of vision over other modalities. This process of adaptation is changed when auditory stimuli are presented during prism exposure: Auditory stimuli lead to a shift of the visual representation. This may be the result of a cortical mechanism performing a statistical reliability estimation, i.e. both audition and proprioception remain unaffected by prism exposure and therefore force vision to realign. We conducted a study using a prism adaptation paradigm to investigate whether sound source localization affects the process of sensorimotor calibration.

Conditions
(1) Stationary: Pointing task was accompanied by auditory stimuli at target position
(2) Shift: Auditory stimulus was shifted by 16.6° (same as prism-offset) under prism exposure

Results
We found a higher contribution of the proprioceptive component compared to the visual one to the adaptation in the stationary and non-localized conditions.
In the shift condition the visual component is dominant. Sound source location affects visuomotor adaptation. Results cannot be explained by a cortical reliability estimation between sensory modalities



Results of the alignment tests in all conditions

Overview A5-[ActionSpace]: Place Cells and Localization

SPATIAL COGNITION
A5-[ActionSpace]

Kerstin Schill

Visually driven Place Cells

Neurobiological findings show that so-called place cells in the hippocampus can be driven by visual input alone. But how exactly can vision support localization? Localization differs in its invariance requirements from other tasks such as object or scene recognition tasks. Therefore, it's not clear which feature vectors used in other areas apply to self-localization tasks.

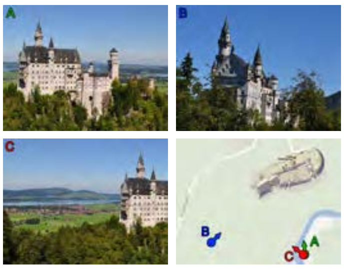


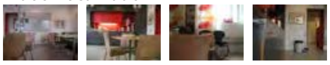
Illustration showing difference between localization and object recognition

Datasets → **Models** → **Classification**

Google StreetView data (world scale, country scale and city scale)

Virtual world screenshot data

Indoor localization



Comparison datasets (Caltech101, Animal/Nonanimal, Scene15)

Landmarks, Sparse features

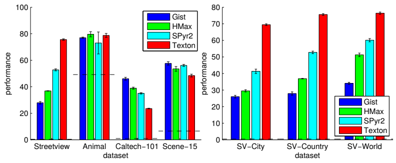
- Object parts (HMax)
- Spatial envelope (Gist)
- Texture distribution (Spatial Pyramids)
- Texture histogram (Textons)
- Luminance Histogram

Holistic image descriptors, Image statistics

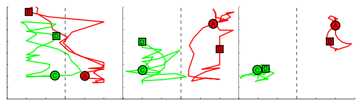
One-versus-all - Linear Regression

Poor performance on landmarks

Strong performance on statistics



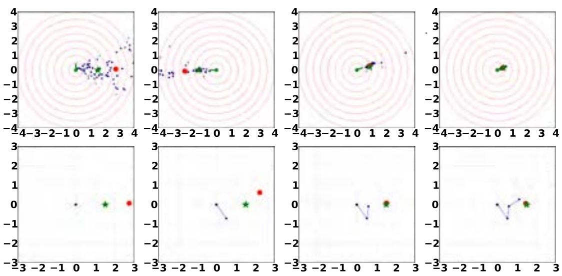
Space untangling by holistic descriptors

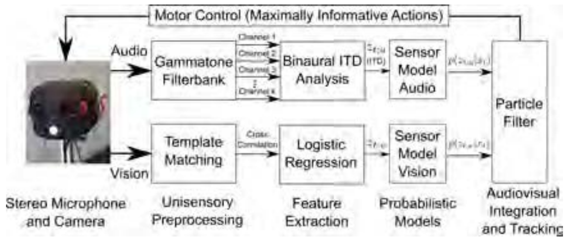


Audiovisuomotor Source Localization

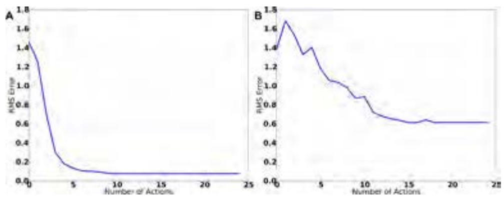
- **Active** audio-visual source localization (2d: azimuth and distance) for use on a mobile robot.
- **Information Gain mechanism** is used for the selection of the most informative action in each step.

System Behaviour





Results: RMS error Information Gain vs Random



Evidential SLAM

Uncertainty in SLAM is usually represented probabilistically. However, this can lead to ambiguities: Is an occupancy probability of 0.5 the result of missing or conflicting measurements? We have developed a SLAM approach based on Dempster-Shafer theory which avoids this ambiguity by introducing additional dimensions of uncertainty.

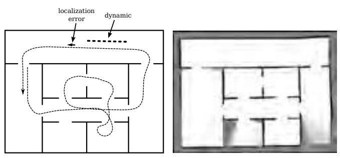
$$\underbrace{m[z_{0:t}, u_{1:t}](x_{0:t}, Y)}_{\text{path/map belief}} = \underbrace{p(x_{0:t}|z_{0:t}, u_{1:t})}_{\text{path belief}} \underbrace{m[x_{0:t}, z_{0:t}](Y)}_{\text{map belief}}$$

$$\underbrace{p(x_{0:t}|z_{0:t}, u_{1:t})}_{\text{path posterior}} \propto \underbrace{pl[x_{0:t}, z_{0:t-1}](z_t)}_{\text{evidential likelihood}} \underbrace{p(x_{0:t}|z_{0:t-1}, u_{1:t})}_{\text{path prior}}$$

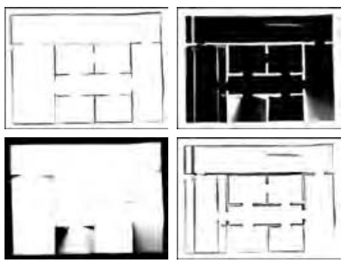
$$\underbrace{m_{\Theta_Y^M}[x_{0:t}, z_{0:t}]}_{\text{map belief}} = \underbrace{m_{\Theta_Y^M}[x_t, z_t]}_{\text{inverse model}} \circledast \underbrace{m_{\Theta_Y^M}[x_{0:t-1}, z_{0:t-1}]}_{\text{map prior}}$$

$$\underbrace{m_{\Theta_Y^M}[x_{0:t}, z_{0:t}]}_{\text{map belief}} = \bigoplus_{i=1}^{M} \underbrace{m_{\Theta_{Y;i}}[x_{0:t}, z_{0:t}]}_{\text{grid cell belief}}$$

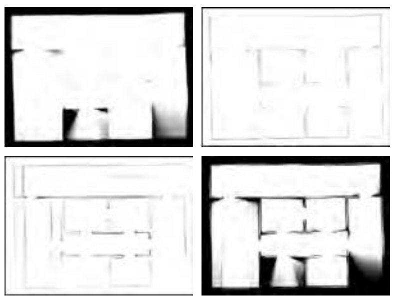
These equations can be approximated by an evidential Rao-Blackwellized particle filter.



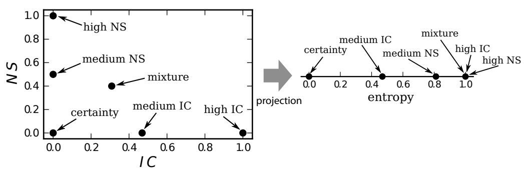
ground truth — probabilistic map



evidential map



uncertainty measures



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Overview A5-[ActionSpace]: Visuomotor Spatial Perception

SPATIAL COGNITION
A5-[ActionSpace]

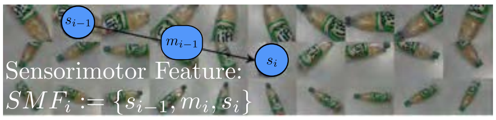
Kerstin Schill

Sensorimotor Object Recognition in 3D Space

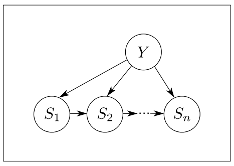
Sensorimotor Approach

Classical views of perception consider only sensory features, as do most object recognition approaches. We propose a probabilistic object recognition approach integrating sensory and motor information in one representation. The recognition system controls a camera attached to a robotic arm in order to obtain different views on an object. Arm movements are generated by minimizing the expected entropy of the posterior distribution over object classes.

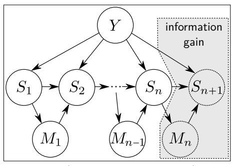
Sensorimotor Features



Bayesian Inference



BN1 (without motor information)
$P(y|s_{1:n}) \propto P(y)P(s_1|y)\prod_{i=2}^{n} P(s_i|s_{i-1},y)$



BN2 (with motor information)
$P(y|s_{1:n}, m_{1:n-1})$
$\propto P(y)P(s_1|y)\prod_{i=2}^{n} P(s_i|s_{i-1},m_{i-1},y)P(m_{i-1}|s_{i-1})$

Information Gain

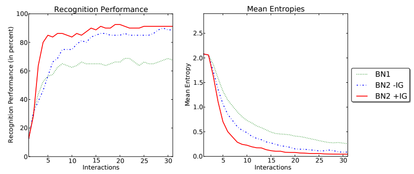
The information gain is defined based on mutual information:

$$IG(m_n) := H(Y|s_{1:n}, m_{1:n-1}) - H(Y|S_{n+1}, m_n, s_{1:n}, m_{1:n-1})$$

Action selection is based on minimizing the expected entropy:

$$m^* = \arg\min_{m_n}\big(\underset{S_{n+1}}{E}[H(Y|s_{1:n}, S_{n+1}, m_{1:n})]\big)$$

Application and Results



Spatial Numerosity

The estimation of the cardinality of objects in a spatial environment requires a high degree of invariance. Numerous experiments showed the immense abstraction ability of the numerical cognition system.

Here we try to approach numerosity from a mathematical perspective. Based on concepts and quantities like connectedness and Gaussian curvature, we provide a general solution to number estimation and apply it to visual stimuli. We show that the estimation only requires derivatives of the luminance function and a multiplicative AND-like combination of these features, which can be realized by neurophysiologically realistic Gabor-like filters and by the neural mechanism of cortical gain control.

$$\int_S K\, dS = \int_{\mathbb{R}^2} \underbrace{\frac{l_{xx}(x,y)l_{yy}(x,y) - l_{xy}(x,y)^2}{(1+l_x(x,y)^2+l_y(x,y)^2)^{3/2}}}_{=:\tilde{K}(x,y)} \chi_S(\phi(x,y))\, d(x,y),$$

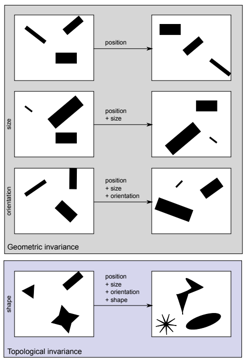
where χ_S is the characteristic function with respect to the set S, and

$$\int_C \kappa_g\, ds = \int_{\mathbb{R}} \underbrace{\frac{l_x^2 l_{yy} + l_y^2 l_{xx} - 2l_x l_y l_{xy}}{(l_x^2+l_y^2)^{3/2}(1+l_x^2+l_y^2)^{1/2}}}_{=:\tilde{\kappa}_g(x(t),y(t))} (x'^2+y'^2)^{1/2} \chi_C(c(t))\, dt,$$

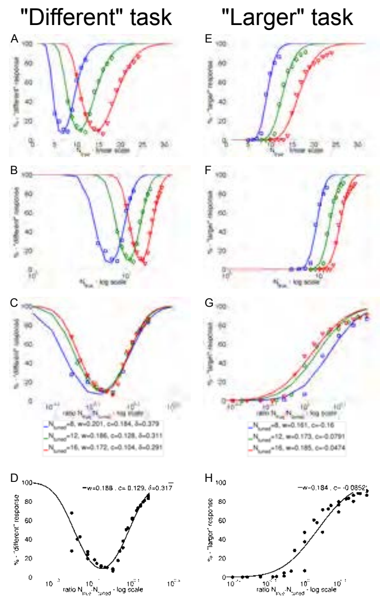
where χ_C is the characteristic function with respect to the set C.

$$2\pi n = \int_{\mathbb{R}^2} \tilde{K}(x,y)\tilde{\chi}_S(x,y)\, d(x,y) + \int_{\mathbb{R}} \tilde{\kappa}_g(x(t),y(t))\tilde{\chi}_C(x(t),y(t))\, dt.$$

Invariance



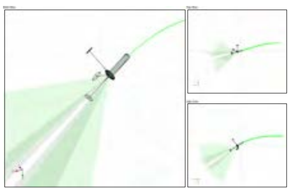
Computational experiments



Future Activities

Space Exploration

Active Localization - Multisensory Processing - Evidential SLAM



Assistance Systems

Sensorimotor representation - Route optimization based on cognitive complexity

Spatial Models in Impossible Worlds

SPATIAL COGNITION

A5-[ActionSpace]

Thorsten Kluss, Tim Hantel, William E. Marsh, Christoph Zetzsche

Impossible Worlds Studies

To investigate mental representations of novel environments, Zetzsche et al. (2009) asked participants using to explore and learn virtual worlds that violated rules of Euclidean geometry and planar topology. Results showed that the "impossibility" of the environment neither affected shortest-path judgements nor could it be recognized by the subjects under forced-choice conditions. These findings indicate that humans do not form image-like cognitive maps - in spite of having the necessary metric knowledge available. An alternative is some form of sensorimotor representation, but it is neither clear how these alternative representation is organized in detail, nor how the results would be influenced if full-body movement and natural sensorimotor feedback would interact with the impossible environments.

We conducted a series of behavioral studies to investigate the nature of the spatial representation in humans. The experimental paradigm features the use of 'impossible' virtual environments (VE), which include severe violations of Euclidean geometry. The experiments were run with an omnidirectional locomotion input device, the "Virtusphere," which is a rotatable 10-foot hollow sphere that allows a subject inside to walk in any direction for any distance, while immersed in a virtual environment.

The main questions were (1) the influence of spatial violations on navigation performance[1], (2) which cognitive resources were required when exploring and building mental representations[3], and (3) the question, whether auditory space is included in an integrated mental representation [2, 4].

Method

(1) Training trials
(2) Exploration and memorization of possible and impossible VEs
(3) Different tasks, such as:
a) finding the shortest path from one landmark to another
b) reproducing the route outside the learning environment
c) drawing sketches of the VE
d) spatial or verbal cognitive tasks
(4) Interview/Questionnaire

Several **Conditions** were compared to each other:
a) impossible vs. possible VEs
b) VEs including auditory landmarks vs. visual-only VEs
c) increasing complexity of VEs
d) increasing difficulty of the tasks

Fig. 1 Omnidirectional Locomotion Input Device (Virtusphere)

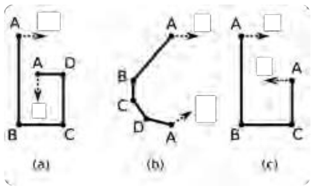


Fig. 2a Impossible Environments

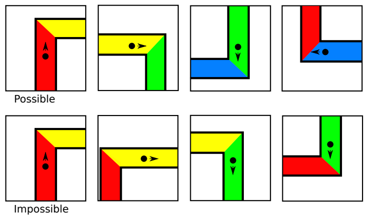


Fig. 2b Possible and impossible virtual environments

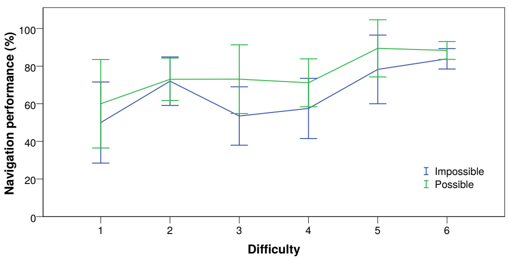


Fig. 3 Study 1 shortest path scores for impossible and possible worlds, respectively, organized by difficulty of the starting position (1 is closest to the symetry point). Performance was similar to the results of the 2009 study, but slightly lower from the more difficult starting positions. (Error bars show +/-1 standard deviation of the mean).

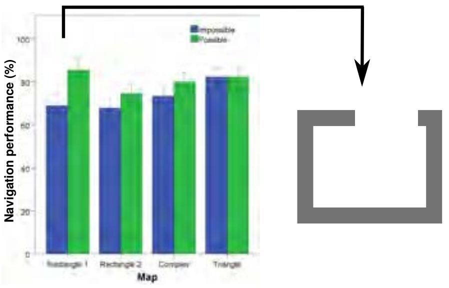


Fig. 4 Study 1 shortest path scores for each map. Performance varied between maps, indicating that characteristics of the maps should be further investigated for their role in the formation and recall of mental representations.

Results & Discussion

Subjects are able to navigate in impossible VEs

The new results resemble the former ones [1], which have been obtained in a traditional VR-setup without sensorymotor feedback, in basic aspects but also show new effects. Since shortest path performance is not systematically affected by the impossible environments there is no indication for the breakdown that would have to be expected if inconstent information from impossible environments would be forced into an image-like map (Fig. 3). However, we found differences on the level of individual environments (Fig. 4). Further studies are reqired to investigate, in how far this could be attributed to the conflicts between ideothetic and allothetic information arising with impossible environments. [1, 3]

Cognitive Load

The Virtusphere as locomotion interface requires cognitive ressources for the novice users and may thus interfere with judgements about the environments. Nevertheless it remains remarkable how normal subjects behave in the impossible environments, in spite of the associated inconsistencies between vision and sensorimotor information [3]. In fact, most participants did not even notice the violations of geometry (s. Fig.).

Indication of a sensorimotor representation of space

Navigation in impossible VEs cannot rely on a map-like spatial representation. A map-like mechanism would be reflected in a decrease of navigation performance in impossible VEs, because these VEs cannot be represented in a geometrically correct way. The results indicate that motor/proprioceptive information may be combined with vision to a sensorimotor representation.

Evidence for auditory influences on the representation of mid-scale spatial structures

There is an effect of auditory stimuli on path reproduction results, which applies particularly on VEs that bear a distinct ambiguous or 'bistable' nature (s. Fig. 5). Other VEs are less systematically affected by auditory stimuli.

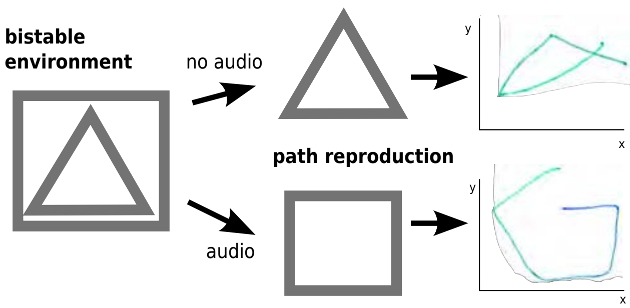


Fig. 5 Results. Plots of the path reproduction outside of the learning environment are examples.

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The visual signature of a place

SPATIAL COGNITION

A5-[ActionSpace]

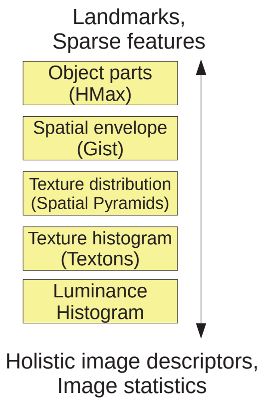
Sven Eberhardt (sven2@uni-bremen.de), Christoph Zetzsche and Kerstin Schill

Place Cells

The ability to make reliable assumptions about their own position in the world is of critical importance for biological as well as for man-made systems such as mobile robots.
Vision is of particular importance for localization, as becomes evident in cases where no reliable prior information about past location is available, e.g. if we need to find our way home after getting lost.
Neurobiological findings show that so-called place cells in the hippocampus can be driven by visual input alone. But how exactly can vision support localization?[1][2]

Models

- Distinct biologically inspired vision models provide visual feature descriptors.
- Descriptors may either respond only to a select number of distinct features (landmark-based) or build histograms over more common features (Holistic descriptors).
- Models from different areas in human visual system modeling are tested on the localization task: Animal detection (HMax)[3], Scene recognition (Gist[4], Spatial Pyramids[5]), Image segmentation (Textons[6])
- Output vectors tested on localization task using one-versus-all linear regression[7]



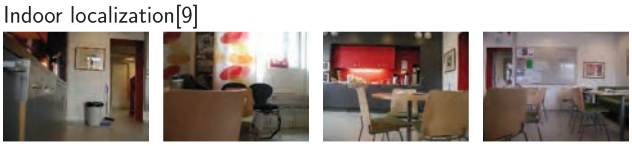
Datasets

Results validated on a wide range of datasets.

- Google StreetView data at world scale, country scale and city scale

- Virtual world screenshot data[8]

- Indoor localization[9]



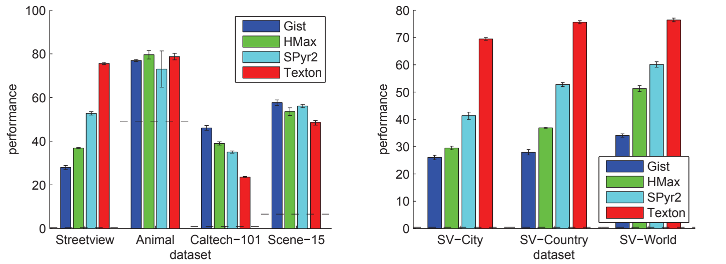
- Comparison datasets: Caltech101, Serre Animal/Nonanimal, Scene15

Localization task

Localization differs in its invariance requirements from other tasks such as object or scene recognition tasks. Therefore, it's not clear which feature vectors used in other areas apply to self-localization tasks.[10]

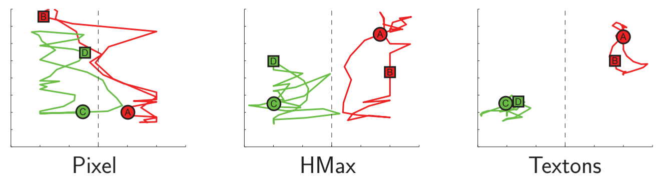
Results

Performances



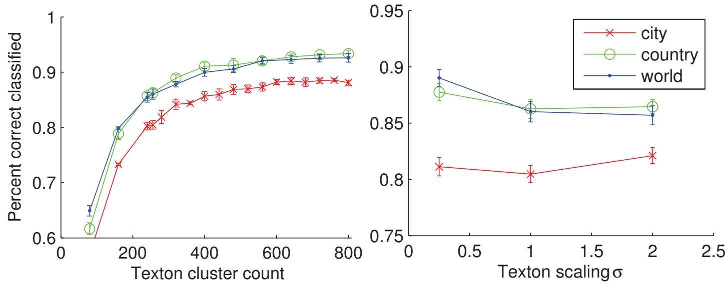
- Simple texture statistics sufficient to provide a strong prior for the self-localization tasks.
- Statistics of common outdoor features: Tree density, foliage type or road structure stronger than landmarks
- Use of such common feature vectors as priors for self-localization systems
- Stable across all datasets (indoor, virtual, streetview) and scales

Location untangling



- Models that separate locations well untangle the space and cause little variation as the observer rotates.

Texton performance



- Small number of clusters (500) sufficient for accurate classification
- Texture sampling from very small image areas ($\sigma = 0.5$) outperforms larger patches

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[10]Photos: ©Stephen & Claire Farnsworth via flickr, license CC-BY-NC. Map: Google maps ©Google inc.

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Information-Driven Audio-Visual Source Localization on a Mobile Robot

SPATIAL COGNITION
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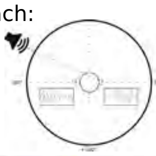
Introduction

- **Active** audio-visual source localization (2d: azimuth and distance) for use on a robot.
- **Information Gain mechanism** is used for the selection of the most informative action in each step.
- Combination of consecutive auditory and visual measurements into a single estimate of the source's position by **particle filtering**
- System is suitable for use in **complex and cluttered environments**, which require movement to detect and disambiguate all possible sources.

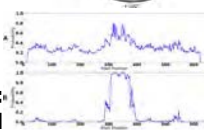

Pioneer P3-DX

Method

- Pioneer P3DX robot
- **Rotatable Head** equipped with **realistic human-like pinnae**
- Robot is equipped with **stereo microphones** inserted directly into the ears, mimicking the human outer ear system (pinna, auditory canal and eardrum) and a **stereo camera**
- **Auditory Processing:**
  - Transformation into a biologically plausible time-frequency representation (**cochleagram**) by a gammatone filterbank
  - **Source Localization** by classic binaural analysis approach: **Interaural time differences** (ITDs)

- **Visual Processing:**
  - Object Detection: **Template Matching** for detection of arbitrary object classes
  - **Logistic Regression** to calculate probabilities for the presence of the source using template matching results based on cross-correlation



- **Multisensory Integration with Particle Filtering:**
  - Probability density function **(PDF) is approximated** by a set of samples (particles)
  - **Integration** of **auditory and visual** measurements
  - **Temporal integration** of consecutive measurements
  - Sensor model for audition designed to enforce front/back confusion

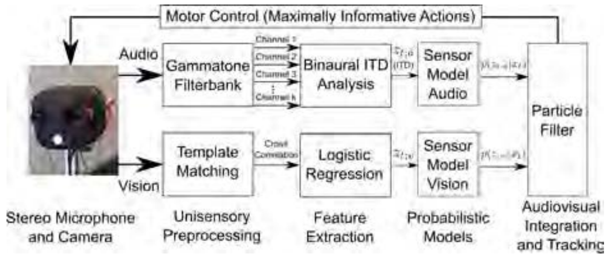
$$\overline{bel}(x_t)=\sum_{x_{t-1}} p(x_t|u_t,x_{t-1})\,p(x_{t-1}|z_{0,t-1},u_{0,t-1})$$

Prediction Step

$$p(x_t|z_{0,t},u_{0,t})=\alpha\, p(z_t|x_t)\,\overline{bel}(x_{t-1})$$

Correction Step

- **Action Selection** by **Information Gain** mechanism
  - System chooses the **most informative action** with respect to current particle distribution; **Minimization of the entropy** of PDF estimate
  - Calculation: Actions are sampled randomly; **Simulates movements** (→ prediction step) **and measurements** (→ correction step) using motion- and sensor model



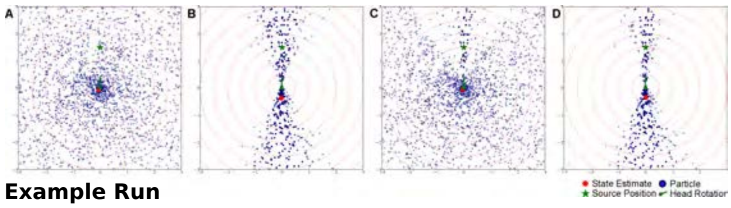
System Overview

Discussion

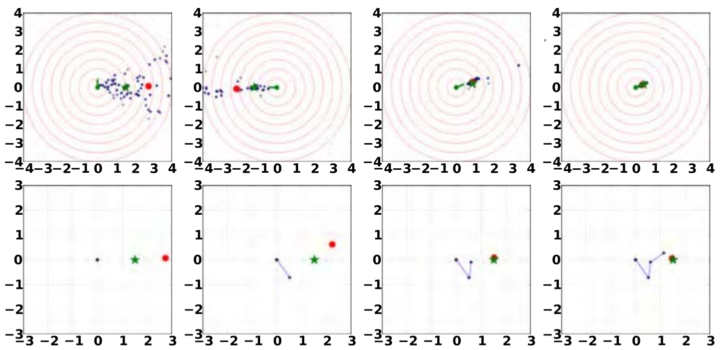
- System is able to **accurately estimate azimuth and distance** of the source, despite simplified unisensory processing and "enforced" front-back-mixups in audition
- **Few actions** needed for accurate estimates
- **Robot estimates distance** of a source without explicit measurements: particle filter combines multiple measurements of angles from different positions into a distance estimate.
- **Entropy** of the estimated PDF **decreases** with each performed action: number of actions needed to achieve an accurate estimate is minimized
- **Reasonable multisensory behaviour**: System utilizes audition to reduce number of hypotheses and vision to achieve better estimates
- Robot systematically approaches source to improve accuracy
- **Alternative** to expensive **microphone arrays (audition)** for mobile robots equipped with cost-efficient standard sensors
- **Applications**
  - **Speaker detection** in automatic camera control systems
  - **Rescue Robotics**
- **Future Work**
  - *Source Separation:* **Multiple dynamic sources**
  - *Localization in* ***median plane***: utilizing filter characteristics of the artificial pinnae (position-dependent HRTF)

Results

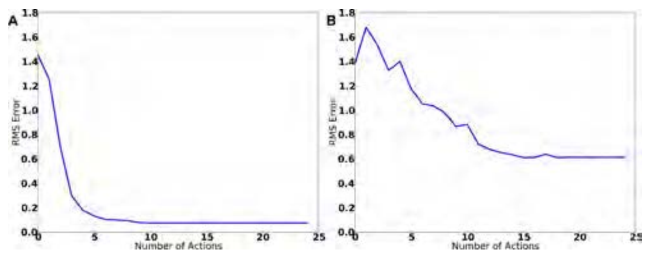
Multisensory Updates



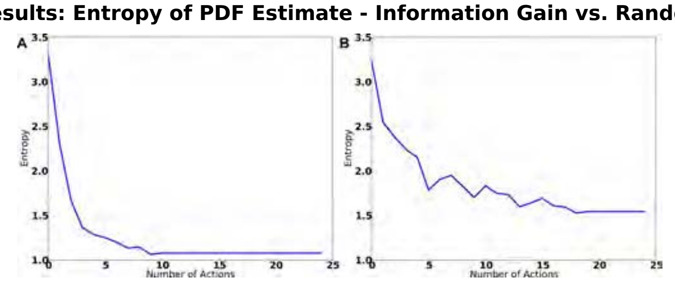
Example Run



Results: RMS Error - Information Gain vs. Random



Results: Entropy of PDF Estimate - Information Gain vs. Random



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Evidential SLAM: Dimensions of Uncertainty in Grid Maps

SPATIAL COGNITION
A5-[ActionSpace]

Thomas Reineking, Joachim Clemens

Evidential FastSLAM

Motivation

Uncertainty in SLAM is usually represented probabilistically. However, this can lead to ambiguities: Is an occupancy probability of 0.5 the result of missing or conflicting measurements? We have developed a SLAM approach based on Dempster-Shafer theory which avoids this ambiguity by introducing additional dimensions of uncertainty.

Belief Functions

Belief functions are defined on the power set of the hypothesis space. Mass assigned to the disjunction of "occupied" and "empty" corresponds to a lack of evidence. In contrast, mass assigned to the empty set corresponds to conflicting evidence.

$$m : \mathcal{P}(\Theta_Y) \to [0,1] \text{ with } \Theta_Y = \{o, e\}$$

$$pl(Y) = \sum_{Y \subseteq \Theta_Y, Y \neq \emptyset} m(Y)$$

Evidential SLAM

Numerous works on mapping based on belief functions exist, however, none have dealt with the joint estimation problem of SLAM.

$$\underbrace{m[z_{0:t}, u_{1:t}](x_{0:t}, Y)}_{\text{path/map belief}} = \underbrace{p(x_{0:t}|z_{0:t}, u_{1:t})}_{\text{path belief}} \, \underbrace{m[x_{0:t}, z_{0:t}](Y)}_{\text{map belief}}$$

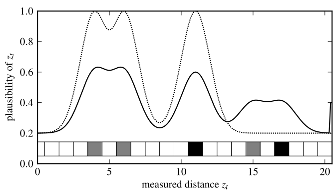
$$\underbrace{p(x_{0:t}|z_{0:t}, u_{1:t})}_{\text{path posterior}} \propto \underbrace{pl[x_{0:t}, z_{0:t-1}](z_t)}_{\text{evidential likelihood}} \, \underbrace{p(x_{0:t}|z_{0:t-1}, u_{1:t})}_{\text{path prior}}$$

$$\underbrace{m_{\Theta_Y^M}[x_{0:t}, z_{0:t}]}_{\text{map belief}} = \underbrace{m_{\Theta_Y^M}[x_t, z_t]}_{\text{inverse model}} \circledast \underbrace{m_{\Theta_Y^M}[x_{0:t-1}, z_{0:t-1}]}_{\text{map prior}}$$

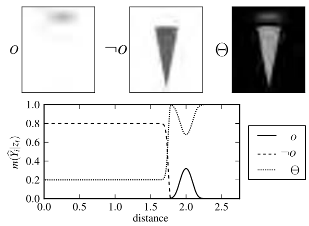
$$\underbrace{m_{\Theta_Y^M}[x_{0:t}, z_{0:t}]}_{\text{map belief}} = \bigoplus_{i=1}^{M} \underbrace{m_{\Theta_{Y;i}}[x_{0:t}, z_{0:t}]}_{\text{grid cell belief}}$$

Approximation based on a Rao-Blackwellized particle filter

Forward Sensor Model



Inverse Sensor Model



Dimensions of Uncertainty

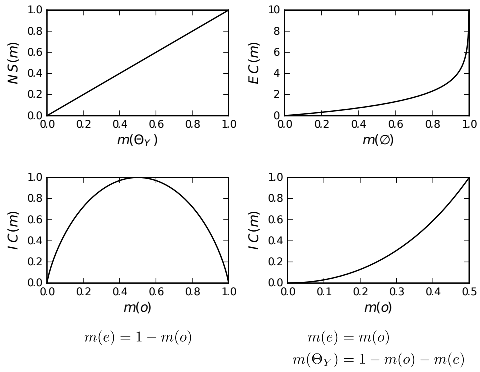
For normalized belief functions, there are two dimensions of uncertainty: non-specificity and conflict. Nonspecificity can be quantified by the Hartley measure while there are different possible measures for conflict. Because we are allowing for unnormalized belief functions (mass can be assigned to the empty set), we further distinguish between internal conflict (related to entropy) and external conflict (resulting from combining conflicting pieces of evidence).

$$NS(m) = \sum_{Y \subseteq \Theta_Y, Y \neq \emptyset} m(Y) \log |Y| = m(\Theta_Y)$$

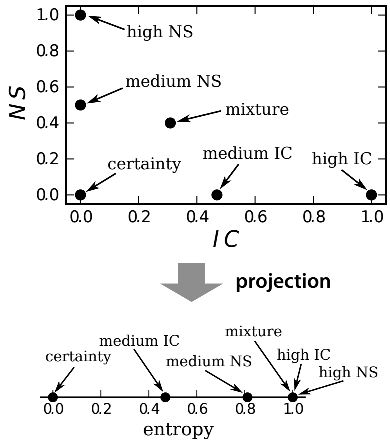
$$IC(m) = -\sum_{Y \subseteq \Theta_Y} m(Y) \log \frac{pl(Y)}{1 - m(\emptyset)}$$

$$EC(m) = -\log(1 - m(\emptyset))$$

Evidential Uncertainty Measures

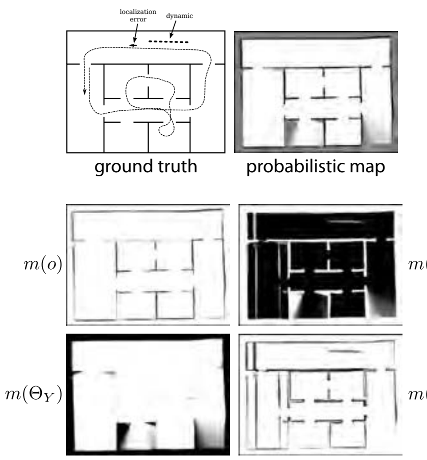


Relation to Entropy

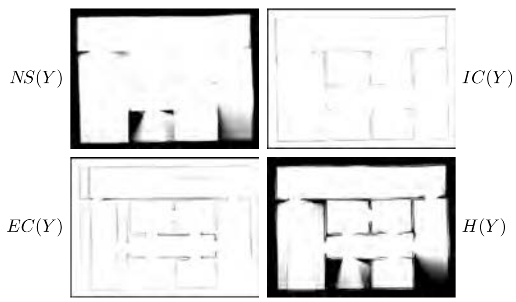


Results and Applications

Additional dimensions of uncertainty can make effects like localization errors and dynamics in the environment explicit which would otherwise be lost.



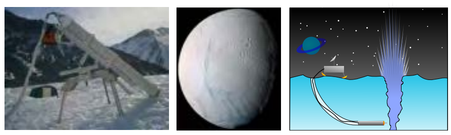
evidential map



uncertainty measures

Application in Space Exploration

The evidential SLAM approach is applied in the context of the "Enceladus Explorer" project where an autonomous melting probe is supposed to analyze samples from the Saturn moon Enceladus in order to search for extraterrestrial life. The evidential SLAM approach is used to map an environment about which very little is known in advance and to extract as much information as possible.



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Affordance-based object recognition using interactions obtained from a utility maximization principle

SPATIAL COGNITION
A5-[ActionSpace]

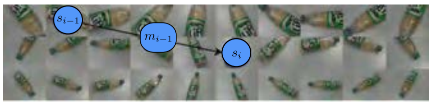
Tobias Kluth, David Nakath, Thomas Reineking, Christoph Zetzsche, Kerstin Schill

Introduction

The interaction of biological agents within the real world is based on their abilities and the affordances of the environment. By contrast, the classical view of perception considers only sensory features, as do most object recognition models. Only a few models make use of the information provided by the integration of sensory information as well as possible or executed actions. Neither the relations shaping such an integration nor the methods for using this integrated information in appropriate representations are yet entirely clear. We propose a probabilistic model integrating the two information sources in one system. The recognition process is equipped with an utility maximization principle to obtain optimal interactions with the environment.

Sensorimotor Representation

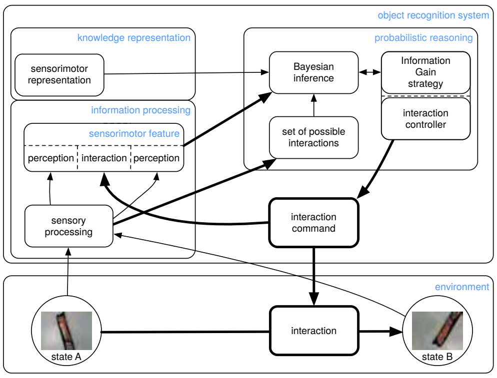
Sensorimotor Feature:
$SMF_i := \{s_{i-1}, m_i, s_i\}$



The *knowledge representation* is comprised of the learned sensorimotor representation (SMR), which is a full joint probability distribution of SMFs and the classes represented by the discrete random variable Y. Every possible SMF is generated on a set of known objects in a training phase. This means that, from every possible state x, the sensory consequence of every possible action u is perceived, resulting in

$$SMR := P(SMF, Y) = P(S_{i-1}, M_{i-1}, S_i, Y)$$

Model



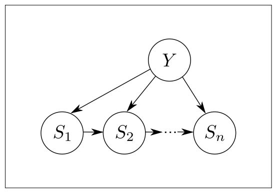
The proposed affordance-based object recognition system consists of the following subsystems:

- *information processing:* raw sensor information is fed into the *sensory processing* module (clustered GIST features) and is subsequently stored in the *sensorimotor feature* (SMF) alongside interaction information.
- *knowledge representation:* provides a learned *sensorimotor representation* in the form of a joint distribution of SMF and object class Y.
- *probabilistic reasoning:* uses a Bayesian network to infer the object class and provides a new interaction command obtained by an information gain strategy.

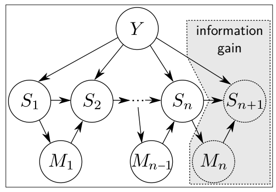
Bayesian Inference / Information Gain

We designed two types of Bayesian networks (BN) which process different kinds of information.

- The *Sensor Network (BN1)* processes only the sensor information with an extended naive Bayes approach which additionally allows for statistical dependencies between the preceding (s_{i-1}) and the current (s_i) sensor information. The information gain strategy can not be employed as no interaction information is available.
- The *Affordance-based Network (BN2)* processes the whole information stored in an *SMF* by assuming that the current sensor information s_i depends on the interaction m_i and the preceding sensor information (s_{i-1}). Additionally, *BN2* allows for statistical dependencies between the interaction m_i and the the preceding sensor information (s_{i-1}). The integration of interaction information allows to use an information gain strategy to choose an optimal next interaction m^*.



BN1
$P(y|s_{1:n}) \propto P(y)P(s_1|y)\prod_{i=2}^{n} P(s_i|s_{i-1}, y)$



BN2
$P(y|s_{1:n}, m_{1:n-1})$
$\propto P(y)P(s_1|y)\prod_{i=2}^{n} P(s_i|s_{i-1}, m_{i-1}, y)P(m_{i-1}|s_{i-1})$

The information gain IG of a possible next action m_n is defined as the difference between the current entropy and the conditional entropy:

$$IG(m_n) := H(Y|s_{1:n}, m_{1:n-1}) - H(Y|S_{n+1}, m_n, s_{1:n}, m_{1:n-1})$$

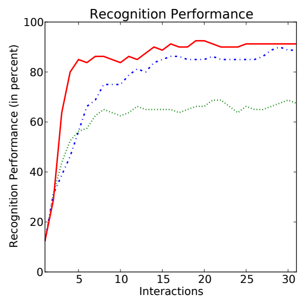
This is equivalent to the mutual information of Y and (S_{n+1}, m_n) for an arbitrary m_n. As the current entropy $H(Y|s_{1:n}, m_{1:n-1})$ is independent of the next action m_n the most promising action m^* can be calculated by minimizing the expected entropy with respect to S_{n+1}:

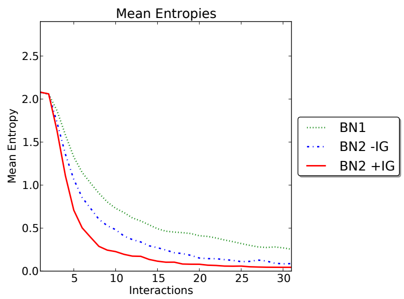
$$m^* = \arg\min_{m_n}(\underset{S_{n+1}}{E}[H(Y|s_{1:n}, S_{n+1}, m_{1:n})])$$

Evaluation and Results

Ten fold cross validation was conducted on a data set made by a robotic arm with a camera attached. The dataset has the following properties:

- 8 Object classes
- 10 objects in each class
- 435 SMFs per object
- 30 absolute positions
- 95 possible relative movements
- 30 interactions conducted





Conclusion

- The integration of affordance-based interaction results in better recognition performance.
- The information gain strategy leads to the acquisition of relevant information with fewer interactions.

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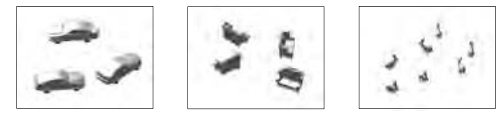
Visual numerosity: A computational model based on a topological invariant

SPATIAL COGNITION
A5-[ActionSpace]

Tobias Kluth, Christoph Zetzsche

Introduction

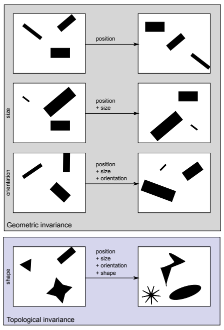
The estimation of the cardinality of objects in an environment requires a high degree of invariance. Numerous experiments showed the immense abstraction ability of the numerical cognition system. Numerosity is assumed to be an abstract feature which is represented on a high level in the processing hierarchy. But there is also evidence for a direct visual sense for number since number seems to be a primary visual property like color, orientation or motion, to which the visual system can be adapted by prolonged viewing (Ross & Burr, 2010) and the precise relation to other low-level features (like density as computed from spatial frequencies) is unclear (Dakin, Tibber, Greenwood, Kingdom, Morgan, 2011). Here we try to approach numerosity from a mathematical perspective. Based on concepts and quantities like connectedness and Gaussian curvature, we provide a general solution to number estimation and apply it to visual stimuli. We show that the estimation only requires derivatives of the luminance function and a multiplicative AND-like combination of these features, which can be realized by neurophysiologically realistic Gabor-like filters and by the neural mechanism of cortical gain control. A neural hardware thus would be able to estimate the number of objects using this neural correlates.



Formal model - Concept

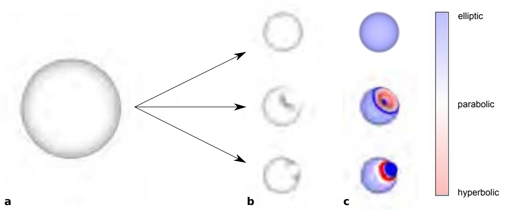
In order to determine the number of objects in a scene in the real world, the following three questions are addressed:

- What is the formal definition of "real world"?
  - *Topological space $\mathbb{R}^3$ with its standard topology.*
- What is an object and which properties does it have?
  - *An object is (simply) connected and 3-dimensional.*
- What is meant by *number* in this context and how are its invariant properties defined?
  - *The expected properties of the invariant n are*
    - **Invariance:** $n(x) = n(f(x))$, for a specific class of operations f.
    - **Additivity:** $n(x \cup y) = n(x) + n(y)$, for disjoint x, y.



Is any invariant known which fulfills these requirements?
- In general not but the Euler characteristic χ with homeomorphisms as possible operations is a good candidate.

Connection to local features - Curvature



Theorem (Gauss-Bonnet). *Let $S \subset \mathbb{R}^3$ be a regular oriented surface (of class C^3), and let R be a compact region of S with its boundary ∂R. Suppose that ∂R is a simple, closed, piecewise regular, positively oriented curve. Assume ∂R consists of k regular arcs ∂R_i (of class C^2), and let θ_i be the external angles of the vertices of ∂R. Then*

$$\int_R K\ dS + \sum_{i=1}^{k} \int_{\partial R_i} \kappa_g\ ds + \sum_{i=1}^{k} \theta_i = 2\pi\chi(R)$$

where K is the Gaussian curvature, κ_g is the geodesic curvature, and χ is the Euler characteristic.

Computational model - Luminance

The projection of the conceptual case to a luminance surface results in the loss of the invariance property. We thus assume a threshold h applied to the luminance function l to define the integration domain $S := \{(x, y, l(x, y)) \in \mathbb{R}^3 | l(x, y) \geq h\}$, parametrized by $\phi(x, y)$, and $C := \partial S$, parametrized by $c(t)$.

$$\int_S K\ dS + \int_C \kappa_g\ ds = 2\pi\chi(S)$$

In order to identify the requirements on the neural implementation, we use

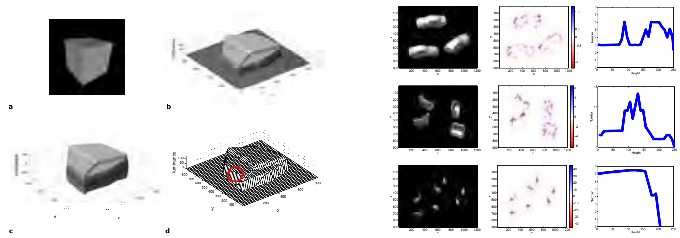
$$\int_S K\ dS = \int_{\mathbb{R}^2} \underbrace{\frac{l_{xx}(x,y)l_{yy}(x,y) - l_{xy}(x,y)^2}{(1 + l_x(x,y)^2 + l_y(x,y)^2)^{3/2}}}_{=:\tilde{K}(x,y)} \chi_S(\phi(x,y))\ d(x,y),$$

where χ_S is the characteristic function with respect to the set S, and

$$\int_C \kappa_g\ ds = \int_{\mathbb{R}} \underbrace{\frac{l_x^2 l_{yy} + l_y^2 l_{xx} - 2 l_x l_y l_{xy}}{(l_x^2 + l_y^2)^{3/2}(1 + l_x^2 + l_y^2)^{1/2}}}_{=:\tilde{\kappa}_g(x(t),y(t))} (x'^2 + y'^2)^{1/2} \chi_C(c(t))\ dt,$$

where χ_C is the characteristic function with respect to the set C. We thus can obtain the number n from

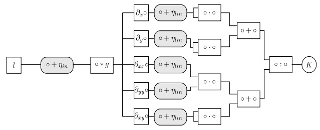
$$2\pi n = \int_{\mathbb{R}^2} \tilde{K}(x,y)\tilde{\chi}_S(x,y)\ d(x,y) + \int_{\mathbb{R}} \tilde{\kappa}_g(x(t),y(t))\tilde{\chi}_C(x(t),y(t))\ dt.$$

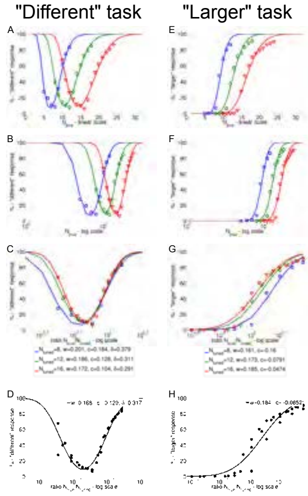


Error analysis

The proposed model is extended by additive normally distributed noise on the input luminance η_{in} and the output of the linear filter operators η_{lin}. The resulting analog quantity is fed into an optimal classifier (receiver-operator-characteristic) to make binary decissions in a "smaller - larger" and a "same - different" task.

We used 51,200 binary test stimuli with rectangular objects, generated as described in Stoianov and Zorzi, 2012 (numbers from 1 to 32 and various cumulative areas).





$\eta_{in} \sim N(0, 0.2)$, $\eta_{lin} \sim N(0, 0.1)$

Conclusion

- The proposed model can deal with arbitrary shapes of objects (simply connected). Not restricted to "blob"-like stimuli (Dehaene et al.,1993).
- All principles to obtain the invariance are clearly defined. No black box (Stoianov and Zorzi, 2012).
- Computation is neuronal plausible; it only requires threshold, linear filter and cortical gain control operations.
- Resulting error fits human behavior, compare results with Piazza et al., 2004, (Fig. 2).

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A7-[FreePerspective]

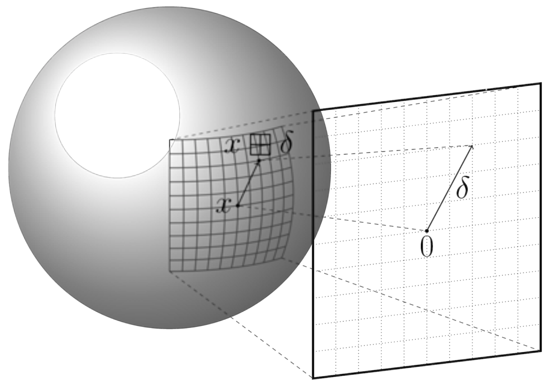
Sparse Least Squares on Manifolds

A7-[FreePerspective]

Christoph Hertzberg, Udo Frese, Thomas Röfer

[+]-Manifolds

- Integration of manifolds into least-squares estimators
- By encapsulating their structure in a [+] operator
- Flexible definition of various state spaces
- Mathematical theory and software framework



Axioms of a [+]-Manifold $\mathcal{S}$

$x \boxplus \delta$ smooth in δ and $y \boxminus x$ smooth in y.

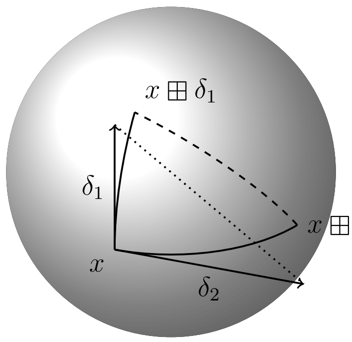
range of unique values $0 \in V \subset \mathbb{R}^n$

$$x \boxplus 0 = x$$

$$\forall y \in \mathcal{S}: \quad x \boxplus (y \boxminus x) = y$$

$$\forall \delta \in V: \quad (x \boxplus \delta) \boxminus x = \delta$$

$$\forall \delta_1, \delta_2 \in \mathbb{R}^n: \|(x \boxplus \delta_1) \boxminus (x \boxplus \delta_2)\| \leq \|\delta_1 - \delta_2\|$$



Probababilistic Concepts on a [+]-Manifold

$$\mathcal{N}(\mu, \Sigma) := \mu \boxplus \mathcal{N}(0, \Sigma),\ \mu \in \mathcal{S},\ \Sigma \in \mathbb{R}^{n\times n}$$

$$X \sim \mathcal{N}(\mu, \Sigma) = \mu \boxplus \mathcal{N}(0, \Sigma) \overset{*}{\Leftrightarrow} X \boxminus \mu \sim \mathcal{N}(0, \Sigma)$$

$$\operatorname{E} X = \operatorname{argmin}_{x \in \mathcal{S}} \operatorname{E}(\|X \boxminus x\|^2)$$

$$\operatorname{Cov} X = \operatorname{E}\left((X \boxminus \operatorname{E} X)(X \boxminus \operatorname{E} X)^\top\right)$$

Gauss-Newton on a [+]-Manifold

$$f(X) - z \sim \mathcal{N}(0, \Sigma)$$

$$J_{\bullet k} := \frac{f(x_i + \varepsilon e_k) - f(x_i - \varepsilon e_k)}{2\varepsilon}$$

$$x_{i+1} := x_i - (J^\top \Sigma^{-1} J)^{-1} J^\top \Sigma^{-1} (f(x_i) - z)$$

$$f(X) \boxminus z \sim \mathcal{N}(0, \Sigma)$$

$$J_{\bullet k} := \frac{(f(x_i \boxplus \varepsilon e_k) \boxminus z) - (f(x_i \boxplus -\varepsilon e_k) \boxminus z)}{2\varepsilon}$$

$$x_{i+1} := x_i \boxplus -(J^\top \Sigma^{-1} J)^{-1} J^\top \Sigma^{-1} (f(x_i) \boxminus z)$$

Example: Stereo-Camera Calibration in <50 Lines of Code

```
typedef MTK::vect<2> vec2;              // 2D vector
typedef pair<vec2, vec2> vec2pair;      // Measurement pair
typedef MTK::vect<3> vec3;              // 3D vector
typedef MTK::SO3< > SO3;                // 3D Orientation
typedef MTK::trafo<SO3> trafo;          // 3D Transformation
typedef MTK::vect<9> CamIntrinsics;     // Camera intrinsics

class Camera : public CamIntrinsics {
    vec2 sensor2image(const vec3& point) const;};

MTK_BUILD_MANIFOLD(StereoCamera,
    ((Camera, left))
    ((Camera, right))
    ((trafo, left2right))
)

SLOM_BUILD_MEASUREMENT(StereoMeasurement, 4,
    ((StereoCamera, K)) ((trafo, left2world)),
    ((vec3, p_world)) ((vec2pair, z_ti)))

SLOM_IMPLEMENT_MEASUREMENT(StereoMeasurement, ret){
    vec3 p_left = left2world->inverse() * p_world;
    vec3 p_right = K->left2right * p_left;
    ret << K->left.sensor2image(p_left)   - z_ti.first,
           K->right.sensor2image(p_right) - z_ti.second;
}
```

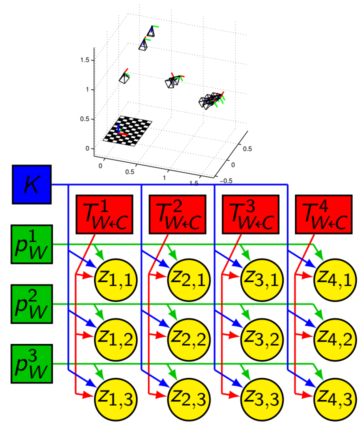
```
vector<vec3> pts_world;   // calibration point positions

Estimator est;                     // Optimizer class
// Camera parameters (shared by all measurements):
VarID<StereoCamera> K = est.insertRV(StereoCamera());

for(int t=0; t<num_images; ++t){
    // collect data, get initial guess for left camera
    vector<vec2pair> z_t;
    trafo left2world_init;
    find_checkerboard(left2world_init, z_t, pts_world);

    VarID<trafo> left2world = // local ID left2world
          est.insertRV(left2world_init);
    for(int i=0; i<num_points; ++i)
        est.insertMeasurement (StereoMeasurement(
              K, left2world,
              pts_world[i], z_t[i]));
}

for(int i=0; i<100; ++i) est.optimizeStep();
cout << "Camera intrinsics " << *K << "\n";
```



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Detailed Modeling and Calibration of a Time-of-Flight Camera

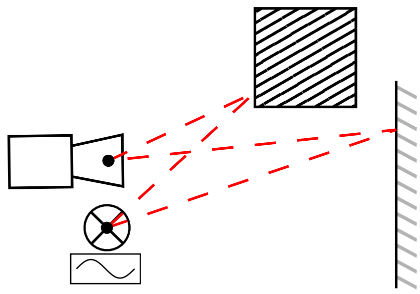
A7-[FreePerspective]

Christoph Hertzberg, Udo Frese, Thomas Röfer

Idealistic Model

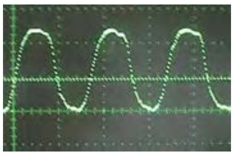
- $\psi(t) = a\sin(2\pi\nu t) + c_O$
- $z(t) = \alpha \cdot \psi(t - \Delta t) + c_B$
- $s^{[k]} = \int_{\frac{k}{4\nu}}^{\frac{k+2}{4\nu}} z(t)\,\mathrm{d}t = c_2 + \frac{A}{2}\cos\left(\frac{\pi}{2}k - 2\pi\nu\Delta t\right)$

- $A = \sqrt{\left(s^{[0]} - s^{[2]}\right)^2 + \left(s^{[1]} - s^{[3]}\right)^2}$
- $\Delta t = \frac{1}{2\pi\nu}\,\mathrm{atan2}(s^{[1]} - s^{[3]}, s^{[0]} - s^{[2]})$
- $Z = (s^{[0]} - s^{[2]}) + (s^{[1]} - s^{[3]})\mathbf{i}$
- $A = |Z|$
- $\Delta t = \frac{1}{2\pi\nu}\arg Z$



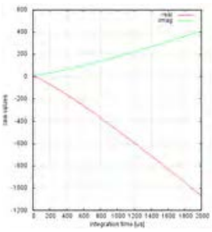
Irregularities

Lens Distortion
Vignetting

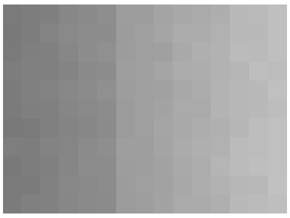


https://www.cayim.com/forum/uploads/monthly_04_2013/post-199-0-71702000-1366139588.jpg

Non sinusoidal light



Non-Linearities



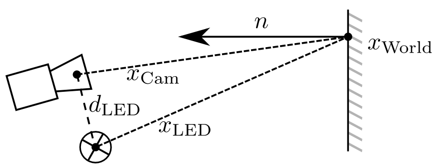
Fixed Pattern Noise

Lens Scattering

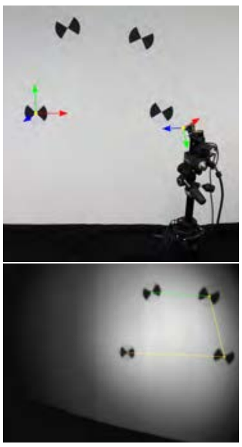
Model

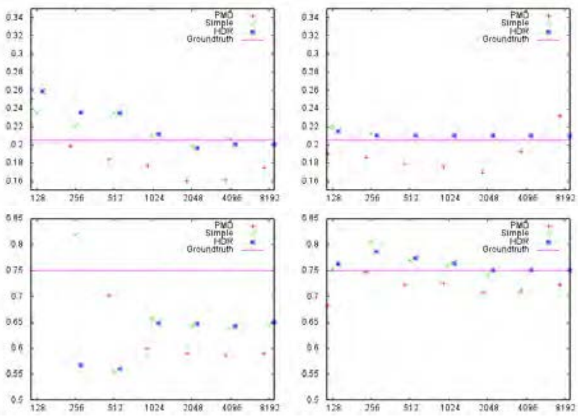
- Vignetting: $\ell_L(x_{\text{LED}})$
- Emitted light: $\psi(t)$ modelled by piece-wise polynomials
  - $\Psi_P(\Delta t) = \int_{\Delta t}^{\Delta t+0.5} \psi(t)\,\mathrm{d}t$
- Sensor non-linearities g_G using rational polynomials
- Fixed Pattern Noise: Complex factor h_p per pixel

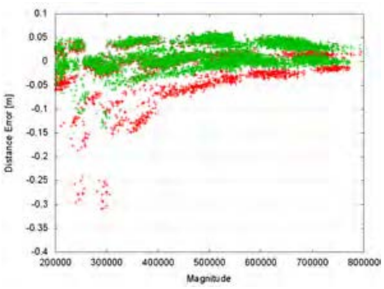
- $A = t_I \cdot \alpha \cdot \ell_L(x_{\text{LED}}) \cdot \frac{\langle x_{\text{LED}}, n\rangle}{\|x_{\text{LED}}\|^3}$
- $\Delta t = \frac{\|x_{\text{LED}}\| + \|x_{\text{Cam}}\|}{\lambda}$
- $Z = h_p \cdot g_G(A \cdot (\Psi_P(\Delta t) + \mathbf{i}\Psi_P(\Delta t + \frac{1}{4})))$
- Unknowns: α, L, $H = (h_p)_{p\in I}$, G, P



Experiments







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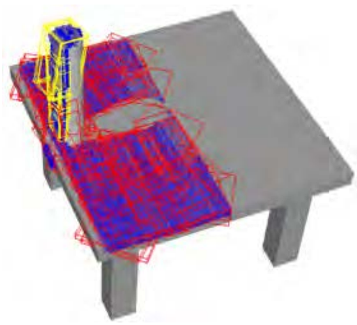
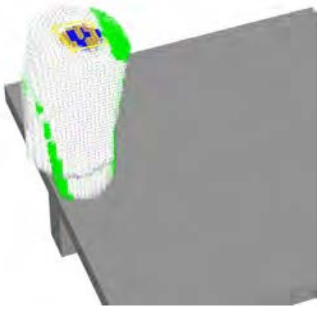
A8-[HumanoidSpace]

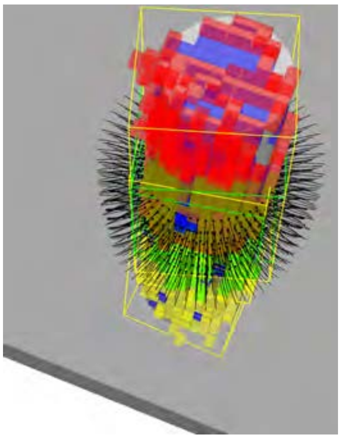
Online Evaluation and Grasping of Arbitrary Objects

SPATIAL COGNITION

A8-[HumanoidSpace]

Judith Müller, Armin Hornung, Maren Bennewitz, Thomas Röfer



Online Calculation of Grasp Points on Unknown Objects

General Conditions

- Grasps are single-handed and form-closure
- Objects or parts of them are limited to certain dimensions to fit into NAO's hand
- Graspable parts are surrounded by free space

Detecting of Grasp Points in Multiple Phases

1. Scanning and building a local map using probabilistic approach (OctoMap)
2. Registering of local map in global frame using ICP
3. Identifying of grasp candidates on basis of OBBs via region growing using dimension constraints
4. Verifying graspable parts by detecting free areas in surrounding cylinder and rasterizing grasp points
5. Calculation of next scan poses using grasp candidate specific information gain and precalculated 6D look-up-table

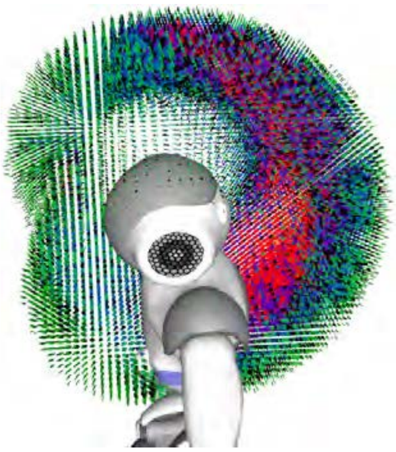
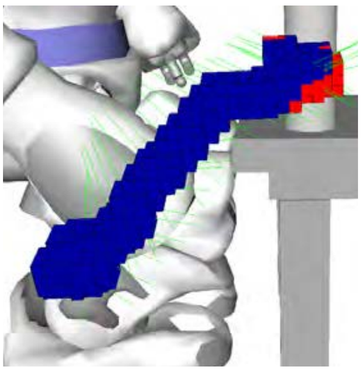
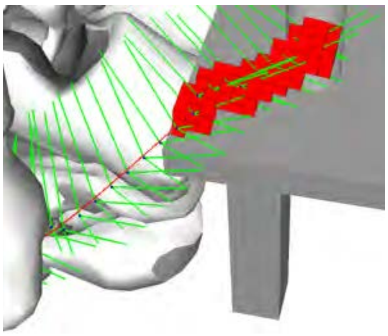
Real-Time Motion Planning

Precalculated Workspace

- Reachability checks per 6D look-up-table containing hand poses and 5D look-up-table containing body poses instead of inverse kinematics
- 6D entries represent reachability of hand positions (3D) with possible lower arm directions (2D) and link to possible body poses (1D)
- 5D entries represent COM-stable body positions (3D) with possible body directions (2D)

Online Motion Planning

- Finding body poses by voting over sum of reachable grasp points per pose using 6D look-up-table
- Frame-wise A* planning of hand motion path in 3D
- Heuristic estimates change in distance and lower arm direction compared to goal node
- Robot body parts and OBBs (obstacles) are modeled as geometric primitives
- Planned path is converted into a Beziér spline using least-squares method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Humanoid Robot Navigation in Complex Indoor Environments

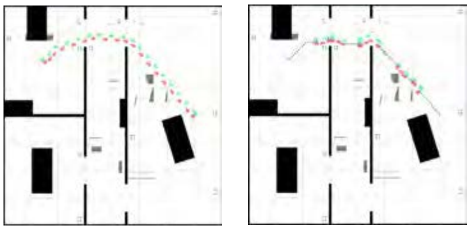
SPATIAL COGNITION

A8-[HumanoidSpace]

Armin Hornung, Judith Müller, Maren Bennewitz, Thomas Röfer

Navigation Planning for Humanoid Robots

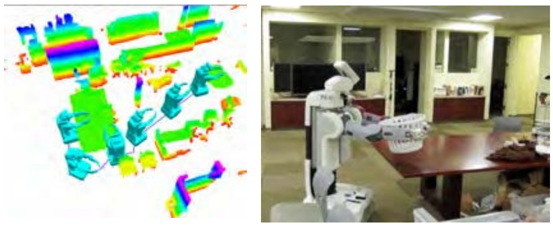
- Anytime search-based footstep planning using the ARA* and R* planners
- Fast planning results with guaranteed suboptimality
- Plans can be improved during execution
- Adaptive level-of-detail: Combination with fast 2D path planner in open spaces



Environment Representation and Efficient Planning in 3D

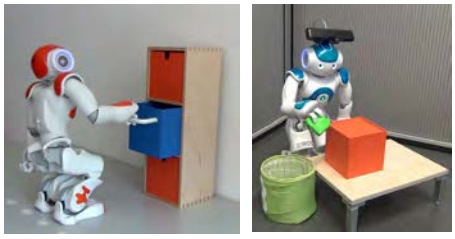
- OctoMap: An efficient probabilistic 3D mapping framework
- Open-source, wide adoption in robotics and beyond as 3D environment representation
- Efficient collision checking for navigation with the PR2 in cluttered environments

in cooperation with A3-[Multibot]



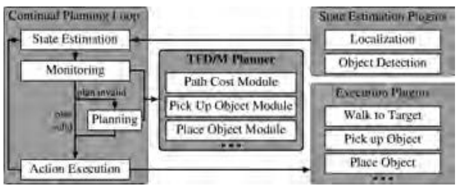
Full-Body Motion Planning

- Whole-body motion planning considering multiple constraints
- Generation of statically stable and collision-free whole-body motions for a humanoid robot
- Probabilistic planning with RRT-CONNECT and inverse kinematics
- Applications: Grasping and manipulation of articulated objects



Integrated Perception, Task Planning, and Action Execution

- Integration with a high-level symbolic planner (PDDL/M)
- Enables a humanoid robot to clean up a cluttered room
- Continual monitoring of action outcome and plan validity
- Foresighted object placement at intermediate intermediate positions in case objects block the path



in cooperation with R7-[PlanSpace]

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I1-[OntoSpace]

SpacePortal and Ontohub

SPATIAL COGNITION

I1-[OntoSpace]

Oliver Kutz, Christoph Lange, Till Mossakowski

Distributed Ontology Language (DOL)

Distributed Ontologies

- Heterogeneity (OWL, FOL, HOL, …)
- Conservative extensions
- Modules, approximation, hiding, filtering
- Theory interpretations
- Alignments, combinations

Semantics

- Theory-level and model-theoretic
- Preserves semantics of individual ontology languages
- Non-monotonicity via circumscription-like structuring

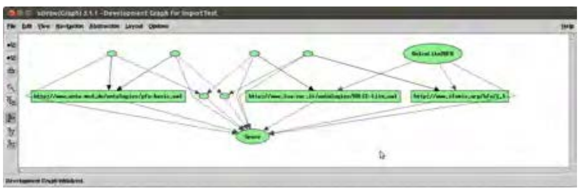
OMG Standard

- Request for proposal issued in 2013
- First version of standard will appear in Dec. 2014
- http://ontoiop.org
- http://www.omg.org/cgi-bin/doc?ad/2013-12-02

Towards an integrated upper Spatial ontology

```
alignment DolceLite2BFO :
  <http://www.loa-cnr.it/ontologies/DOLCE-Lite.owl>   to
  <http://www.ifomis.org/bfo/1.1> =
 endurant = IndependentContinuant,
 physical-endurant = MaterialEntity,
 physical-object = Object, perdurant = Occurrent,
 process = Process, quality = Quality,
 spatio-temporal-region = SpatiotemporalRegion,
 temporal-region = TemporalRegion,
 space-region = SpatialRegion
alignment DolceLite2GFO :
  <http://www.loa-cnr.it/ontologies/DOLCE-Lite.owl>   to
  <http://www.onto-med.de/ontologies/gfo-basic.owl> = …
alignment BFO2GFO :
  <http://www.ifomis.org/bfo/1.1>   to
  <http://www.onto-med.de/ontologies/gfo-basic.owl> = …
ontology Space =
 combine BFO2GFO, DolceLite2GFO, DolceLite2BFO
```

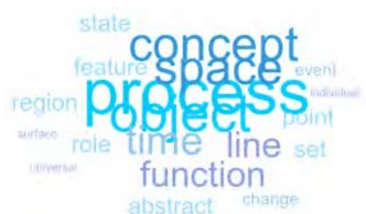
Alignments between foundational ontologies DOLCE, BFO and GFO using DOL syntax



Combination of the foundational ontologies

Example: classification of SFB papers

Tag-based browsing a repository of SFB papers



Upper Ontology-based browsing a repository of SFB papers

spaceportal.org and ontohub.org/spaceportal

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Towards Ontological Blending

SPATIAL COGNITION
I1-[OntoSpace]

Joana Hois, Oliver Kutz, Till Mossakowski, and John Bateman

Ontology Reasoning and Blending with Hets/OntoHub

Ontology Languages

- OWL support / Manchester Syntax
- Common Logic (CL) support
- Structuring constructs for OWL and Common Logic

Structuring & Reasoning

- Reasoning with various ontology languages and structuring, e.g.:
  - OWL: Pellet and FACT++
  - First-order & Common Logic
- Use of morphisms, e.g. translations and interpretations

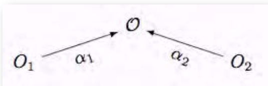
The DOL Language

- Combines simplicity and tool support for OWL with the more complex blending facilities of OBJ3 (Goguen) or Haskell.
- “views” are used to relate theories and build the blending diagram.

Combining Ontologies

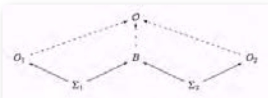
Integration

- Reference Ontology

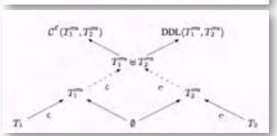


Connection

- Bridge Ontology

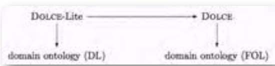


- Modular Languages: DDL / E-Connections



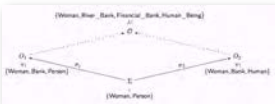
Refinement

- Subontologies, and Equivalence



Alignment

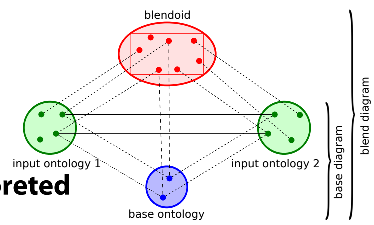
- Homonymy/Synonymy/ Polysemy



Blending Ontologies

Blending

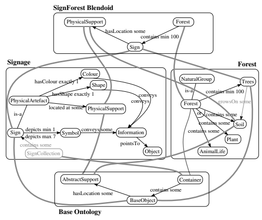
- **“Creative mix”** of ontologies through common base.
- The Base is **reinterpreted** in the two input ontologies.
- The “**Blendoid**” is computed via a **colimit** computation.



Blending Forests with Signs

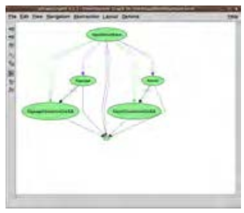
- An example of seemingly unrelated ontologies that share (partial) structure
- The common base has to be formally specified (e.g. theory intersection, analogy search)

Analogies between signs and forests



Formal specification of the SignForest Blend

Blending specification in Hets



Blending specification after colimit computation

References

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- F. Neuhaus, O. Kutz, M. Codescu, T. Mossakowski. Fabricating Monsters is Hard - Towards the Automation of Conceptual Blending Proc. of Computational Creativity, Concept Invention, and General Intelligence (C3GI at ECAI-14), Prague, 2014.
- O. Kutz, J. Bateman, F. Neuhaus, T. Mossakowski, M. Bhatt. E pluribus unum. Formalisation, Use-Cases, and Computational Support for Conceptual Blending. In T. R. Besold et al., editors, Computational Creativity Research: Towards Creative Machines, Atlantis/Springer, Thinking Machines, 2014.
- O. Kutz, T. Mossakowski, J. Hois, M. Bhatt, J. Bateman. Ontological Blending in DOL. Computational Creativity, Concept Invention, and General Intelligence (C3GI at ECAI-12), 2012.
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DO-ROAM: Activity-Oriented Search & Navigation with OpenStreetMap

SPATIAL COGNITION

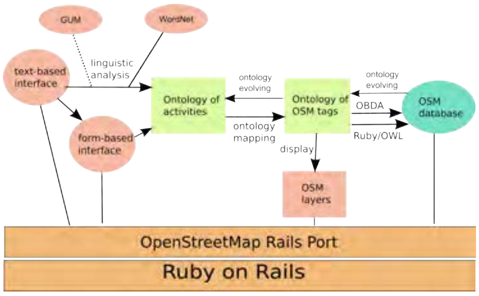
I1-[OntoSpace]

Oliver Kutz, Mihai Codescu, Till Mossakowski

Motivation and Goals

- Navigation based on users' spatially-related activities
- Focus on the "what", and only roughly indicate the "where"
- Provide use case for ontology-based data access
- Provide ontological structure for OpenStreetMap data and tags

Activity-based navigation



System architecture

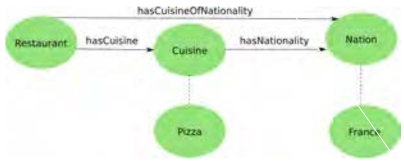
Ontology-based data acces at work

Ontologies & databases

- Ontology of spatially-related activities
- Ontology of OpenStreetMap tags
- OSM database

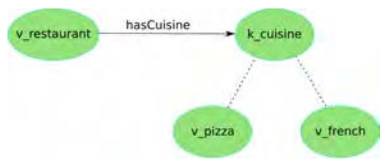
- Activity Ontology ↦ Activity Ontology (expanded) ↦ Tag Ontology
- ChargingStation ↦ ChargingStation
  ↦ ∃amenity. charging_station ⊔ ∃fuel_electricity. yes
- Gastronomy ↦ Bar ⊔ Café ⊔ FastFood ⊔ Pub ⊔ Restaurant
  ↦ ∃amenity. bar ⊔ ∃amenity. cafe ⊔ ∃amenity. fast_food ⊔ ...
- ItalianRestaurant ↦ Restaurant ⊓∃ hasCuisineOfNationality . Italian
  ↦ ∃amenity. restaurant ⊓ ∃cuisine . Italian

Mapping example

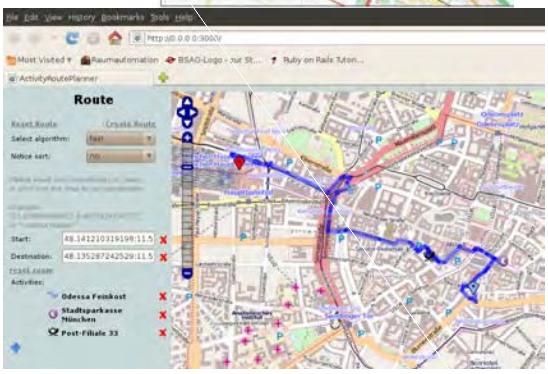


Activity ontology

Tag ontology: concepts



Tag ontology: roles



User interface at do-roam.org

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Ontology-Based Data Access

I1-[OntoSpace]

Carsten Lutz, İnanç Seylan

Ontology-Based Data Access (OBDA)

Data (also called ABox)

- The data is stored in a relational database system (RDBMS)
- E.g., OpenStreetMap (OSM) with annotations

Ontology-Based means we have background knowledge

- The background knowledge is also called TBox
- E.g., every Scandinavian company is based in a Scandinavian country

Access means asking database style queries.

- Mostly conjunctive queries (CQs), which are SQL queries of the form

  SELECT ... FROM ... WHERE $x_0 = x_1$ AND ... AND $x_n = x_{n+1}$

Algorithms for Reasoning in OBDA

Let $\mathcal{T}$ be a TBox, $\mathcal{A}$ an ABox, q a CQ.

$q(\mathcal{T}, \mathcal{A})$ denotes the answers of q over $\mathcal{T}$ and $\mathcal{A}$.

We are interested in computing $q(\mathcal{T}, \mathcal{A})$.

Two main approaches to reasoning in OBDA.

1. **QUERY REWRITING**:
Compile q and $\mathcal{T}$ into SQL query $\mathsf{perfect}_q^{\mathcal{T}}$ such that for every ABox $\mathcal{A}$, we have

$$q(\mathcal{T}, \mathcal{A}) = \mathsf{perfect}_q^{\mathcal{T}}(\emptyset, \mathcal{A})$$

2. **COMBINED APPROACH**:

- Extend $\mathcal{A}$ to new finite ABox $\mathcal{A}_{\mathcal{T}} \supseteq \mathcal{A}$ and
- Rewrite q into SQL query $q_{\mathcal{T}}$

  such that

$$q(\mathcal{T}, \mathcal{A}) = q_{\mathcal{T}}(\emptyset, \mathcal{A}_{\mathcal{T}})$$

PROBLEM:
$\mathsf{perfect}_q^{\mathcal{T}}$ and $q_{\mathcal{T}}$ may blow up exponentially.

First-order Rewritability

In the query rewriting approach, it is a desired property for an ontology language L that

- for every TBox $\mathcal{T}$ in L and
- for every CQ q

we have that $\mathsf{perfect}_q^{\mathcal{T}}$ is always a SQL query without recursion.

This property is called first-order rewritability.

It allows us to use any RDBMS, e.g., PostgreSQL, IBM DB2, for computing $q(\mathcal{T}, \mathcal{A})$ if $\mathcal{A}$ is already stored in RDBMS.

PROBLEMS:

- Only very simple ontology languages from the OWL2 QL profile enjoy first-order rewritability.
- There are many ontologies formulated in the OWL2 EL profile and its extensions and these languages do not satisfy first-order rewritability.

Mixing Open- and Closed-World Semantics

Let $\mathcal{T} = \{\mathsf{ScandComp} \sqsubseteq \exists \mathsf{basedIn}.\mathsf{ScandCountry}\}$,
let $\mathcal{A}$ consist of the following
$\mathsf{ScandComp}(cp)$,
$\mathsf{ScandCountry}(den), \mathsf{ScandCountry}(nor), \mathsf{ScandCountry}(swe)$
$\mathsf{TimberExp}(den), \mathsf{TimberExp}(nor), \mathsf{TimberExp}(swe)$
and let $q = \exists y\ \mathsf{basedIn}(x, y) \wedge \mathsf{TimberExporter}(y)$

cp is not a certain answer to $q(x)$ in $\mathcal{A}$ given $\mathcal{T}$. In contrast, if we interpret ScandCountry with closed-world semantics, then cp is a certain answer.

PROBLEM:
We want to mix open- and closed-world semantics in OBDA but it leads to intractability of query answering.

Contributions

ALGORITHMS FOR REASONING IN OBDA:
We proposed the filtering approach, which avoids exponential rewritings [ISWC13].
Let $\mathcal{T}$ be a TBox and $\mathcal{A}$ an ABox. The idea is to

- extend $\mathcal{A}$ to a new finite ABox $\mathcal{A}_{\mathcal{T}} \supseteq \mathcal{A}$ and
- for every CQ q, generate a procedure $\mathsf{filter}_q^{\mathcal{T}}$ such that

$$q(\mathcal{T}, \mathcal{A}) = \mathsf{filter}_q^{\mathcal{T}}(q(\emptyset, \mathcal{A}_{\mathcal{T}}))$$

We implemented the filtering approach in the system Combo along with a benchmark for testing OBDA systems.

http://code.google.com/p/combo-obda/

The experiments show *very encouraging* results!

FIRST-ORDER REWRITABILITY:
We have provided characterizations of FO-rewritable TBoxes in Horn description logics, i.e., OWL 2 EL and extensions, and determined the computational complexity of deciding FO-rewritability of a given TBox [IJCAI13a]. Practical algorithms are also on their way [DL14]!

MIXING OPEN- and CLOSED-WORLD SEMANTICS:

- Complete complexity characterization, i.e., a precise condition that delineate tractable cases from intractable ones [IJCAI13b].
- In the tractable cases, it is still possible to have integrity constraints on the data and use full SQL as a query language.

MOREOVER:

- Discovered a novel connection between OBDA and constraint satisfaction problems, which allowed us to provide a very fine-grained analysis of OBDA data complexity [PODS13].
- Gave characterizations for uniform interpolation and approximation in $\mathcal{EL}$, which are relevant for extracting relevant parts of an ontology for some signature (set of vocabulary items). For deciding uniform interpolation, we also provided a worst-case optimal algorithm [KR12].
- Studied OBDA for finite models and devised novel algorithms for the problem in extensions of $\mathcal{EL}$ [KR14].

In total 16 publications among which 5 are IJCAI, 4 KR, 1 ISWC (Best Paper Award), 1 PODS papers.

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I2-[MapSpace]

mapIT

“What You See Is What You Map”

Falko Schmid, Chunyuan Cai, Lutz Frommberger, Christian Freksa

SPATIAL COGNITION
I2-[MapSpace]
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Idea and Workflow

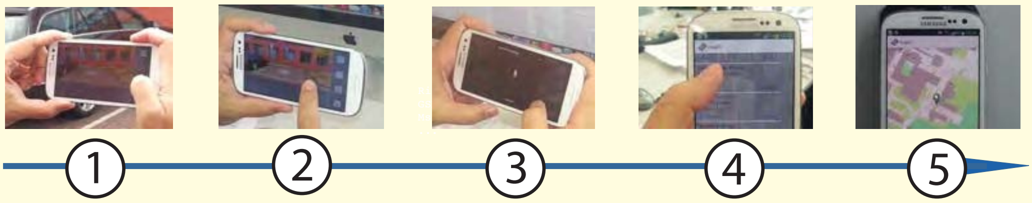
WYSIWYM: What you see is what you map

Micro-mapping of small geographic objects

Geo object with exact geometry

Taken from smartphone photo

Targets technically unskilled users



1 Take a photo
2 Outline the object
3 Annotate by speech
4 Upload to geo-server
5 Inspect the entity

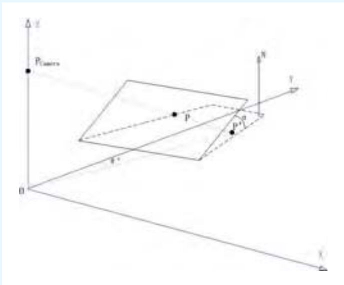
Geodata Acquisition

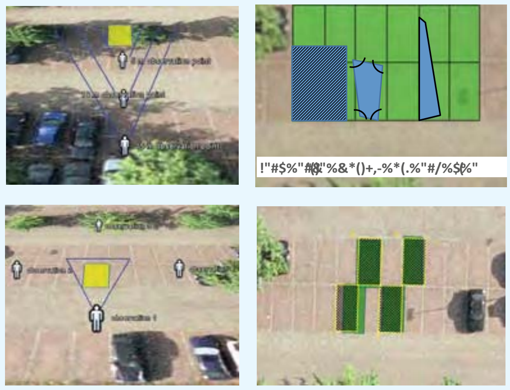
Calculation of object geometry based on GPS, compass, and tilt sensors

Inverse perspective transformation

Less than 5% error wrt. area, angles, perimeter

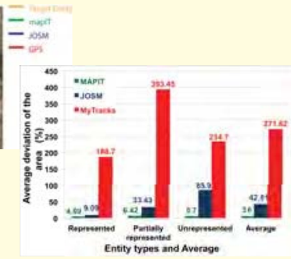
Variation	Area	Perimeter	Angle
Multiple perspectives	3.44%	4.46%	5.99%
Multiple distances	4.30%	4.25%	5.88%
Multiple entities	4.90%	3.84%	6.26%
Overall Deviation	3.82%	4.33%	5.99%





Accessibility / Usability

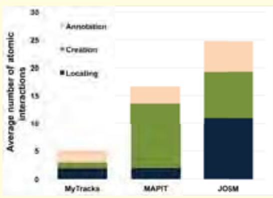
Comparison of Mapping Approaches



WYSIWYM (mapIT) vs. GPS trajectory tracking (MyTracks) vs. satellite image annotation (JOSM)

Three types of visibility for target entities

WYSIWYM: Highest precision, shortest duration, few interactions



Target User Study (Villagers in Rural Laos)

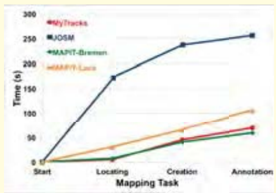
„Map your village“

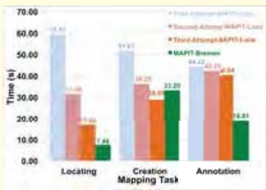
Technically unskilled users - first smartphone usage

Steep learning curve

Neglectable difference in core mapping task

Suitable workflow





Publications

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Schmid, F., L. Frommberger, C. Cai, and F. Dylla, "Lowering the Barrier: How the What-You-See-Is-What-You-Map Paradigm Enables People to Contribute Volunteered Geographic Information", ACM Symposium on Computing for Development (DEV-4), Capetown, South Africa, 2013.

Frommberger, L., F. Schmid, and C. Cai, "Micro-mapping with Smartphones for Monitoring Agricultural Development", ACM Symposium on Computing for Development (DEV 2013), Bangalore, India, 2013.

Schmid, F., L. Frommberger, C. Cai, and C. Freksa, "What You See Is What You Map: Geometry-preserving Micro-mapping for Smaller Geographic Objects with mapIT", Geographic Information Science at the Heart of Europe: Springer, pp. 3-19, 2013.

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Ensuring Quality of Volunteered Geographic Information

SPATIAL COGNITION
I2-[MapSpace]

Ahmed Loai Ali, Falko Schmid, Rami Al-Salman, Tomi Kauppinen

Heterogeneous Quality of VGI

Problems:

- Inaccurate or incomplete results
- Wrong handling of data by algorithms
- Unreliable data quality

Reasons:

- Heterogeneous contributors
- Various tools and technologies
- Loose classification mechanisms

Administrative boundaries are hierarchically organized

Classification Problems:

- *Hierarchical Inconsistency*: inconsistency with hierarchical classification
- *Implausible Classification*: classification does not match inherent properties
- *Classification Ambiguity*: potential membership to several classes


a) a grass land appropriately classified as "garden"

b) a water body classified as "lake" or "pond"

Plausibility and ambiguity

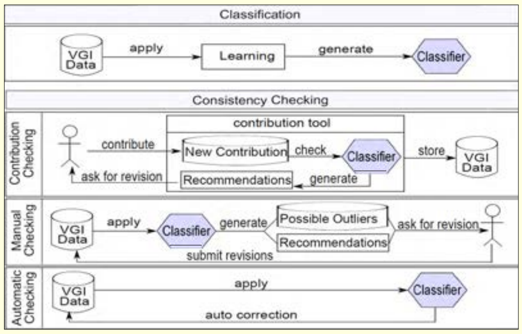
Integrity Checking to Ensure Classification Quality:

Rule-Based Approach:

- Formulation of constraints into a rule-based model
- Checking the integrity of contributions by the rule-based model

Leaning-Based Approach:

- *Classification:* learning properties by analyzing similar entities
- *Consistency Checking:* contribution, manual and automatic checking



Learning-based integrity checking approach

Hierarchical Inconsistency

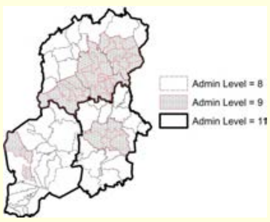
Administrative boundaries entities should follow the following rules:

$$\forall u \in U_i \quad where\ 1 \leq i \leq 11 \qquad (1)$$

$$\forall u_a \in U_{i>1}, \exists u_b \in U_{j>i}: u_a \subset u_b \qquad (2)$$

$$\forall U_j, U_k \subset U_i : U_j \cap U_k = \emptyset \qquad (3)$$

The rules allow detection of three types of outliers: *Incorrect class* (rule 1), *Inconsistency* (rule 2) and *Duplication* (rule 3)

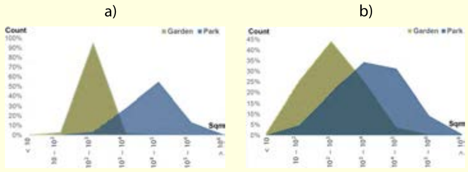


Example of inconsistent classification

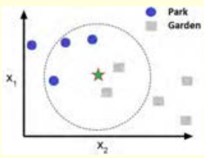
About 10 % of all administrative boundaries entities were detected as potentially problematic.

Classification Plausibility

Analyzing geometric properties is one possibility to distinguish between the classes "park" and "garden".



Areas of classes "park" and "garden" a) Birmingham b) London



The learning – based approach to distinguish entities, utilizing K-NN classifier

a)

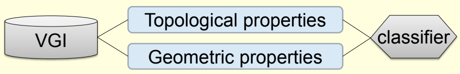
b)


Examples of detected implausible classifications of "park" entities: a) roundabout b) house roof

Classification Ambiguity

An entity covered with grass can belong to various classes like "*garden*", "*grass*", "*park*" or "*meadow*".

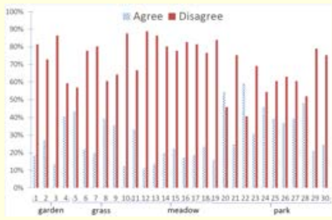
Due to inherent properties, one class typically is more appropriate than the others.



a)

b)


Examples of detected implausible classifications: a) grass b) park



Our study showed disagreement with respect to the classifications of detected problematic entities.

Publications:

- *Data Quality Assurance for Volunteered Geographic Information*, GIScience 2014, Vienna, Austria, *to appear*.
- *Ambiguity and Plausibility: Managing Classification Quality in Volunteered Geographic Information*, ACM SIGSPATIAL 2014, Dallas, TX, USA, *to appear*.

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Crowdsourced Disaster Alerting and Reporting

CapacityLab

SPATIAL COGNITION

I2-[MapSpace]

Lutz Frommberger, Falko Schmid, Christian Freksa

Mobile4D: Disaster Alerting and Reporting

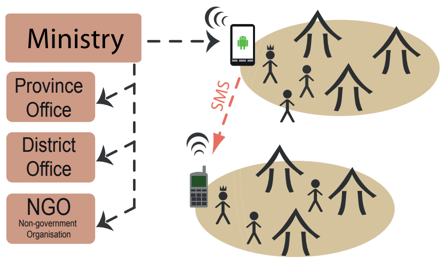
- Bi-directional system
- Official disaster warnings and reports of users affected
- Also focuses on "small-scale" disasters
- Cooperation with Ministry of Agriculture and Forestry, Lao PDR
- Components: smartphone app, web frontend, central server

Intuitive, easy workflow

- Guided dialogues
- Step-by-step procedures
- Text-free interfaces

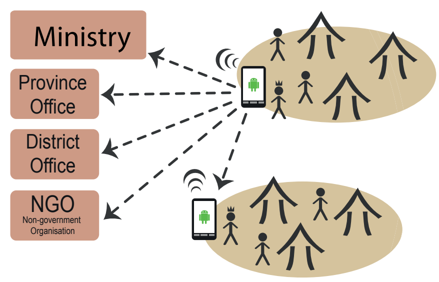
Bi-directional flow of information

- Tightly integrated into institutional workflows
- Implicit model of administrative structures



Top-down view

Official disaster warnings and information material



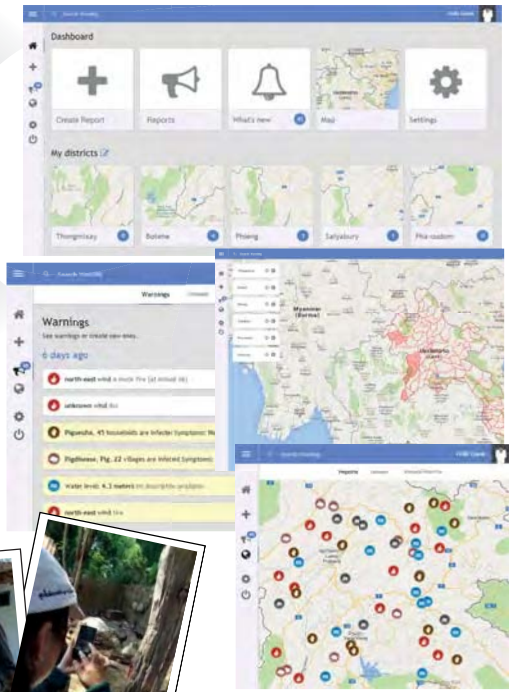
Bottom-up view

Crowdsourced disaster reporting

Android App

mobile4D

Web Frontend



Field Test in Laos

- Technical functionality proven
- Training of local officers
- Data collection
- Feedback sessions

Features

- Location-based information flow
- Real-time notifications (Push technology)
- Verification system
- Very low bandwith requirements
- Alerts via SMS, RSS, Twitter, Facebook, ...
- Buffered data transmission
- Common Alerting Protocal (CAP) compatibility
- Buffered data transmission

System Properties

- Reliable flow of data
- Real-time distribution of alerts
- Ease of use
- Cost-efficicient
- Connecting people

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OpenScienceMap

Map-based Research for the Public

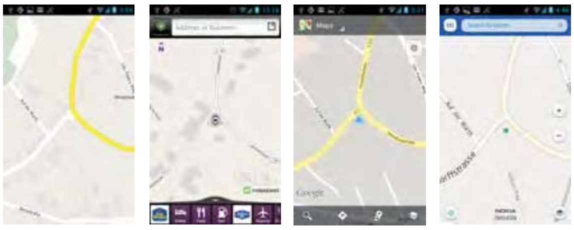
I2-[MapSpace]

Falko Schmid, Christian Freksa, Hannes Janetzek, Michal Wladysiak, Bo Hu, Yasser Maslut

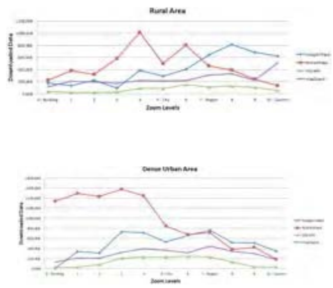
Data and Infrastructures for Vector Maps

Open Infrastructure, Algorithms, Data, Results

- Entirely open source
- Based on the complete OpenStreetMap database
- Own server to serve vector tiles
- Huge impact in open source mapping community
- Large number of users, especially in developing countries



OpenScienceMap MapQuest GoogleMaps Nokia Maps



Bandwidth Analysis of OpenScienceMap PBF

- Availability of maps crucial for all parts of the world
- In developing countries: low bandwidth especially in rural areas
- Identification of 10 similar and relevant zoom steps
- Dense urban area (Manhattan), semi-rural area (Worpswede)
- Analysis of required network traffic to render a 480x800 screen

	Bandwidth			
	14.4 kbps	28.8 kbps	33.6 kbps	56 kbps
20kB	11s	5s	4s	2s
50kB	28s	14s	12s	7s
100kB	56s	28s	24s	14s
800kB	07m35s	03m47s	03m1s5	01m57s
1MB	09m42s	04m51s	04m09s	02m29s

Road Network Generalization of OSM Data

Generation of a meaningful road network essential for small scales of topographic maps: communication of general connectivity, visualization of settlements.

OSM Data Quality Issues

Street network only displaying *highway:motorway*, *highway:trunk*, and *highway:primary*. The network is too dense and cluttered.

Disconnected street network in OSM only displaying streets tagged with *highway:motorway*, *highway:trunk*. The network is highly fragmented.

Identification of Places

Result of SELECT-PLACES (population >10.000). Places represented by large dots are selected (dark = large, bright = small).

Result of place selection with population >50.000.

Road Network Computation

Voronoi-diagram for selected places, links between nearest neighbors are red, neighbors of 2nd degree blue. The extended neighborhood ensures the detection of important network links.

Result of the road network computation for the Voronoi diagram. The road network is homogeneously distributed and at the same time sparse.

Result


```
Algorithm   SELECT-PLACES
Input:      Set of places where place is a tuple of (location, population)
            minimal-distance definitions minDist
Output:     Reduced set of places

result = places
forall p1, p2 in asPairs(places):
if (population(p1) < population(p2):
   d = distance(location(p1), location(p2))
   if getMinimalDistanceForPopulation(minDist, p1) < d:
         result = result \ {p1}
return result
```

```
Algorithm:  COMPUTE-STREETNETWORK
Input:      Set of places (places, voronoi-diagram, street-network)
Output:     Reduced street network between places

network = {}
forall p_i in places:
  forall n_j in getNeighborCells(p_i, voronoi-diagram):
    network = network U computeRoute(p_i, n_j, street-network)
    forall n_k in getNeighborCells(n_k, voronoi-diagram):
      network = network U computeRoute(p_i, n_k, street-network)
return network
```

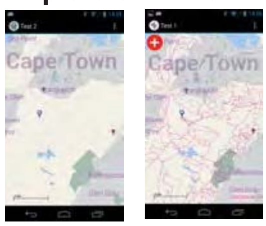
Map Interaction and Visualization

Task-specific Interaction

Offscreen Visualization

Consistent Labeling

Task-Specific Map Customization



- F. Schmid: *DistanceTouch@ OpenScienceMap: Towards task-specific map interaction*, Proceedings of the 1st ACM SIGSPATIAL International Workshop on MapInteraction, 2013
- F. Schmid, H. Janetzek: *A method for high-level street network extraction of OpenStreetMap data in OpenScienceMap*, Proc. of the 26th International Cartographic Conference, 2013
- F. Schmid, M. Wladysiak, H. Janetzek, B. Hu: *OpenScienceMap: Open and Free Vector Maps for Low Bandwidth Applications*, ACM Symposium on Computing for Development, 2013

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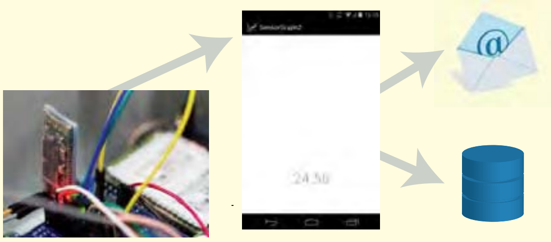
CapacityLab

WellComm
A Communication Hub for Remote Areas

I2-[MapSpace]

Daniele Tatasciore, Giorgio De Felice, Falko Schmid, Lutz Frommberger

Bluetooth-Android data connection



E-mail

Remote Server

SMS-based configuration

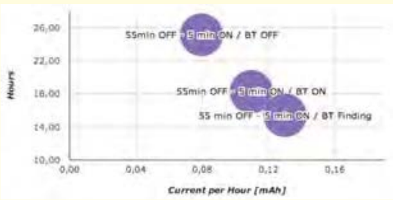
Cheap and reliable communication mean, widely used in developing countries. Allows for configuring:

- Warning messages
- WellComm status

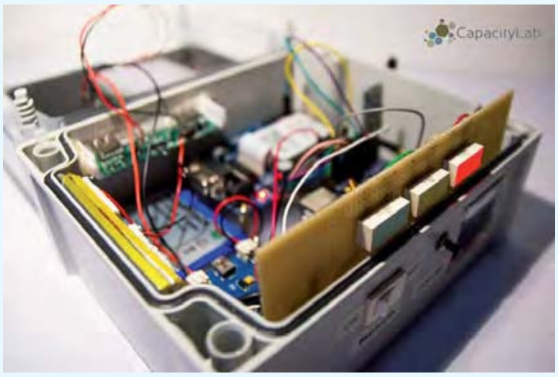
Independent solar based power

Solar panel for system power

Solar panel for charging station



What is WellComm?



Communication and information hub for remote areas: charging station as a mean for social information distribution and collection, and environmental monitoring.

- Self-sustaining system design
- Solar power based
- SMS-based administration

Web-based administration tool

Centralized tool for configuring the device:

- Set LED status
- Set messages
- Define GSM Sleep/Awake period

Visual information output

LED panel for immediate communication

Multiline LCD display for detailed information communication:

- Messages
- System status
- Sensor measures

Sensor support

Any sensor can be attached. Currently we have a flexible and waterproof temperature sensor. Allows for measuring:

- Atmospheric temperature
- Liquid temperature

WellComm components and costs

- Arduino UNO - ATmega 328 microcontroller (19,99 €)
- Siemens TC35 GSM controller (27 €)
- Wireless Serial 4 PIN Bluetooth RF (12 €)
- Lithium Ion Battery 2A (12,90 €)
- 1.5W Solar Panel 81x137 (9,90 €)
- LiPo Rider Pro (15,89 €)
- 10000mAh Dual USB Solar Power (20,60 €)
- Fibox - TA201610T (13,10 €)
- DS18B20 Temperature sensor (6,60 €)
- Led, LCD, Jumpers, Box, Switches (30 €)

Everything is possible

- Wider multiline LCD display
- E-Ink display
- ZigBee radio connection
- Mesh Potato internet connection
- Full waterproof container
- ODK integration
- Integration of any kind of sensor
- GPS board

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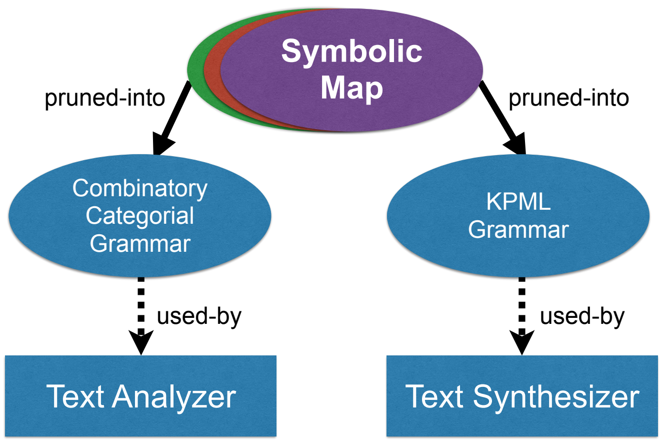
I5-[DiaSpace]

Towards a description of symbolic maps

SPATIAL COGNITION
I5-Diaspace

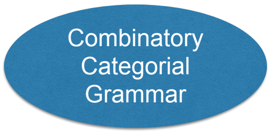
Daniel Couto Vale, Elisa Vales, Rumiya Izgalieva

What can be achieved



Other Attempts

Use of CCG for text synthesis



Halliday and Matthiessen (2004)

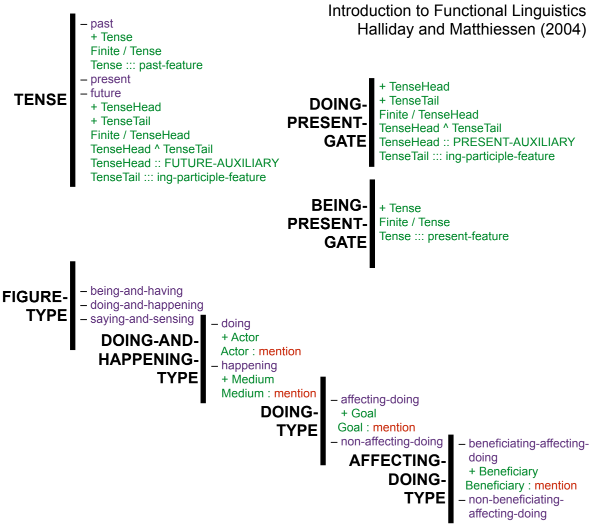
Use of KPML for text analysis

How KPML works

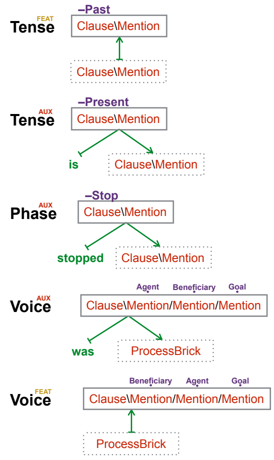
Introduction to Functional Linguistics
Halliday and Matthiessen (2004)

Missing Uses

gives
gave
given
giving
is
was
been
being



How OpenCCG works



Missing Systems

Tense[FEAT] + Voice[FEAT]
The duke gave the teapot to my aunt.

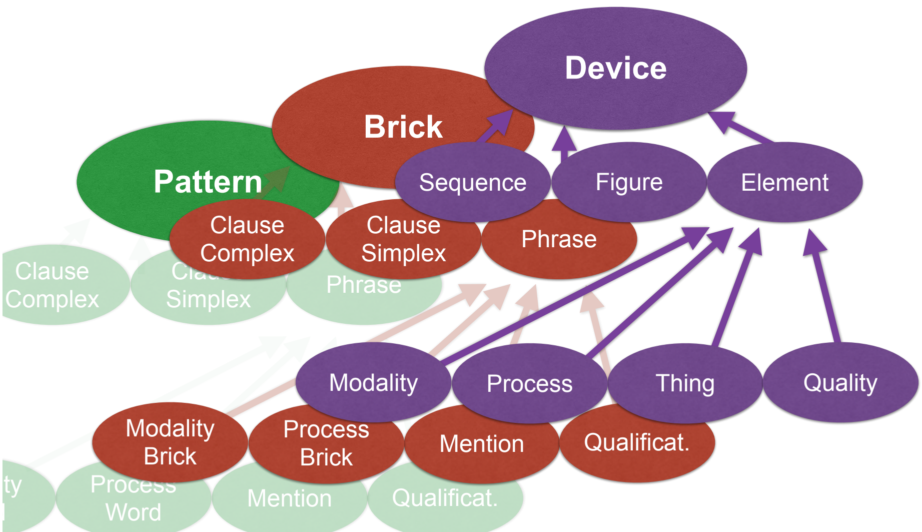
Tense[AUX] + Voice[FEAT]
The duke is giving the teapot to my aunt.

Phase[AUX] + Tense[FEAT] + Voice[FEAT]
The duke stopped giving the teapot to my aunt.

Tense[FEAT] + Voice[AUX]
My aunt was given the teapot by the duke.

Tense[FEAT] + Voice[FEAT]
The duke is here.

Trinocular View



Preliminary analysis

Contact
danielvale@uni-bremen.de

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Tacit contracts for wheelchairs

Daniel Couto Vale

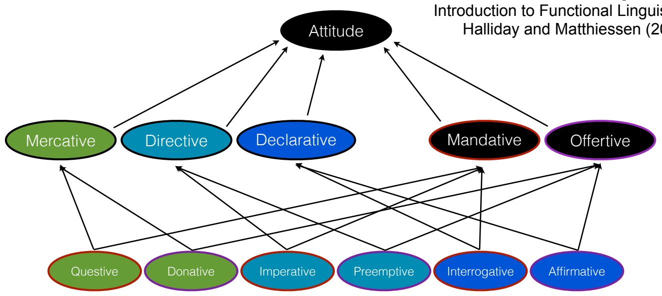
Rolland-BAALL Corpus

Anastasiou & Couto Vale (2012)

Attitude

Small Fragment of the Ontology

Exchange Theory
Introduction to Functional Linguistics
Halliday and Matthiessen (2004)



Imperative

[please] take me to the kitchen
- "fahr mich [bitte] in die Küche"

will you please take me to the kitchen
- "fährst du mich bitte in die Küche"

can you please take me to the kitchen
- "kannst du mich bitte in die Küche fahren"

Interrogative

will you take me to the kitchen
- "fährst du mich in die Küche"

can you take me to the kitchen
- "kannst du mich in die Küche fahren"

Affirmative

I would like to go to the kitchen
- "ich möchte in die Küche fahren"

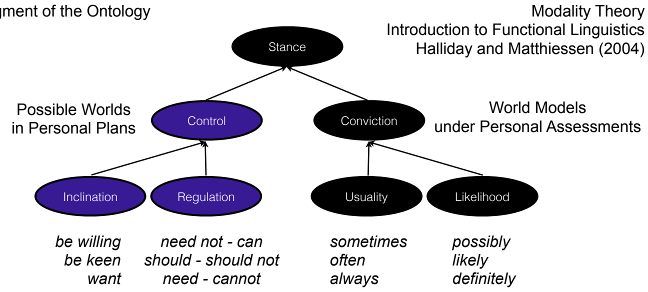
I need to open the door
- "ich muss die Wohnungstür öffnen"

I would like to do a mouth wash
- "ich würde gern eine Mundspüllung machen"

Stance

Small Fragment of the Ontology

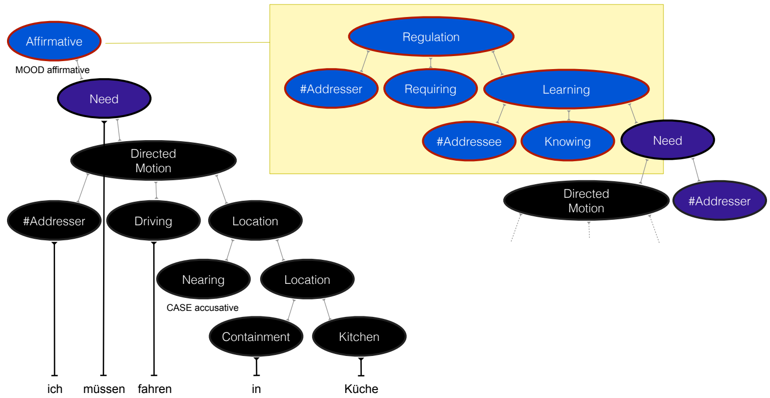
Modality Theory
Introduction to Functional Linguistics
Halliday and Matthiessen (2004)



Grammatical Metaphor

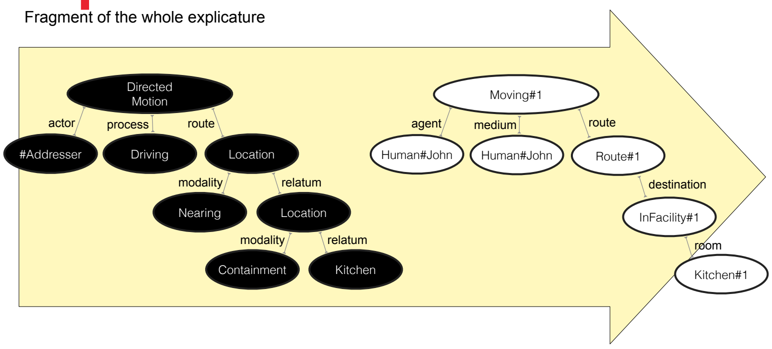
I need to go to the kitchen
"ich muss in die Küche fahren"

Grammatical Metaphor
Introduction to Functional Linguistics
Halliday and Matthiessen (2004)

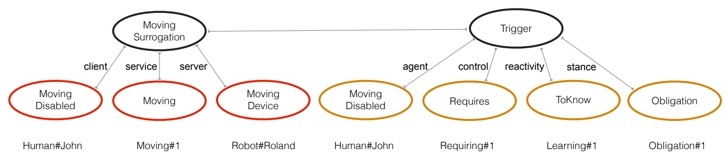


Explicature

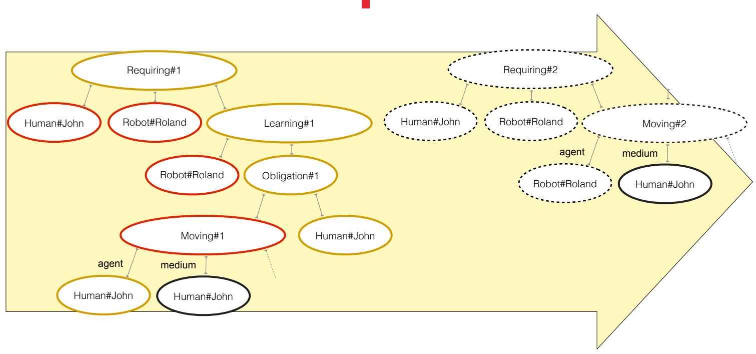
Fragment of the whole explicature



Tacit Contract



Contractual Implicature



Contact
danielvale@uni-bremen.de

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Uni Freiburg
Spatial Cognition I5-Diaspace

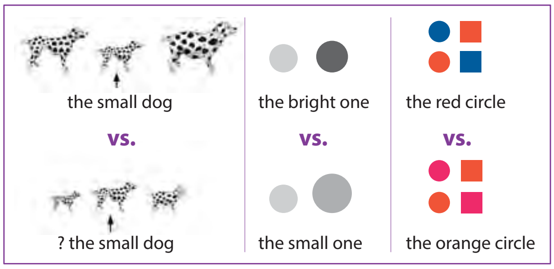
Context and Vagueness in REG

SPATIAL COGNITION
University of Bremen

Vivien Mast (viv@tzi.de), Diedrich Wolter (dwolter@informatik.uni-bremen.de)

Gradedness and Vagueness in REG

- Meaning of graded properties depends on context
- When several properties allow discrimination, humans choose the one with largest contrast to distractor set
- Category assignment is vague and always depends on context



gradedness *contrast* *vagueness*

A probabilistic framework for object descriptions

- Jointly maximize **discriminatory power** $P(x|D)$ and **acceptability** $P(D|x)$ of a description

$$D^* := \arg\max\left((1-\alpha)P(x|D) + \alpha P(D|x)\right)$$

- Probabilistic semantics for vague properties and spatial relations
- General modular feature modeling

Probabilistic Semantics

- $P(D|x)$: Probability that human accepts *D* as description of x
- $P(x|D)$: Probability that human selects object x given description D.

Calculated using Bayes' law: $P(x|D) = \frac{P(D|x) \cdot P(x)}{P(D)}$

- $P(x)$: Probability of randomly choosing object x: $P(x) := \frac{1}{N}$
- $P(D)$: Probability that D suits arbitrarily chosen object

$P(D) = \frac{\sum_{i=0}^{N} P(D|o_i)}{N}$

- Extends to descriptions with several objects: $P(x|y) \cdot P(y)$

Modeling Features as Conceptual Spaces

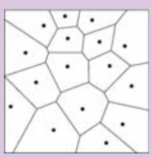
Gärdenfors' Conceptual Spaces

- Mixed multi-dimensional parameter space
- Similarity from proximity

Categorization

- Prototypes from sample members
- Voronoi tesselation: assign category of closest prototype

Color Space



Voronoi tesselation

Similarity

- Calculated based on Distance d:

$s(i,j) := e^{-c \cdot d(i,j)}$

- c: sensitivity function

Feature Models using Discretization

- Extreme cases form prototypes
- Categorization by Voronoi tesselation
- Acceptability [0,1]: normalized proximity to prototype
- Covers non-pareto-optimal combinations

	physical features			description features			
id	height h [cm]	weight w [kg]	w/h	height	$P(D\|x)$	corpulence	$P(D\|x)$
1	46	27	0.59	SHORT	0.08	SKINNY	0.87
2	35	20	0.57	SHORT	0.92	SKINNY	1.00
3	55	45	0.82	TALL	0.62	FAT	1.00
4	60	45	0.75	TALL	1.00	FAT	0.45
5	34	26	0.76	SHORT	1.00	FAT	0.57

- Context influences description

Feature Models using Similarity

- Graded acceptability]0,1] based on similarity function
- No explicit categorization
- Sensitivity c depends on generality of category (more general → smaller c)
- Usage of secondary category for better distinction if necessary

	description features				description
id	$P(tall\|x)$	$P(short\|x)$	$P(skinny\|x)$	$P(fat\|x)$	
1	0.141	0.237	0.976	0.005	the tall skinny dog
2	0.002	0.990	1.000	0.002	the short skinny dog
3	0.779	0.012	0.002	1.000	the tall fat dog
4	1.000	0.001	0.041	0.628	the tall dog
5	0.001	1.000	0.024	0.751	the short fat dog

Outlook

- Similarity-based acceptability values for complex features
- Learning of dimension weights and sensitivity parameters from experimental data using Machine Learning technique

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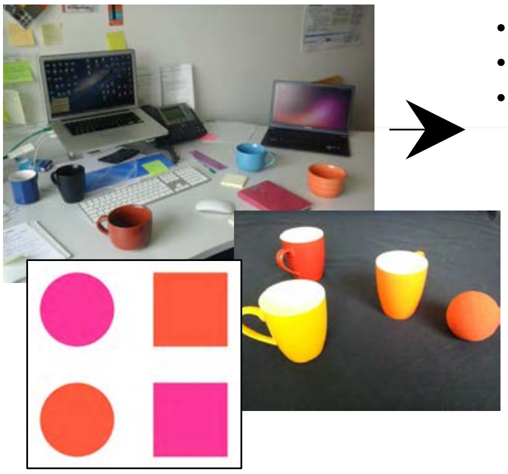
Referential Grounding for Situated Communication

Vivien Mast (viv@tzi.de), Daniel Couto Vale, Zoe Falomir, Mohammad Fazleh Elahi

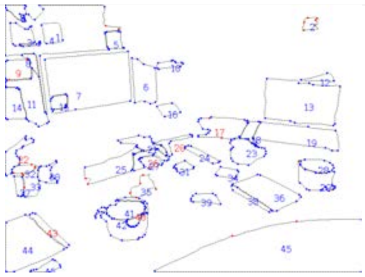
SPATIAL COGNITION
I5-Diaspace

Scene



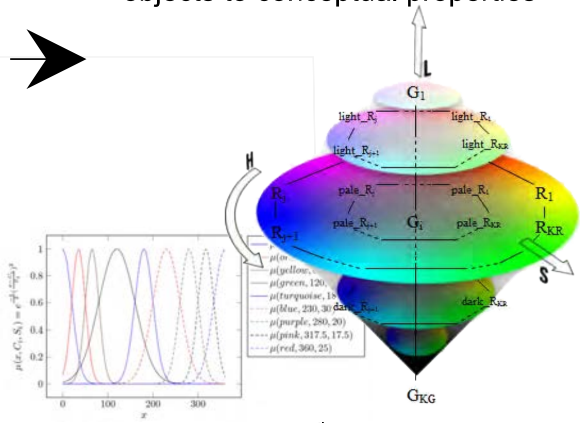
Perceptual Module

- Detect objects
- Extract relevant points
- Extract metric property values



Property Models

- Probabilistic mapping from objects to conceptual properties



Probabilistic Reference and Grounding Mechanism

- **Acceptability/Nomenclatory Power**: $P(D|x)$
  Probability that humans accept description *D* for object x
- **Resolvability/Discriminatory Power**: $P(x|D)$
  Probability that humans identify object x with description D

$$P(x|D) = \frac{P(D|x) \cdot P(x)}{P(D)}$$

- **Appropriateness**: $(1-\alpha)P(x|D) + \alpha P(D|x)$

Referring Expression Generation:
Description rank by appropriateness

Reference Resolution:
Object rank by acceptability

Grounding Dialogue

Success

```
R: Where do you want
   me to go?
H: To the large box.
R: The large box?
   Ok, I'm going
   there.
```

Confirmation

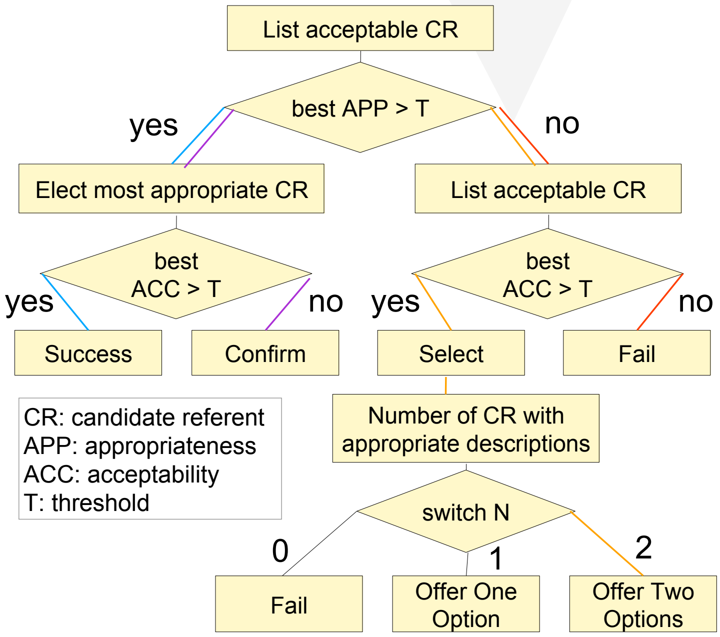
```
R: Where do you want
   me to go?
H: To the small box.
R: Do you mean the
   one in front of
   the small ball?
H: Yes.
R: Ok, I see it,
   I'm going there.
```

Selection

```
R: Where do you want
   me to go?
H: To the box.
R: Do you mean the
   large box or the
   one in front of
   the small ball?
H: I mean the large
   one.
R: Ok, I'm going
   there.
```

Failure

```
R: Where do you want
   me to go?
H: To the long box.
R: Sorry, I don't
   see any long box.
```



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MARIE CURIE ACTIONS
UNI FREIBURG

I6-[NavTalk]

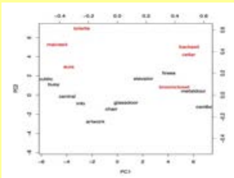
I6 The inference process

I6-[NavTalk]

How do people find their way in complex environments?

- Which clues from the environment do people attend to?
- How do they interpret and use these clues as a basis for navigation decisions?
- How does generic previous knowledge come in?
- What strategies do they use to fill in their knowledge gaps when navigating unknown complex environments?

Freiburg experiments

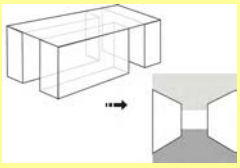


1. Questionnaire: Assessing participants' expectations about spatial relations between targets and certain landmarks

Targets: common targets in public buildings, e.g., main entrance, back exit, restrooms, main auditorium etc.

Landmarks: common landmarks found in public buildings, e.g., stand-up display, artwork etc.

2. Picture selection task: Participants choose the picture with the hallway leading them to the target, pictures were snapshots from a virtual environment differing in landmarks and geometry



3. Validation of findings in navigation task using the virtual environment of Experiment 2, collecting language data

Bremen empirical studies

1. Early cognitive mapping in a complex real building
- Route descriptions of an unfamiliar complex building
- Route following of expert and novice indoor route descriptions

2. Of a procedurally experienced room
Descriptions of a collapsed mock-up environment

3. Of an impossible virtual environment
Think aloud during navigation; verbal report during sketch drawing

Methods

Think aloud during navigation and retrospective reports reveal inference processes involved in early cognitive mapping

Descriptions of environments based on incomplete information reveal properties of the partially developed cognitive maps

Results

Spatial inferences in real and virtual buildings

Global structures

Expectations about architectural features of central and peripheral areas which support cognitive mapping and navigation

Local structures

Layout inferences based on knowledge about geometric forms and prior experience with buildings

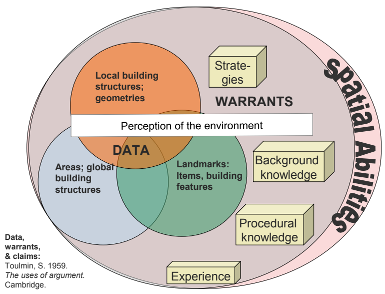
Landmarks, items

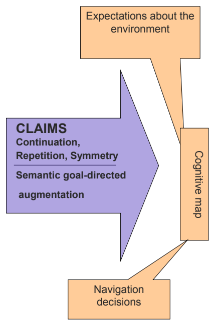
Inferences based on building features and items: goal-specific associations based on sensory input:
- objects and landmarks
- architectural features – corridor geometry, spaciousness
- decoration – illumination, furnishing, wall paint, artwork
- crowdedness
- auditory input: (noise, chattering, elevator)

Analytic categories used and refined

- spatial elements
- linguistic structure
- coherence
- granularity
- linguistic markers

All shed light on the underlying cognitive map and on cognitive states of the speaker





Frankenstein, J., Büchner, S., Tenbrink, T., & Hölscher, C. (2010): Influence of geometry and objects on local route choices for wayfinding. *Spatial Cognition VII,* 41---53.
Frankenstein, J., Brüssow, S., Ruzzoli, R., & Hölscher, C. (2012). The language of landmarks: the role of background knowledge in indoor wayfinding. *Cognitive processing 13*(1), 165---170.
Tenbrink, T., Bergmann, E. & Konieczny, L.; Wayfinding and description strategies in an unfamiliar complex building.
Proc. 33rd Annual Conference of the Cognitive Science Society, 1262---1268.
Bergmann, E., Tenbrink, T. Hertzberg, C. & Gondorf, C (in prep.): How descriptions structure an unstructured environment.

Conclusion

- Previous experience guides interpretation of global building structure as well as local building features and landmarks to support navigation decisions

- Low-level inference processes fill in information to support the development of a cognitive map while high-level semiotic interpretation guides goal-directed search

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Basis for inferences: human cognitive maps

SPATIAL COGNITION

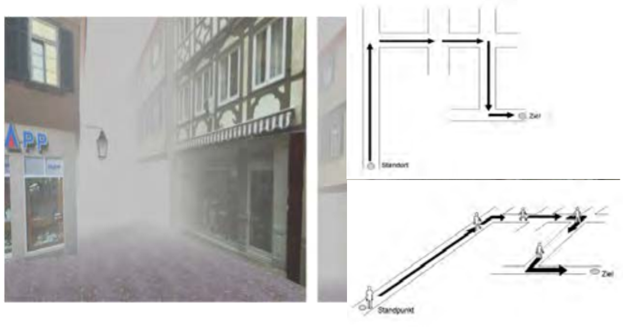
The relation between route and survey knowledge

Method: 23 participants were tested in Virtual Reality on their spatial knowledge of their home town. Performance in the route knowledge task (from two different perspectives) was compared, and related to a survey knowledge task within the same area.

→ While participants relied on a North-up reference frame for the survey task (pointing), they did not do so for they route knowledge task (indicating a route).

→ Most likely, route and survey knowledge rely on different mental representations.

Meilinger, T., Frankenstein, J., & Bülthoff, H. H. (2013): Learning to navigate: Experience versus maps. Cognition 129, 24---30



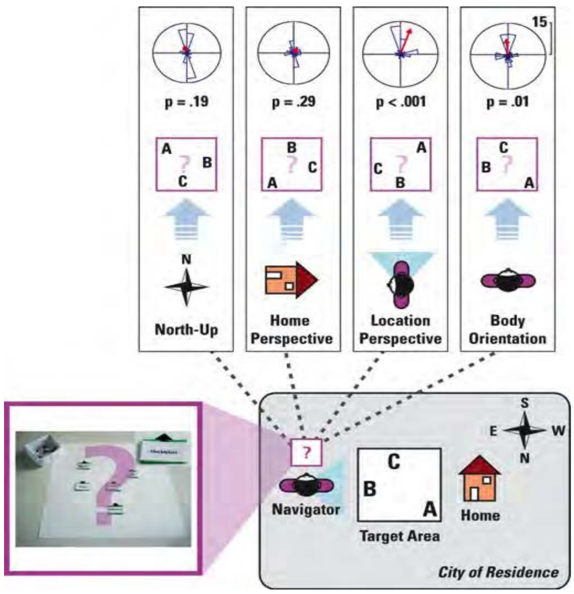
Participants facing a virtual model of their hometown (left side) indicated route sequences imagining a map perspective (upper right hand picture) or walking perspective (lower right hand picture).

Are cognitive maps adjusted based on viewing direction or position within the environment?

Method: 60 visitors in pubs located North, East, West, South and within the city centre of Tübingen were asked to map the spatial configuration of well-known targets located within the city centre.

→ Participants tended to adjust their maps due to viewing direction (e.g., draw a South-up map when facing South) or their position relative to the target area (e.g., draw a West-up map when located East of the target area).

Meilinger, T., Frankenstein, J., Simon, N., Bülthoff, H. H. & Bresciani, J. P.: Humans use combined ego-allocentric reference frames. (submitted).



Circular histograms: obtained map orientations relative to the four orientations. P-values indicate clustering around the predicted orientation.

Are cognitive maps adjusted due to moving direction or spatial planning?

Method: 36 participants drew a map of Freiburg, facing East while driving West in a tram (or facing West while driving East).

→ Maps reflected participants' viewing direction rather than their moving direction.

The case of spatial planning: data analysis in progress. 40 participants were asked to conduct a "plan a day" task, and sketch a map of the spatial relation of the locations visited in the task.

Targets within the Freiburg city centre used for the experiments on moving direction and spatial planning.
Tram line

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Spatial inferences in unknown buildings

SPATIAL COGNITION

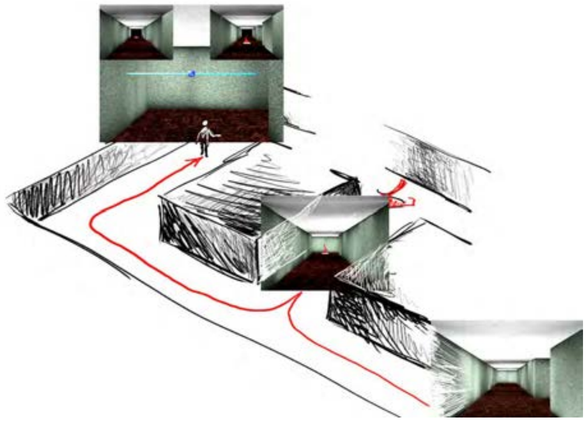
Spatial expectations in built environments

Experiment 1 (explorative paradigm)

Method: 40 participants watched video sequences leading them along a trajectory in a rectangular, building-like virtual environment. Stopping at an intersection, participants were asked to sketch the expected ongoing geometry on a sheet of paper.

Sketches revealed:

- Participants expect rectangular structures.
- Participants tended to close loops (i.e., connect already experienced parts of the environments).
- Participants expected regular structures, i.e., if the explored environment suggested a certain pattern (i.e. regularities), participants tended to expect patterns to repeat.



Experiment 2 (confirmative paradigm)

Methods like in Experiment 1, but participants had to pick out of two images the alternative they expect to show the more likely continuation. Pictures were designed to either suggest loops, ongoing symmetry or pattern repetition.
Data analysis is in progress, we test for strategy preferences depending on the properties of the environment experienced, as well as for general preferences depending on spatial ability.

Method: Participants watched a film leading them along a trajectory in a virtual environment. Stopping at an intersection, they either sketched ongoing structures expected on paper (Experiment 1) or picked out of two images the alternative showing the more likely continuation (Experiment 2)

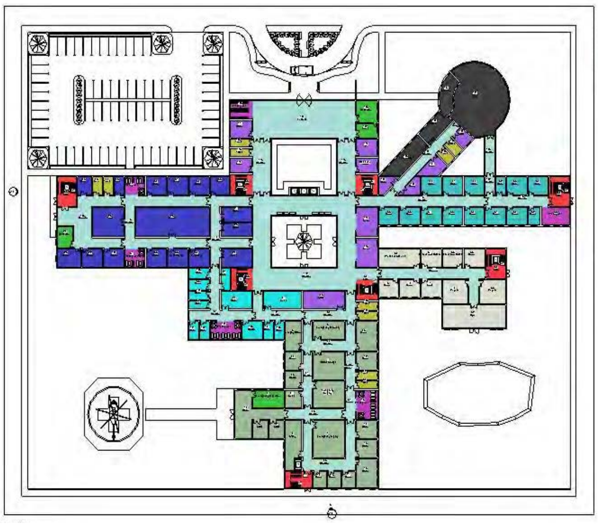
Individual differences in spatial inferences within complex environments

We are currently piloting an experiment based on a very complex, more naturalistic environment, a virtual hospital building containing several building parts and three floors.

Method: Participants learning the position of indoor targets by navigating along a guided route, while experiencing views of the hospitals surroundings.

Task: Participants are asked to point to the targets learned. Starting locations involve not only locations visited along the route, but locations in the surroundings only viewed from inside the hospital (e.g., the parking lot, the helicopter patch).

To solve the task of pointing from not yet experienced locations, participants have to infer their position by completing their cognitive map, by perspective change, expectation or guessing. We expect participants' abilities and strategies to vary with spatial ability, therefore, the experiment includes spatial tests like e.g., Mental Rotation, SBSODS and the Bergen Left-Right Discrimination Test.



Virtual hospital environment
This environment has been designed for spatial experiments in cooperation with architects. While it is not a virtual copy of an existing hospital, it has the properties of a hospital (i.e., is architecturally and functional plausible) while meeting the needs of an environment suitable for complex spatial experiments.

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Representation of a collapsed environment

SPATIAL COGNITION

A7-[FreePerspective]

I6-[NavTalk]

Motivation

Search & Rescue equipment poses challenges to the user

Perceptual and conceptual challenges:

Discrimination of objects and persons

Unusual perspective(s)

Device movements

Lack of discriminative features

Can novices derive coherent representations based on this input?

What effect does time pressure have?

Empirical Study

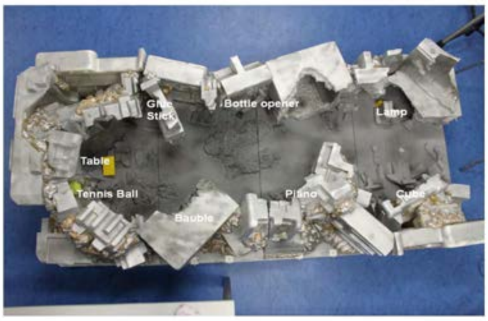
36 students without prior knowledge

Material: mock-up of a collapsed room

Tasks:

- Participants watched and navigated a film shot inside the mock-up, and memorized object locations
- They described where they had found them
- and drew a sketch of the room

Conditions: time pressure / no time pressure



Analysis

Performance measures:

Coherence of texts and specificity of localisations

Coherence: consistent description strategy

Specificity: use of global markers (i.e. projective terms)

Accuracy of sketches

Also: spatial ability test (Cross Section Test)

Sketches and descriptions alike show variation from incoherent collages to integrated representations

Sample sketch of object locations

Sample sketch of object locations

Results

- Identification of objects was harder than discrimination
- Localisations lacked the coherence and specificity of typical room descriptions

Conditions:

We computed a generalized linear model with sketch accuracy, time pressure and spatial ability as fixed effects, and specificity as response variable. Time pressure was not decisive for specificity, but sketch performance ($p < .05$) and spatial ability ($p < .05$) predicted the quality of descriptions

Progression

The first room I went into, there was something. In the second room was the lamp, thus it was left, stood there in the corner on the ground. Then, in the third, there was this I don't know.. dogleash or what it was down on the ground. Then, there left again was the camera up there or, well it probably wasn't a camera

Temporal structure
Markers: ordinals, motion verbs, sequentials

Anchor

If you look from the start view, then there was the tennis ball squeezed in in the middle. And next to it, hidden was something silvery, matte, I don't know. And uhm, a little further to the right was the bottle opener. Then, uhm, to the left side of the tennis ball was this cube, that you can turn. And right, the lamp, it was uhm, uh, also a little right of the tennis ball.

One single salient relatum: the tennis ball
Markers: relational terms with target relata

Room

When I had finally understood how the film functioned I know that at the front, well, at the very front directly on the right side must have been such a little lamp, such a table lamp. And on the left side at the front was this little cube which was a key ring, this magic cube or how you say that. And I think at the very back and left was something like, I don't know, whether it was a perfume flask.

Fixed viewpoint onto the room
Markers: room-related projective terms

Collage

[I remember] The ball, because it was often displayed. It was squeezed in between the stones. And then in front of it on the ground was such a hubcap. And then there was a bottle opener. And what else did I see? Right, this cube. But where it was, I don't know. The lamp was on the floor, if you go towards the ball and then turn right, as far as I remember. And there was something at the end, too. That was somewhere left and above the ball.

Collage of localisation types
Markers: progression, room and anchor markers

Conclusion:

Time pressure was less decisive than spatial skill when integrating this perceptually difficult environment

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Inferences during exploration

SPATIAL COGNITION

A5-[ActionSpace]

I6-[NavTalk]

Impossible worlds paradigm

If humans generated integrated cognitive maps online, they should detect violations of euclidean metrics right away

But: performance rates in possible and impossible worlds are equivalent

- Which processes are involved when acting in possible and impossible virtual environments?
- What kind of representation is generated?
- How are violations handled when they are detected?

Empirical Study

Participants: 40 University students

Material: 4 virtual environments; 2 possible, 2 impossible

Conditions: between subjects: think aloud/ no think aloud

Procedure: navigation + shortest path task + sketching

Questionnaires: spatial ability, spatial strategies

Preliminary Results

Shortest Path Performance

Equivalent performance in possible and impossible worlds

Think aloud has no effect on performance

The Mental Collage

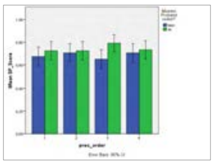
- abstract shape representation
- object order
- distance information
- .. all exist side by side

If forced to integrate, mismatches MAY clash - but typically DON'T

Verbalisation during sketching participant 21	Stages of awareness, participant 21	Consolidation processes (between subjects)
No awareness or unconscious consolidation processes		
This time it was a rectangle. [spontaneously and confidently draws rectangular shape]	abstract representation is retrieved	no awareness: rectangle consolidation: triangle: during navigation, angles are ignored
In the short corridor, there was for once the p-	object order and distance are added	consolidation (unconscious): misrepresentation of distances, angles or number of objects
Conscious detection of mismatches		
[hesitation] oh, uhuh. painting- and[hesitation] table- But I said that [break] Well, I can position the objects: painting, table [draws objects on opposite sides], the three points and the lamp. But that doesn't match the corridor's lengths. [sighs, break] I am certain the lamp and the painting were in the short corridors. But the lamp was after the painting. [break]	mismatch is noticed	problems are detected
But this is- [begins new figure] short, short, long- [break] yes.	new attempt to integrate perceived object order, distances and angles	mismatches are either resolved or explained with lack of memory
But this is-. Well, this is not possible, that short, short- because there was no kurve there- and then long, long: that's not possible! Yes, that is not possible.	awareness of impossibility	solution

Think Aloud during Navigation:

- Layout inferences based on angles
- Consolidation processes to handle violations in triangular environment
- No awareness in rectangular environments



Sketching:

Overall symmetric shapes that misrepresent either

- distances,
- angles, or even
- number of landmarks

Stages of awareness:

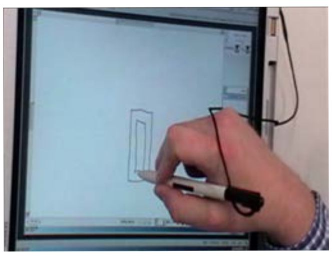
1) no observable trace of doubts unconscious consolidation

2) detection of problems conscious consolidation

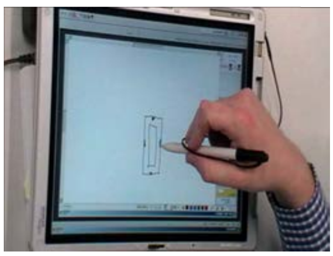
3) detection of problems leads to revision of symmetric shape

4) and full integration/ awareness

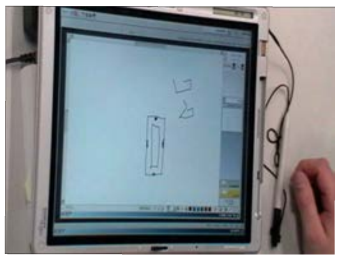
abstract geometrical shape



object order and distance



don't match



Conclusion

No online integration during navigation and performance

Full integration through offline reasoning is the exception

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Navigational Strategies in Unfamiliar Urban Street Networks: The Case of Soho

SPATIAL COGNITION [I6–NavTalk]

Claudia Cialone, Thora Tenbrink, Christoph Hölscher, Hugo Spiers

In an unfamiliar urban street network:
How do people navigate with an incomplete map?
How do they conceptualize the environment in sketch-maps?
What is their orientation and sense of direction accuracy ?
How do they feel whilst 'wayfinding' ?

Maps and Routes for the Study

Incomplete Map of Soho & Landmarks


Preto Brazilian Stakehouse


Pizza Pilgrims

Meeting & Debrief point

Soho Square Gardens

End training &Start testing point

Regents Place


St. James Tavern


John Snow Pub


Vasco&Piero Pavillion


COS

Soho Illustrative Plan of Navigation

Soho with all the streets shown
Red Line =Training route
Red dots = 6 Landmarks
Light blue line = Testing route
Dark blue numbered dots = 36 Decisional Points

The maps are a pen-paper remake of a Soho Google Map.

Method

Participants
17 participants: 6 male, 11 female; mean age: 30 years; native English speakers; not very familiar or not familiar with Soho

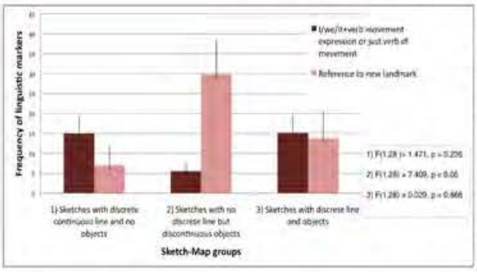
Procedure
Tasks at each decision point on the complex testing route, with respect to each of the 6 landmarks learned on the simple training route :

1) Euclidean distance in meters
2) Shortest walking path
3) Direction to get to the landmark
4) Choice to consult the incomplete map for 'some time'.

Final Debrief
General questions about the experience.
Map-sketch task: to complete the Soho incomplete map by adding in everything remembered from the testing route.
SBSOD (Hegarty et al., 2006) and FRS Self-Assessment navigational tests.

Think Aloud verbalizations were collected during navigation and tasks-accoplishement.

First Results



Cognitive Discourse Analysis (CODA)
Of sketch-map TAs (Tenbrink, 2014), allowed the distinction of 2 main linguistic markers systematically used by participants :
1) Expressing first person movement in space: (subject) + verb of motion
2) Expressing objects position in space: (there is/are) + landmark

They were grouped into 2 cognitive semantic categories defined as:
1) Dynamic route conceptualization/memorization
2) Static landmark conceptualization/memorization
3) Dynamic&Static conceptualization/memorization

Sketch-Maps | **Corresponding TAs**

1


...so I think *we went... we started* at Regents place, and *we went down* this way, and then *we went* that way and then I think *we came back up* again... hum... that way then *we went towards* Piccadilly, Regents street and then *we sort of came back up towards* Soho...I know *we crossed* over there cose at one stage *we got to* ... Carnaby street is up here... then I think *we came back across* couple of times...

2


...I know *there was a Rustle & Bromley* here so I'll put a Rustle & Bromley and *there was also a Hamneys* cose people were blowing bubbles at us.. and I know *there was Hugo Boss*... somewhere...and then I know *there was also like Banana republic* or whatever...I can give you the shop names probably...*Poland street*... I know *there's a road there* that continues on...

3


...I do remember *stopping* many different times.. seemingly *came across up North*... how did *we go North of* JS pub.. I can remember seeing.. I can remember seeing *the BT tower*... what did we do.. maybe *we came*... we didn't certainly ...*didn't get to* Poland street so perhaps something a bit like this... I mean *there were building works* dotted around the place...*there's many different stop-off points* hum...

Sketch-map Analysis
Sketches were classified according to visual patterns (cf. Klippel et al., 2003) as follows:
1) A discrete continuous line expressing the sequence of route steps from start to end.
2) A cluster of statically positioned landmarks
3) A dynamic discrete line with few static landmarks

Statistical GLMM analysis
Shows a conceptualization alignment between the sketch-map groups and the linguistic categories

Preliminary Conclusions
People memorise travel through an unfamiliar space with reference to either:

1. The landmarks encountered
2. The route travelled
3. Both landmarks and the path

Hegarty, M., Montello D.R., Richardson, A.E., Ishikawa T., Lovelace K. (2006). Intelligence, 34, 151-176.
Klippel, A., Tappe H., Habel, C. (2003). Pictorial Representations of Routes: Chunking Route Segments during Comprehension.
Tenbrink, T. (in press) Cognitive Discourse Analysis: Accessing Cognitive Representations and Processes Through Language Data. Language and Cognition.

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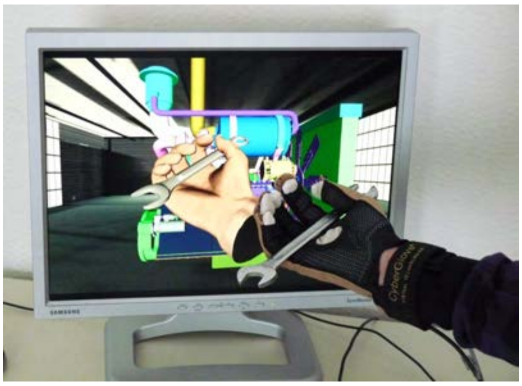
I8-[DextrousSpace]

I8-[DextrousSpace]
Dextrous Spatial Interactive Manipulation of Virtual Objects

René Weller — *University of Bremen*
Matthias Teschner — *University of Freiburg*
Gabriel Zachmann — *University of Bremen*




Virtual assembly simulation

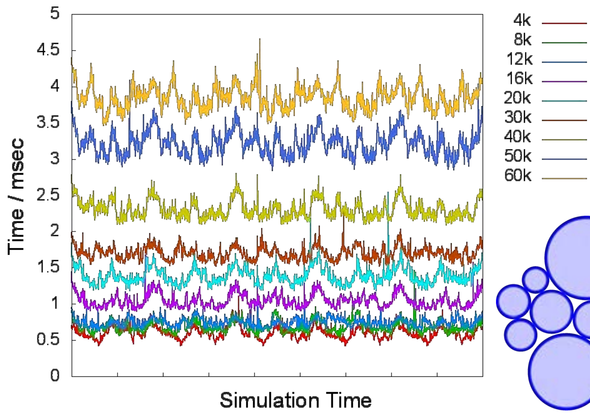

Entertainment

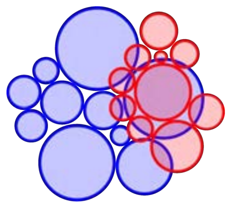
Natural Interaction

- Direct spatial manipulation methods for virtual objects
- Grasping, manipulation, movement
- Physical plausibility
- Real-time applicable

Collision Detection for Deformable Objects in Constant Time[1]

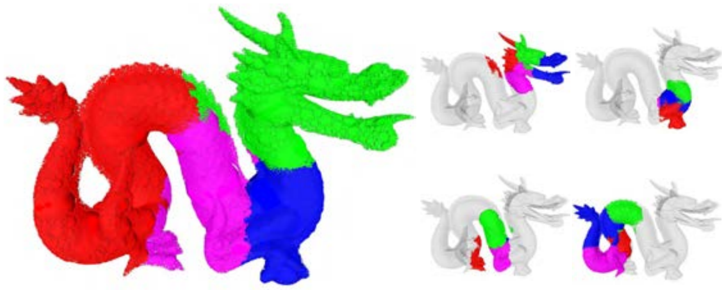
- Proven O(n) complexity for the overlap of two sphere packings
- New collision detection algorithms
  - Worst case sequential time: O(n)
  - Worst case parallel time: O(1)
- Running time: < 1msec for 30k spheres





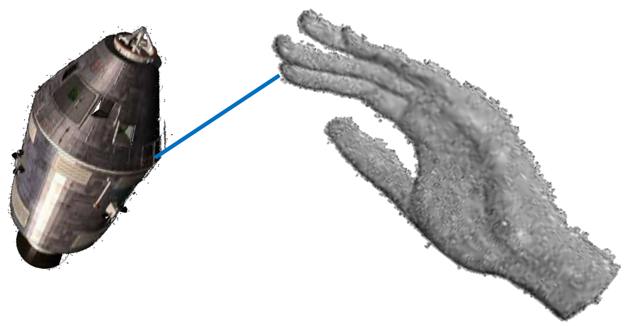
Improved Bounding Volume Hierarchies[2]

- BVHs for higher branching factors
- New hierarchical parallel Batch-Neural-Gas clustering algorithm
- 4 times faster query times than simple heuristics



Real-Time Distance Queries for Point Clouds[3]

- Online hybrid CAD/point cloud proximity computations
- Supports cheap point cloud sensors like Kinect
- New massively-parallel algorithm using GPU acceleration
- Running time: < 10 msec for 5 million points



Publications:
1) Weller, Frese, Zachmann, „Parallel Collision Detection in Constant Time“, Vriphys 2013
2) Weller, Mainzer, Srinivas, Teschner Zachmann, „Massively Parallel Batch Neural Gas for Bounding Volume Hierarchy Construction“, Vriphys 2014
3) Kaluschke, Zimmermann, Danzer, Zachmann, Weller, „Massively Parallel Proximity Queries for Point Clouds“, Vriphys 2014

Spatial Cognition
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N1-[SocialSpace]

N1-[SocialSpace]: Social Learning for Cognitive Robots

Junior Research Group within SFB/TR8

Kai O. Arras, *Social Robotics Lab, University of Freiburg*

SPATIAL COGNITION

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Overview

- **Motivation**: growing number of robots deployed in human environments
- **Research objectives**: give cognitive systems the ability to sense and act in a socially acceptable way:
  - Develop key technologies for socially informed perception, (spatial) cognition, learning, and action
  - Safer, more effective and more acceptable robot systems

Infrastructure (WP1)

- **Goal:** establishing the Junior research group
- **Robot DARYL**
  - general-purpose HRI research platform
  - unique, custom-made design
  - expressive, mildly humanized look
  - 10 degrees of freedom
  - sound, LED, pointing modality
  - real-time RTOS XO/2

People Tracking under Social Constraints (WP2)

- **Goal:** to "socially inform" a people tracker by incorporating domain knowledge on humans either learned from data or described by models from cognitive and social science
- **Tasks and achievements:**
  - Person detection in 2D, 3D, RGB-D data *[AAAI'10, IROS'11, ICRA'11, ICRA'12]*
  - Socially informed people tracking *[ICRA'10, ICRA'11, IJRR'11]*
  - Unsupervised learning of dynamic objects *[RSS'08, AURO'09]*
  - Tracking groups of people *[ICRA'09, IJSR'10, RSS'13]*

Socially-Aware Robot Navigation (WP3)

- **Goal:** achieve efficient yet socially-aware navigation behavior by informing a motion/task planner by learned human behavior models
- **Tasks and achievements:**
  - Learning to plan under social constraints *[ICRA'11, IROS'11, ICAPS'11]*
  - Slipstream navigation *[CogSys'08, STAR'10, IROS'12]*
  - Unsupervised learning of crossing trajectories *[IROS'12]*
  - FLIRT: interest points for 2D range data *[ICRA'10, ISER'10, STAR'14]*
  - Learning to navigate human crowds *[IROS'14]*

Multi-Hypothesis Grouping and Tracking

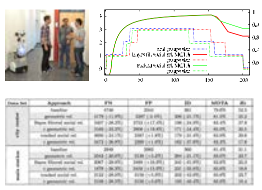
- **Motivation:** analyze human groups, learn socially normative motion behaviors for navigation and interaction
- **Contributions:** *recursive* social grouping hypothesis approach, moving sensor, real-time, 2D laser data *[RSS'13, award nomination]*
- **Approach:** extension of multi-hypothesis tracking (MHT) approach by intermediate tree level at each time step, on which **social grouping hypotheses** spring off from parent hypotheses *[Lau et al. ICRA'09, IJSR'10]*
  - In this way, we can **simultaneously hypothesizes** over data associations (between observations and tracks) and models (group formations)

Learning socio-spatial relations

- Detection of social relations via coherent motion indicators from social science
- Leads to social network graph, graph-cutting produces group candidates

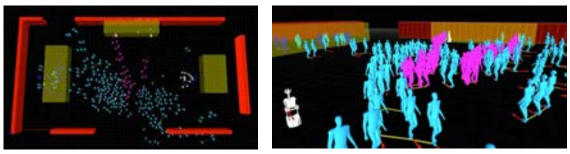
- Individuals in groups form stable patterns
- We learn such patterns in an on-line fashion using a particle filter with Brownian proposals and priors from social science
- Both relations **improve person-level tracking** by enabling constraint-based motion predictions of occluded tracks and adaptive track occlusion probabilities

- **Results**
  - Two large unscripted outdoor data sets collected at the Freiburg city center
  - Our approach reflects group formation changes much faster than baseline
  - 40% fewer track identity switches and 28% fewer false negative tracks
  - Cycle time 17,6 Hz on laptop PC

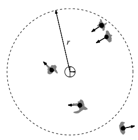


Learning to Navigate Crowds of People

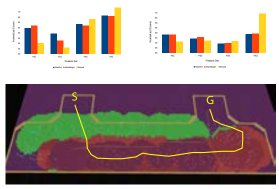
- **Motivation:** learning navigation behavior from demonstration for dense crowds of people
- **Contributions:** pedestrian simulator with state-of-the-art models from social science, comparative study on different features and learning algorithms, efficient yet socially conform behavior *[IROS'14]*



- **Approach:** inverse reinforcement learning (IRL) , allows to model the factors that motivate actions, not only the actions themselves
  - Characterizing the robot's social surrounding by different feature sets that encode person density, relative proximity, speed, and motion direction
  - Learning from few operator demonstrations
  - For inference, IRL produces dynamic cost maps used to guide a Dijkstra-based motion planner



- **Results**
  - Defining *objective* (task-related) and *subjective* (user comfort-related) performance measures
  - Robot has learned to efficiently join, cross and leave pedestrian streams
  - Results from three different scenarios give valuable insights on feature design (important), IRL algorithm (less important), state space representation (very important)



Best path from start (S) to goal (G)

Dissemination and Outreach

- **Publications:** 25 peer-reviewed journal and conference papers (e.g. IJRR, AURO, RSS, AAAI, ICRA, ICAPS, IROS), 4 workshop papers, 3 editorials
- **Teaching:** 1 PhD thesis, 5 Ms/diploma theses, 10 Bs theses, 1 specialized course "Human-Oriented Robotics"
- **Awards and distinctions:** RSS 2013 **best student paper award** finalist, **most cited paper** of IROS 2011 (32% acceptance rate)
- **Follow-up:** [N1-SocialSpace] has led to the EU FP7-project **SPENCER**, "Social situation-aware perception and action for cognitive robots", K.O. Arras (coord.)

[DesignSpace]

Assistive Intelligence for Spatial Design

Carl Schultz, Mehul Bhatt

www.design-space.org

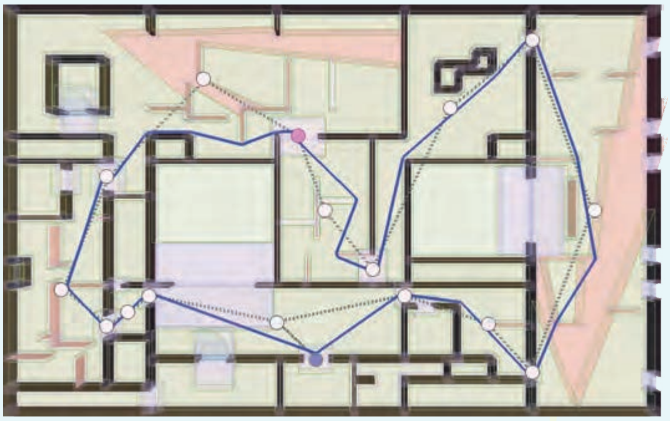
SPATIAL COGNITION

SFB/TR 8 Spatial Cognition
Project [DesignSpace]

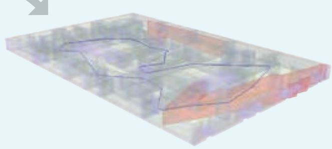
Computational Design Analysis

User-centred design analyses during the master-planning stage should be one of the most crucial considerations in the spatial design of large-scale public environments such as airports, museums, train stations, exhibition halls, hospitals; all places with clearly definable functional purposes. In our research on computational design analysis in Project DesignSpace, we developed a range of analytical aids that support the designer from the during the early master-planning stage. In the context of wayfinding analyses for circulation planning, our system: **(1)** derives the logical structure of topological connectedness, **(2)** generates all possible topological and geometric routes, **(3)** derives affordance-based routes aimed at predicting the motion pattern of special interest groups, **(4)** performs hypothetical 'what-if' scenarios by providing comparative analyses, **(5)** visualizes not only the explicitly existing physical space, but also the implicitly existing affordance spaces, physical and non-physical artefacts etc. Our system conforms to emerging standards such as Industry Foundation Classes (IFC), Building Information Model (BIM), and commercial design software (e.g., ArchiCAD).

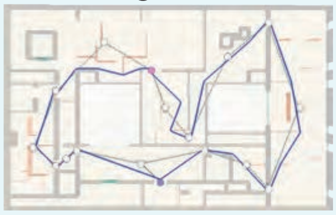
Standard Route Graph



Museum Calouste Gulbenkian, Lisbon, Portugal



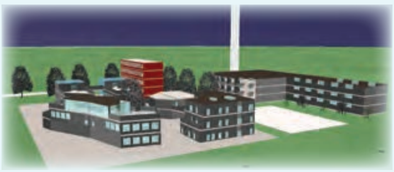
Walking Route



Wheelchair Route

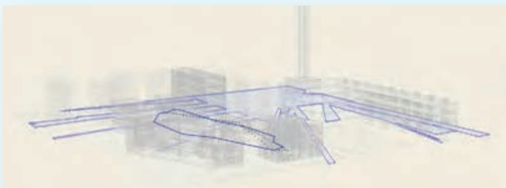
Isovist

Multi-storyed Building

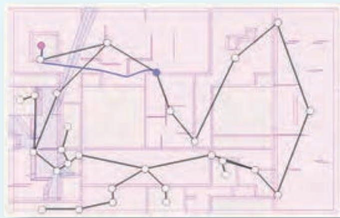


Case-study: Academic Interchange, Bremen

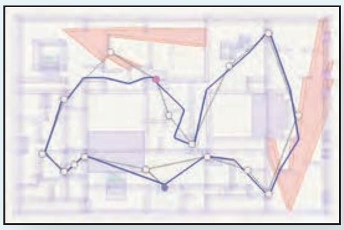
Macro Circulation Patterns



Routes and Visiblity



Indoor Navigation



Avoid Functional Spaces

Privacy / Security

Avoid Range Space of Camera

Emergency Scenario

Avoid Empty Space or Follow Walls

References

- Bhatt, M., Schultz, C., Thosar, M. (2014). Computing Narratives of Cognitive User Experience for Building Design Analysis: KR for Industry Scale Computer-Aided Architecture Design, in: Principles of Knowledge Representation and Reasoning: Proceedings of the 14th International Conference, KR 2014, Vienna, Austria.
- Universal Design and the Built Environment. http://www.design-space.org/edra45

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CLP(QS) - A Declarative Spatial Reasoning System

Carl Schultz, Mehul Bhatt

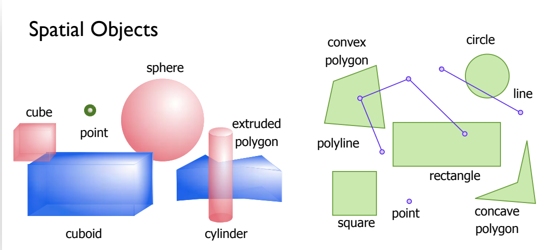
email: {cschultz,bhatt}@informatik.uni- bremen.de

www.spatial-reasoning.com

SPATIAL COGNITION
SFB/TR8 Spatial Cognition
Project [DesignSpace]

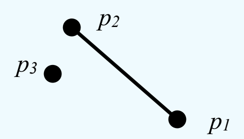
Abstract

We present results of the ongoing development of a declarative spatial reasoning system within the context of Constraint Logic Programming (CLP). The system is capable of modelling and reasoning about qualitative spatial relations pertaining to multiple spatial domains, i.e., one or more aspects of space such as topology, and intrinsic and extrinsic orientation. It provides a seamless mechanism for combining formal qualitative spatial calculi within one framework, and provides a Prolog-based declarative interface for AI applications to abstract and reason about quantitative, geometric information in a qualitative manner. Based on previous work concerning the formalisation of the framework [1], we present ongoing work to develop the theoretical result into a comprehensive reasoning system (and Prolog-based library) which may be used independently, or as a logic-based module within hybrid intelligent systems.



Introduction

- spatial reasoning is **hard** - infinite domains, multiple constrained dimensions
- qualitative spatial reasoning - commonsense abstractions of geometric relations
- constraint logic programming (CLP) - extend logic programming to handle constraints over different domains e.g. CLP(Reals)
- **idea**: CLP over qualitative spatial domains - express and solve declarative, high-level constraints over spatial entities (e.g. points, line segments, regions)
- encoding qualitative spatial relations as polynomial expressions, solve by dedicated algebraic solvers

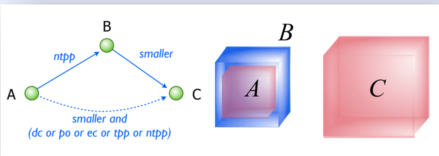


$p_3\ \textit{left}\ p_1 p_2 \equiv x_2y_3 + x_1y_2 + x_3y_1 - y_2x_3 - y_1x_2 - y_3x_1 > 0$

- seamless integration with standard KR
- QSR with complete ***unknowns***
- mix ***types*** of spatial ***relations***
  - *- topology* *- orientation*
  - *- mereology* *- distance*
  - *- size* *- translations, rotations*

```
?- A=cube(_,_), B=cube(_,_), C=cube(_,_),
|      topology(rcc8(ntpp), A,B),
|      size(smaller, B,C),
|      size(SizeRel, A,C),
|      topology(rcc8(TopoRel),A,C).

 SizeRel = smaller,
 TopoRel = dc,
```



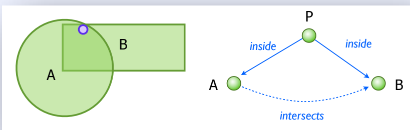
CLP(QS) in action

- enable declarative reasoning with real data
- applications in architectural design and urban planning
- automatically managed optimisations and datastructures
- utilise solvers: CLP(R), SMT, CAD

- mix spatial object **domains**
- mix **numerical** and **qualitative** information
- access geometric constraints

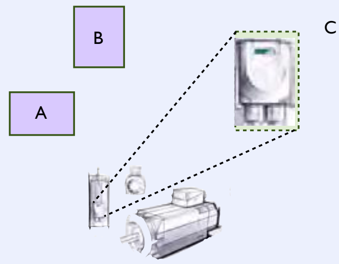
```
?- A=circle(point(2,2),_),
|   B=rectangle(_,6,_),
|   P=point(3,4),
|   topology(inside,P,A),
|   topology(inside,P,B),
|   topology(Relation,A,B).

Relation = intersects,
-----------------------------------
CLP(QS) Constraints:
(1)          A.x=2
(2)          A.y=2
(3)          B.width = 6
(4)          A.radius>2.23607
(5)          B.y=<2.0
(6)          B.height+B.y>4.0
(7)          B.x> -3.0
(8)          B.x=<2.0
-----------------------------------
```

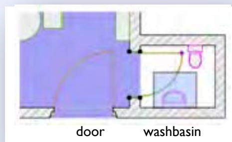


- surfaces in product design

```
?- A=rectangle(_,_,_),B=rectangle(_,_,_),
|  C=rectangle(_,_,_),
|  size(bigger, C,A),size(bigger, C,B),
|  mereology(rcc5(p), C, union(A,B)).
true.
|  ...
|  topology(rcc8(dc), A, B).
|  mereology(rcc5(p), C, union(A,B)).
false.
```



- door operational spaces must not overlap with functional space of activity objects (e.g. washbasins)




```
?- (furnishing(id(ObjA),_); flowelement(id(ObjA),_)),
functional_space(id(ObjA),representation(FuncGeom)),
operational_space(id(ObjB),representation(OpGeom)),
topology(intersects,OpGeom,FuncGeom).
```

Conclusions

We are developing a system for reasoning in a high-level manner about space, the physical extension of objects, and their regions of influence, or spatial artefacts. Our system manages the computational complexity by combining high-level constraint logic programming control with select calls to underlying algebraic solvers. Thus, a user can provide a (possibly incomplete) geometric and qualitative description of an environment and then check high-level rules about their application domain, such as connectedness and movement, visibility along routes with respect to occupant experience, privacy and security, and potential collisions of functional spaces of objects. In this paper we have focused on the application domain of computer aided architectural design (CAAD).

[1] Carl Schultz, Mehul Bhatt, 'Declarative Spatial Reasoning with Boolean Combinations of Axis-Aligned Rectangular Polytopes', in 21st European Conference on Artificial Intelligence (ECAI 2014)

[2] Mehul Bhatt, Carl Schultz, Madhura Thosar, 'Computing Narratives of Cognitive User Experience for Building Design Analysis: KR for Industry Scale Computer-Aided Architecture Design', in Principles of Knowledge Representation and Reasoning (KR 2014)

[3] Carl Schultz, Mehul Bhatt, 'Toward a Declarative Spatial Reasoning System', European Conference on Artificial Intelligence (ECAI 2012)

[4] Mehul Bhatt, Jae Hee Lee, and Carl Schultz, 'CLP(QS): A declarative spatial reasoning framework', in Conference on Spatial Information Theory (COSIT 2011)

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COGNITIVE VISION: The ROTUNDE Initiative

Jakob Suchan, Mehul Bhatt

http://www.cognitive-vision.org

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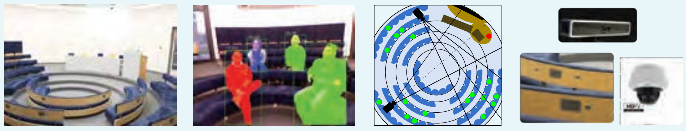
The ROTUNDE Initiative

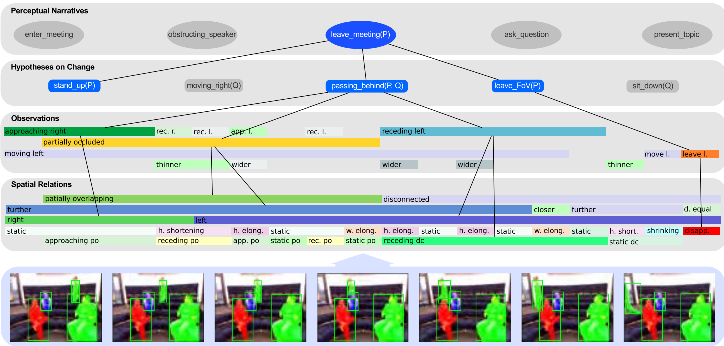


Automatic Meeting Cinematography

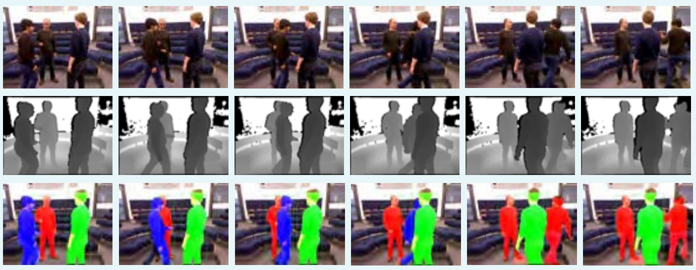
- people, artefact, and interaction tracking
- high-level cognitive interpretation
- real-time dynamic collaborative camera control

General Tools and Benchmarks

- functionality-driven benchmarks
- general tools for the commonsense cognitive interpretation of dynamic scenes



Qualitative Abstractions of Space and Motion



Domain Independent Theory

Σ Space - Spatial relations representing the scene

Topology | Orientation | Position | Distance | Size

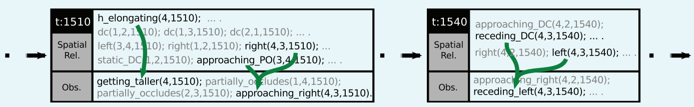
Σ Motion - Perceived motion of individuals

Movement | Size-Motion | Rotation

Spatial Dynamics of Individuals in the Scene

Visibility | Movement Patterns | Multiple Viewpoints | Complex Individuals

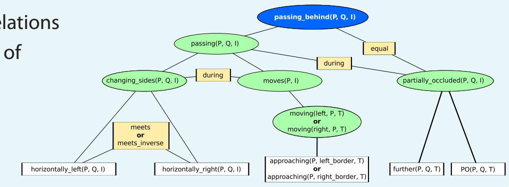
High-Level Declarative Model



Human Activities grounded in Spatial Change

Associate observed spatial change with hypotheses on real world interactions

- **Interactions**
  spatio-temporal relations based on intervals of space and motion
- **Operations**
  basic elements of an Interaction

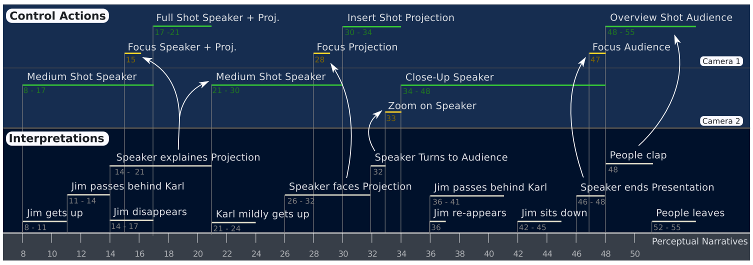


Perceptual Narratives of Human Activities

Hypothesised object relations are semantically interpreted as activities in the context of the domain

Examplary Sequence of Observations:
Region P elongates vertically, region P approaches region Q from the right, region P partially overlaps with region Q while P being further away from the observer than Q, region P moves left, region P recedes from region Q at the left, region P gets discrete from region Q, region P disappears at the left border of the field of view

Hypothesised Interpretation:
Person P stands up, passes behind person Q while moving towards the exit and leaves the room.



Interpretation Guided Spatial Control

Interpreting ongoing activities, for explanation of incomplete observations, and for projection to the near future to anticipate next interactions.

Explanation of perceived interactions in the context of the activities in the meeting

Prediction of immediate next interactions based on the previously observed interactions

Planning of control actions by utilizing the before mentioned methods

Control actions based on the interpretation

References

- Suchan, J., Bhatt, M., and Santos, P. (2014). Perceptual Narratives of Space and Motion for Semantic Interpretation of Visual Data, in: Proceedings of International Workshop on Computer Vision + Ontology Applied Cross-Disciplinary Technologies (CONTACT) at ECCV 2014, Zurich, Switzerland.
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- Bhatt, M., Suchan, J., and Freksa, C. (2013) ROTUNDE – A Smart Meeting Cinematography Initiative. In M. Bhatt, H. Guesgen, and D. Cook, editors, Proceedings of the AAAI-2013 Workshop on Space, Time, and Ambient Intelligence (STAMI)., Washington, US. AAAI Press.
- Suchan, J., and Bhatt, M. (2012). Toward an activity theory based model of spatio-temporal interactions - integrating situational inference and dynamic (sensor) control. In Kersting, K., and Toussaint, M., eds., STAIRS, volume 241 of Frontiers in Artificial Intelligence and Applications, 318–329. IOS Press.

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ExpCog: An Experimental Cognitive Robotics Framework

www.commonsenserobotics.org

SPATIAL COGNITION

SFB/TR 8 Spatial Cognition
Project [DesignSpace]

Brian Tietzen, Jakob Suchan, Manfred Eppe, Mehul Bhatt

Motivation

A Generic Domain Description Language

- Usable with arbitrary control approaches within the framework

Multiple Control Approaches

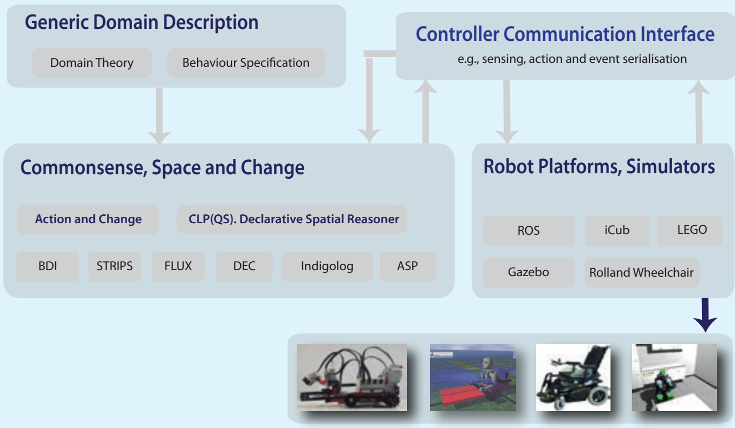
- Based on formalisims for reasoning about action and change

Application Platform Independence

- Should work in diverse real-robotic as well as simulated settings

Experimental and Pedagogical Function

- For use in teaching / courses on robotics and artificial intelligence



The ExpCog Framework

From a conceptual viewpoint, ExpCog architecture consisting of:

A Generic Domain Description Language

- Consistent with standard domain description languages (e.g., *Planning Domain Definition Language (PDDL)*)
- Uniformly utilisable across all control calculi within the control module

The Control Apparatus - Calculi for Reasoning about Space, Actions, and Change

- Provides multiple, independently utilisable control approaches that have a formal basis for reasoning about action and change in general
- Formal logic based approaches - *Situation calculus, Event calculus and Fluent calculus*
- Utilise high-level languages that are based on the stated calculi - *Golog, conGolog, FLUX* etc
- Reasoning about different aspects of space (e.g., *topology, orientation*) by qualitative spatial reasoning in constraint logic programming using CLP(QS)

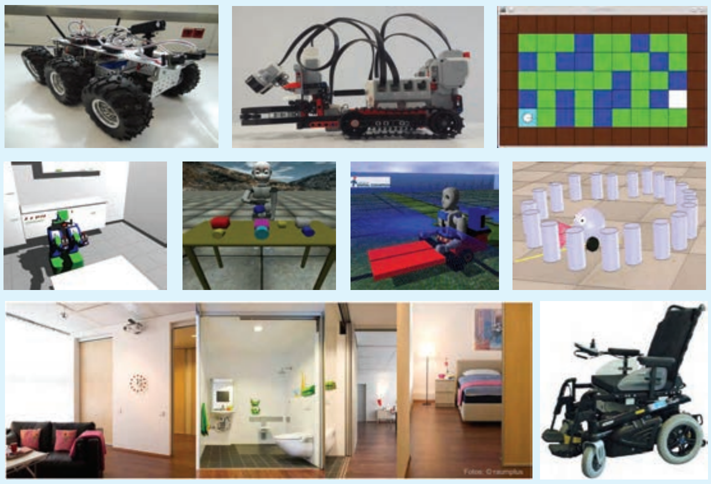
Controller Communication Interface

- Independent of robotic platform or agent simulation environment
- Defines low-level actions and provides sensing Information

Robot Platforms, Simulators

- the real / simulated robot (platform)

Implemented Platforms



Lego • Polar Bear • Gazebo • ROS - Robot Operating System • Robotcub - iCub v-rep • Rolland Wheelchair (in Collaboration with Manfred Eppe)

Collaboration

- Integrating planning and postdiction - BAALL - Bremen Ambient Asistence Living Lab
- Dynamic spatial relations for embodied robot interaction - Sony CSL, Tokyo
- Spatial reasoning for robot navigation - Warsaw University

References

- Suchan, J., Spranger, M., Bhatt, M., Eppe, M., (2014) Grounding Dynamic Spatial Relations for Embodied (Robot) Interaction - Integrating Cognitive Linguistic Semantics and Commonsense Spatial Reasoning, in: The 13th Pacific Rim International Conference on Artificial Intelligence (PRICAI 2014), Queensland, Australia (to appear)
- Eppe, M., Bhatt, M., Suchan, J. and Tietzen, B., (2014) ExpCog: Experiments in Commonsense Cognitive Robotics, in: The 9th International Workshop on Cognitive Robotics. European Conference on Artificial Intelligence (ECAI 2014), Prague, Czech Republic
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[SignTrack]

SignTrack: Signage, Eye-Tracking & Airport Navigation

SPATIAL COGNITION
T3-[SignTrack]

Simon Büchner, Lars Konieczny, Bernhard Nebel, Christoph Hölscher

Project Overview

Strategic project with a total duration of two years

Project Partners

1. the Center for Cognitive Science, University of Freiburg,
2. the Department of Computer Science (IIF), University of Freiburg, and
3. the operator of Frankfurt Airport (Fraport AG), Frankfurt

Primary Goals

- Validate results of eye tracking lab studies with results of mobile eyetracking studies in the real environment
- Advise Fraport with respect to signage placement and design
- Explore and model sign use in wayfinding behavior

Results and Achievements

Multi Agent Simulation

- Development of a multi-agent approach in Unity: implementation of sign fixation and interpretation (Becker-Asano et al. 2014)

VR Model

- Virtual model of airport parts in Unity for interactive VR experiments with Oculus Rift (Leymann et al. 2014).

Lab Studies and Consulting

- Evaluation of signage alternatives

→Redesigned signage improved confidence and decision making in a lab study (Büchner et al. 2012)

- Pretesting of signage alternatives for planned terminal

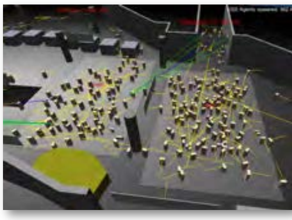
→Improved sign placement, additional signs where necessary, dispensing unnecessary signs

Field Studies with Mobile Eye Tracking

- Comparison of eye tracking results in lab and field (Schwarzkopf et al. 2013)
- Analyses of wayfinding behavior with different signage alternatives

Method Development

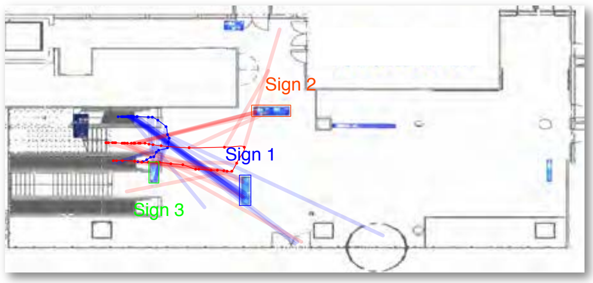
- Using sight vectors to analyze the relation of body movement and gaze behavior (Müller-Feldmeth et al. 2014)



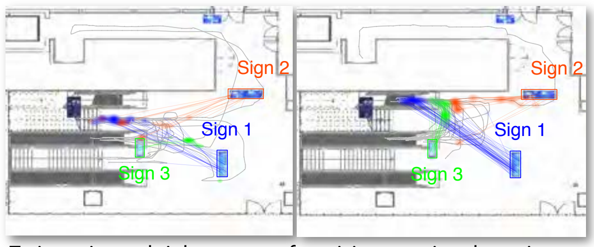
Multi agent simulation with sign usage

VR model of airport terminal

Fixation maps on VR-screenshots of planned terminal with different signage alternatives



Trajectories and sight vectors of two participants, one using the stairs, one using the escalator



Trajectories and sight vectors of participants using the stairs (left) or the escalator (right).

References:

Becker-Asano, C., Ruzzoli, F., Hölscher, C., & Nebel, B. (2014, accepted). A Multi-Agent System based on Unity 4 for virtual perception and wayfinding. In *Pedestrian and Evacuation Dynamics 2014 (PED2014)*.

Büchner, S., Wiener, J., & Hölscher, C. (2012). Methodological Triangulation to Assess Sign Placement. *Proceedings of ACM ETRA 2012, Eye-tracking Research and Applications,* Santa Barbara, CA, March 2012.

Leymann, S., Hölscher, C., Becker-Asano, C., & von Stülpnagel, R. (2014). Der Einfluss einer Speed-Accuracy Manipulation auf schildergeleitetes Navigationsverhalten in einer virtuellen Umgebung. 56. *Tagung experimentell arbeitender Psychologen*, Gießen.

Müller-Feldmeth, D.*, Schwarzkopf, S.*, Büchner, S.J., Hölscher, C., Kallert, G., von Stülpnagel, R., & Konieczny, L. (2014, accepted). Location Dependent Fixation Analysis with Sight Vectors. Locomotion as a Challenge in Mobile Eye Tracking. Paper to present at the 2nd International workshop on eye tracking for spatial research, ET4S 2014, Vienna. *equal contribution, alphabetical order

Schwarzkopf, S., von Stülpnagel, R., Büchner, S.J., Konieczny, L., Kallert, G., & Hölscher, C. (2013). What Lab Eye Tracking Tells us about Wayfinding. A Comparison of Stationary and Mobile Eye Tracking in a Large Building Scenario. Paper presented at the 1st International workshop on eye tracking for spatial research, ET4S 2013 (in conjunction with COSIT 2013), Scarborough.

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Proposed Transfer Project: Tracking and Modeling Sign Use Behavior

SPATIAL COGNITION
T3-[SignTrack]

Simon Büchner, Lars Konieczny, Bernhard Nebel

Project Overview

A transfer project with a duration of two years (2015/16) submitted to DFG.

Project partners

1. the Center for Cognitive Science, University of Freiburg,
2. the Department of Computer Science (IIF), University of Freiburg, and
3. the operator of Frankfurt Airport (Fraport AG), Frankfurt

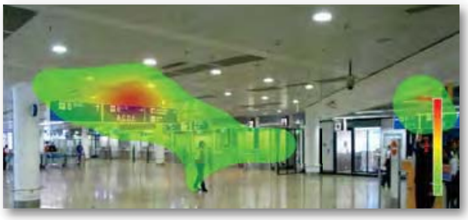
Primary goals

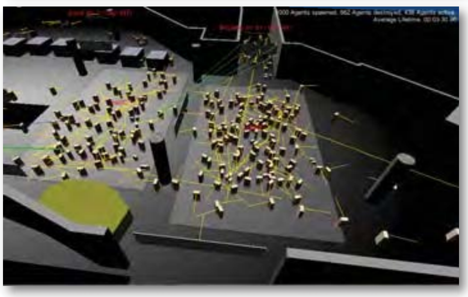
- Improve Fraport's passenger flow simulator (CAST): integration of a signage module
- Transfer knowledge about spatial navigation and cognitive models of human wayfinding to the prediction and simulation of passenger flow in Frankfurt Airport terminals
- Advance and validate theories and methods on spatial cognition and wayfinding in the highly relevant real-world setting "airport" as well as in a multi-agent simulation of this environment

Methods

We use multiple methods in order to gain empirical knowledge, transfer it to modeling parameters and to pretest them in our Unity model before implementing them in Fraport's passenger flow simulator:

- Mobile eye tracking studies at the airport
- Multi agent modeling in Unity for interactive VR-eyetracking studies
- Observation and analysis of passenger behavior at the airport
- Pretesting agent and sign parameters in the Unity multi-agent model
- Evaluating the success of the signage module





Project Plan

WP1 – Passengers' reactions to signs

- When is a sign perceivable?
- Which sign types are fixated with which probability?
- How does gaze behavior affect walking behavior?

WP2 – Complexity and semantics of signs

- How does semantic complexity of a sign influence its interpretation?
- How is directional information re-mapped to the environment?
- Which influence has time pressure on confidence and performance?

WP3 – Social influences on attention and wayfinding

- Does group navigation support or impede wayfinding?
- How does the social context influence attention?
- How does the crowd influence individual behavior?

WP4 – Passengers and agents getting lost

- When do passengers notice that they are lost?
- How do people behave after getting lost?

Affect Simulation in Crowd Environments

SPATIAL COGNITION
T3-[SignTrack]

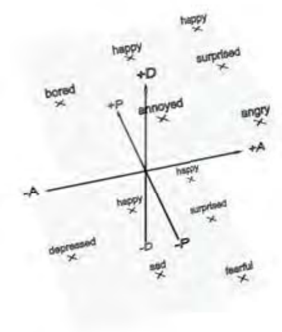
Jan Mortensen, Christian Becker-Asano, Bernhard Nebel

Objectives

- How does affect influence the behavior of single persons in a crowd?
- Integrate affect simulator WASABI into a simulation of an airport terminal
- Test in simulation how events change the emotional states of the agents and how emotions, in turn, impact agent behavior

Affect simulation with WASABI

- Three dimensional PAD space for emotions (pleasure, arousal, dominance)
- Emotions and each agent's emotional state are defined in this space
- Emotion intensity is calculated by a distance measure in this space
- Emotional change induced by positive or negative impulses



Integration into Crowd Simulation

- Visualization of emotions achieved by color-codes, for example:
  - Happy: green
  - Fear: red
  - Sadness: blue
- Only emotion with highest intensity is displayed
- Emotional state of single agents and cluster of emotions at a certain location can easily be determined.

First Results

Very simple tests delivered promising results.
The following rules for emotional impulses were implemented:

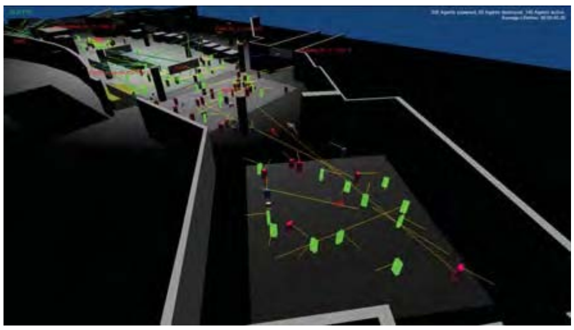
- Negative impulses when an agent is surrounded by many other agents
- Negative impulse when the agent fails to read a sign
- Positive impulse when the agent successfully reads a sign

These trigger the following change in behavior:

- Change the chance to read a sign successfully

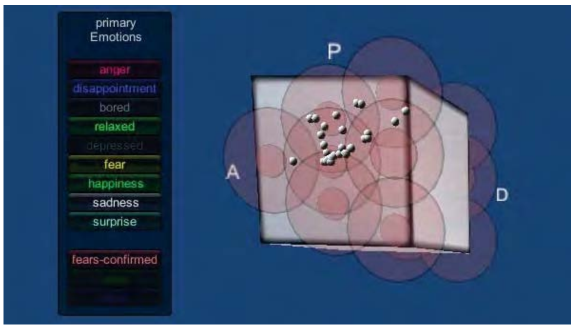
Results in behaviors comparable to real world behaviors, e.g.:

- Stressed people in a full airport hall
- Spread of panic



Future Research

- Evaluation of WASABI, applied to crowd simulation
- WASABI to be compared to an implementation of an established model of emotion psychology, namely OCC
- Perform empirical studies to evaluate the reliability of WASABI
- Compare simulated passenger behavior with real world data



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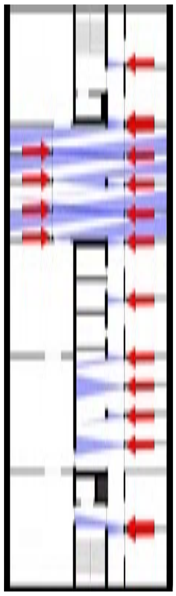
SIL – Spatial Interaction Lab

Spatial Interaction Lab (SIL)

Jasper van de Ven (jasper.vandeven@informatik.uni-bremen.de)

Creating an ambient intelligence and smart environment laboratory

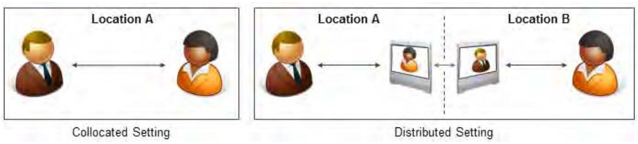
(Jasper van de Ven, Falko Schmid, Christian Freksa)

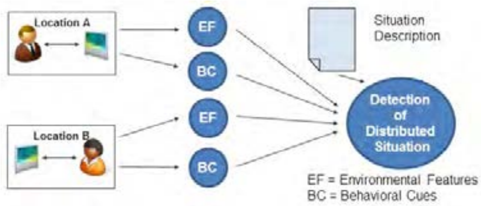


- 18 smart doorplates
- 1.2GHz VIA-C7
- 1 GB RAM
- 8GB flash HDD
- 12" touchscreen
- camera, microphone, speakers

Enabling spontaneous and informal communication in spatially distributed groups

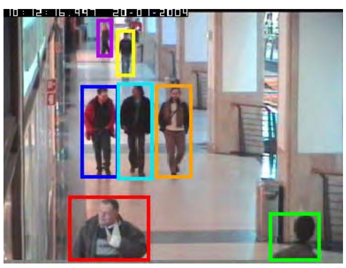
(Cognitive Systems, University of Bremen and Media Informatics and Multimedia Systems Group, University of Oldenburg)

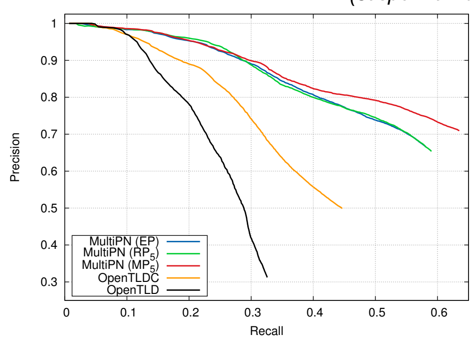


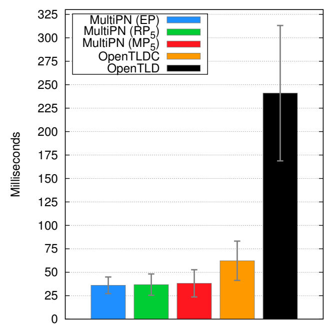


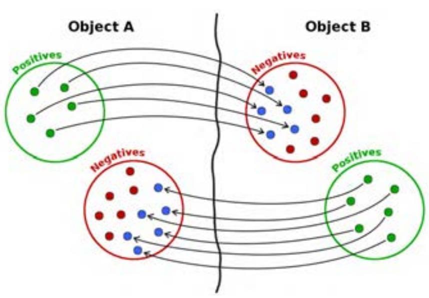
OpenTLD$_{Multi-PN}$ – Tracking multiple objects using a PN-learning approach

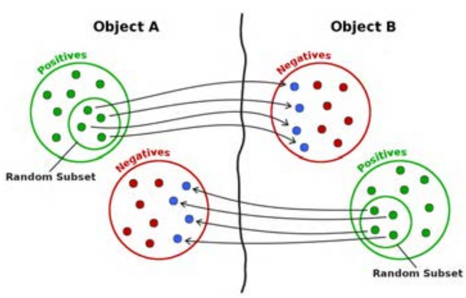
(Jasper van de Ven, Arne Kreutzmann, Sascha Schrader, Frank Dylla)

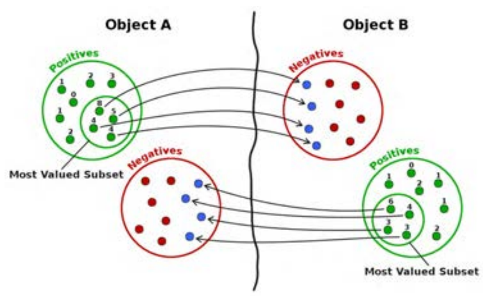












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Martin Brösamle: Image, Text, Trajectory