Universität Hamburg
DER FORSCHUNG | DER LEHRE | DER BILDUNG

MIN Faculty
Department of Informatics

Introduction to Robotics

Lecture 11

Lasse Einig, Jianwei Zhang
[einig, zhang]@informatik.uni-hamburg.de

University of Hamburg
Faculty of Mathematics, Informatics and Natural Sciences
Department of Informatics
Technical Aspects of Multimodal Systems

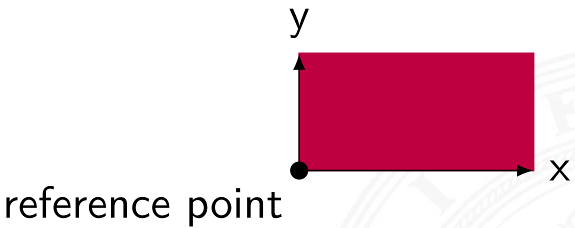
June 28, 2018

Outline

Outline (cont.)

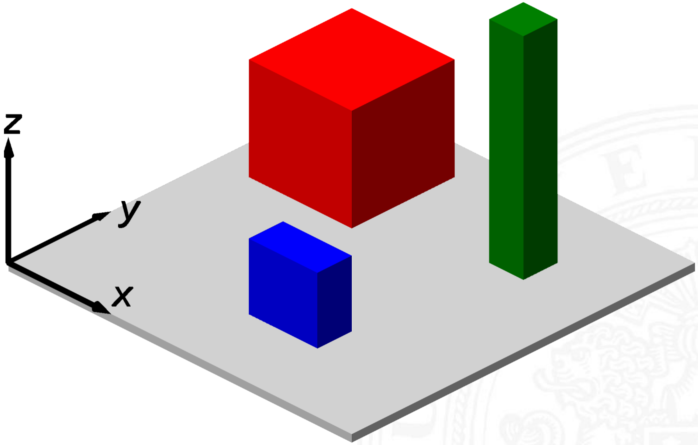
Task-level Programming – Basics

Robot Single reference point with physical attributes



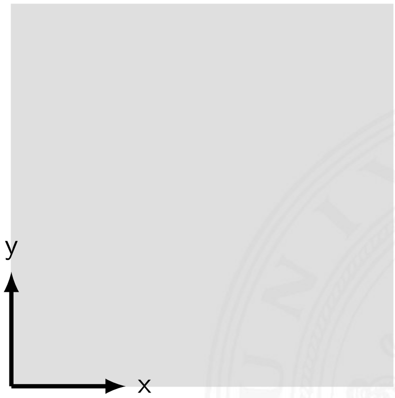
Task-level Programming – Basics

Work space The cartesian space of the environment



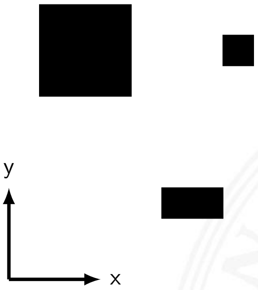
Task-level Programming – Basics

Configuration space C Set of all possible configurations

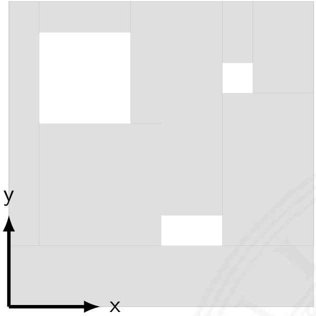


Obstacles in work space `C-Obstacles` in configuration space

Obstacle space $C_{obstacle}$ Union of C-Obstacles



Free space C_{free} the complement of Obstacle space



Task-level Programming – Basics

Robot Single reference point with physical attributes

Work space The cartesian space of the environment

Configuration space C Set of all possible configurations

Obstacles in work space `C-Obstacles` in configuration space

Obstacle space $C_{obstacle}$ Union of C-Obstacles

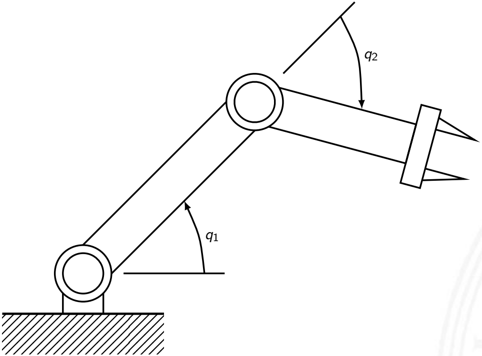
Free space C_{free} the complement of Obstacle space

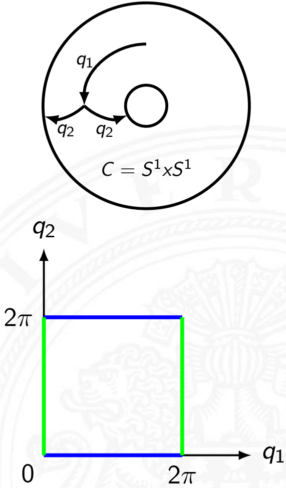
Path-planning for Work-/Configuration-Space

Search for a path for the reference point of the artifact in the free space.

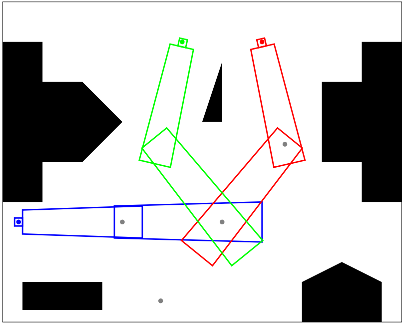
Configurations of the artifact in free space have no intersection with obstacles

Work Space to Configuration Space – Illustration

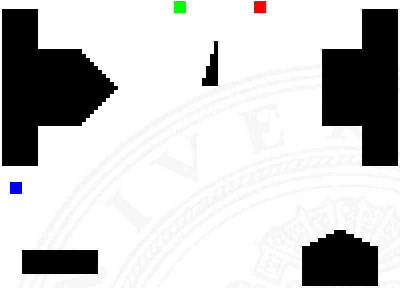




Work Space to Configuration Space – Example

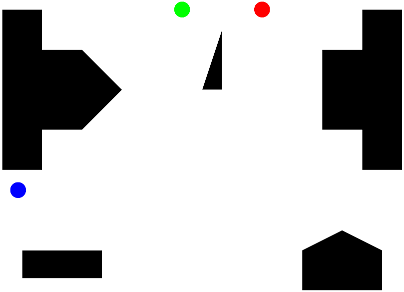


Workspace scheme with start and goal positions

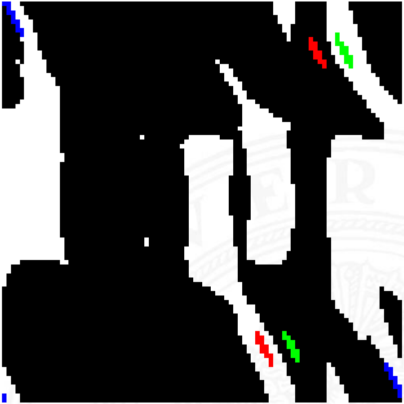


Discretized workspace
$xscale = 100$, $y^{scale} = 80$

Work Space to Configuration Space – Example

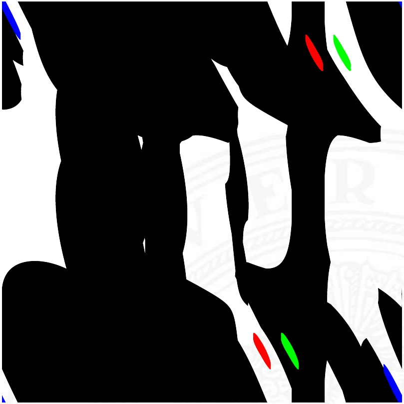


Discretized workspace $x^{scale} = 2000$, $yscale = 1600$



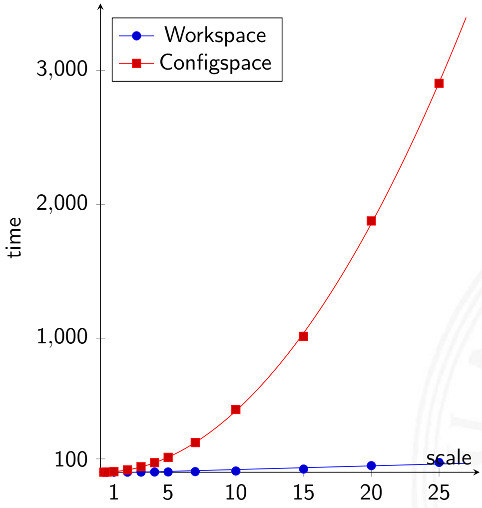
Discretized configuration space $q_1^{scale} = 90$, $q_2^{scale} = 90$

Work Space to Configuration Space – Example



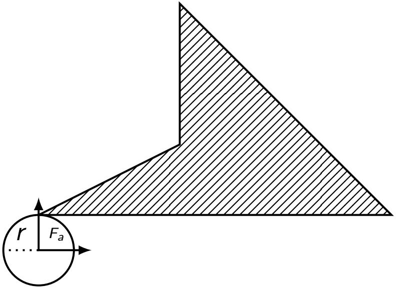
Discretized configuration space $q_1^{scale} = 3600$, $q_2^{scale} = 3600$

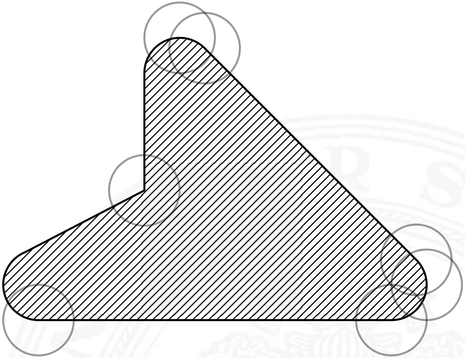
Work Space to Configuration Space – Complexity



- Python
- Brute forward kinematics
- using polygon collisions
  - shapely library
- 56 cpus
  - Intel® Xeon® E5-2690 v4 (2.60GHz)

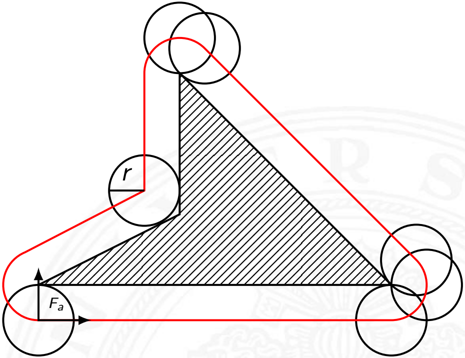
C-Obstacle for a circular artifact





Obstacle & artifact (radius r) Expanded C-Obstacle

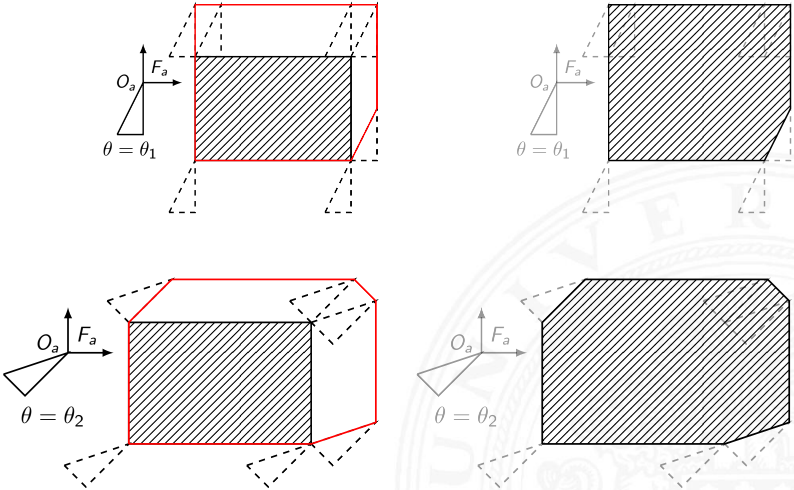
C-Obstacle for a circular artifact



Obstacle & artifact (radius r)

Path of minimal distance to obstacle

C-Obstacle for Polygons



Obstacle & polygon artifact with $\theta = \theta_1 \vee \theta_2$; minimum distance to obstacle.

Minkowski Sum & Difference

A C-Obstacle of a fixed, convex obstacle with respect to a moving convex robot (part) may be theoretically represented as the `Minkowski Sum` of the corresponding objects.

$C_O(H)$ is the C-obstacle of a fixed convex polyhedra H, with respect to the (moving) convex object O.

Minkowski-Sum (Minkowski-Difference) of H and O (H and $-O$)

$$C_O(H) = H \ominus O = H \oplus (\ominus O)$$

where

$$H \ominus O := \{h - o \mid h \in H \land o \in O\}$$

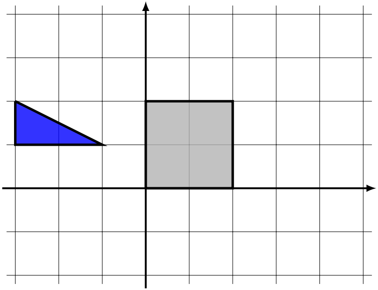
Minkowski Sum & Difference – 2D Example

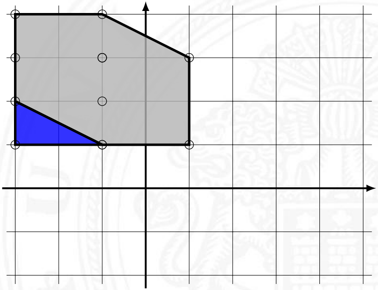
$$A = \{(0,0),(2,0),(2,2),(0,2)\} \qquad B = \{(-1,1),(-3,2),(-3,1)\}$$

$$A \oplus B = \{(-1,1),(-3,2),(-3,1),(1,1),(-1,2),(-1,1),$$
$$(1,3),(-1,4),(-1,3),(-1,3),(-3,4),(-3,3)\}$$

The convex hull (eliminating duplicates & inner points)

$$conv\{A \oplus B\} = \{(-3,1),(1,1),(1,3),(-1,4),(-3,4)\}$$





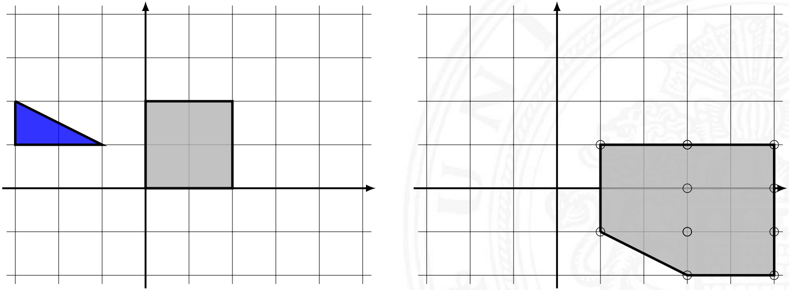
Minkowski Sum & Difference – 2D Example (cont.)

$$A = \{(0,0),(2,0),(2,2),(0,2)\} \qquad B = \{(-1,1),(-3,2),(-3,1)\}$$

$$A \ominus B = \{(1,-1),(3,-2),(3,-1),(3,-1),(5,-2),(5,-1),(3,1),(5,0),(5,1),(1,1),(3,0),(3,1)\}$$

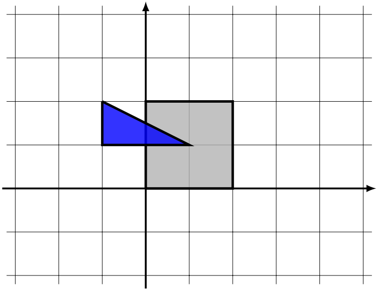
The convex hull (eliminating duplicates & inner points)

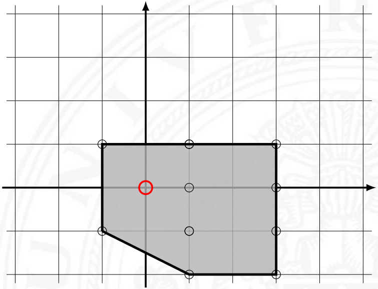
$$conv\{A \ominus B\} = \{(1,-1),(3,-2),(5,-2),(5,1),(1,1)\}$$



Collision detection

Two objects are colliding, if their Minkoswki difference contains the origin of the coordinate frame.

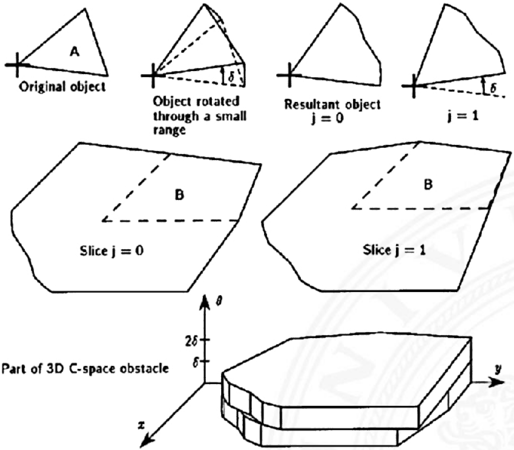




There is an interactive applet on the web:

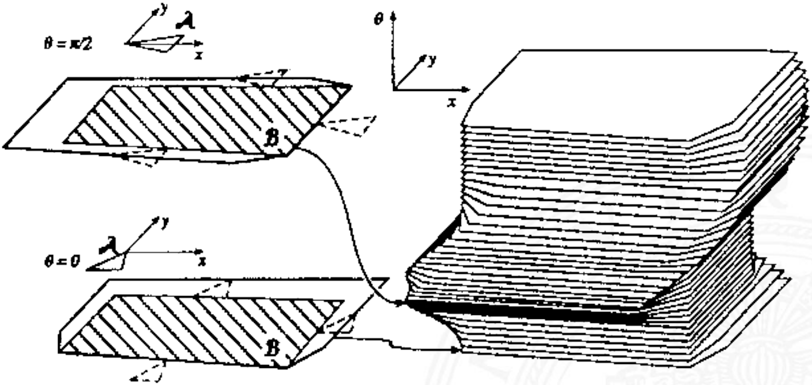
`http://www.cut-the-knot.org/Curriculum/Geometry/PolyAddition.shtml`

C-Obstacles for 2-D translation and 1-D rotation



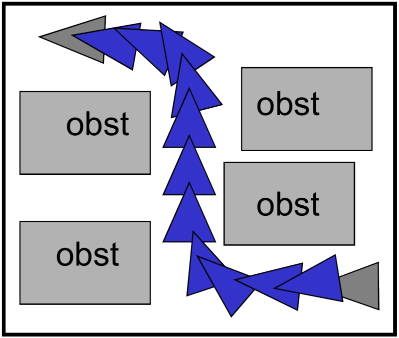
Represent rotational configuration of the C-obstacle as slice for each θ configuration of the robot.

C-Obstacles for 2-D translation and 1-D rotation (cont.)

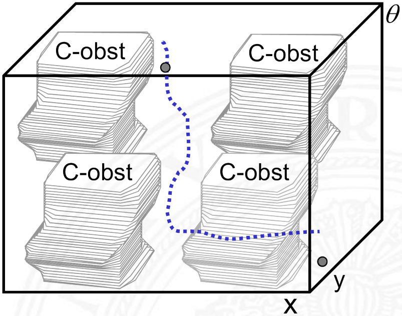


The configuration space for a *k*-DOF robot is a *k*-Dimensional coordinate system.

C-Obstacles for 2-D translation and 1-D rotation (cont.)

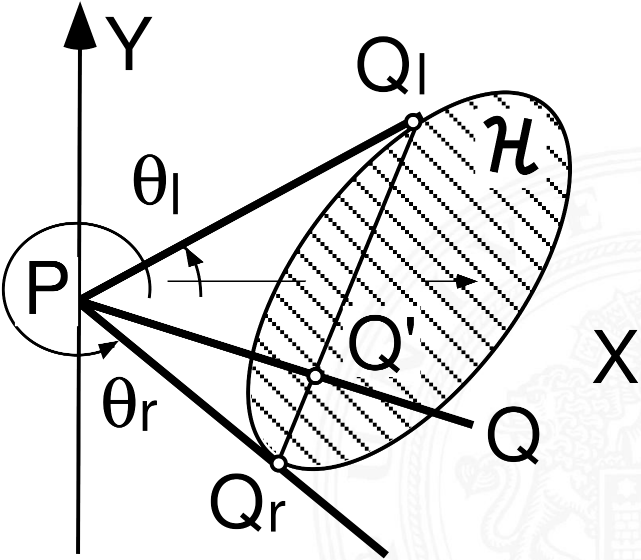


Work space (x, y)

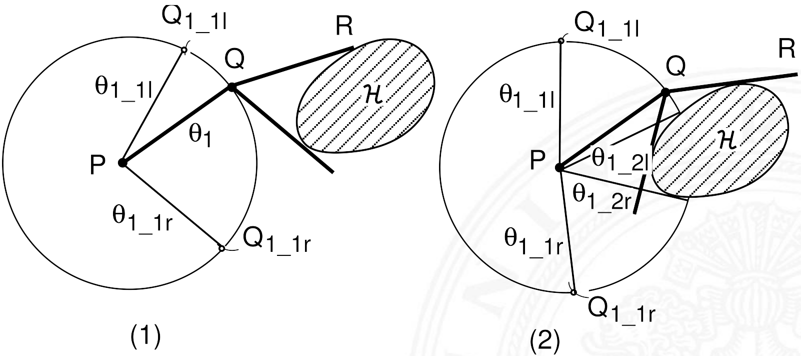


Configuration space (x, y, θ)

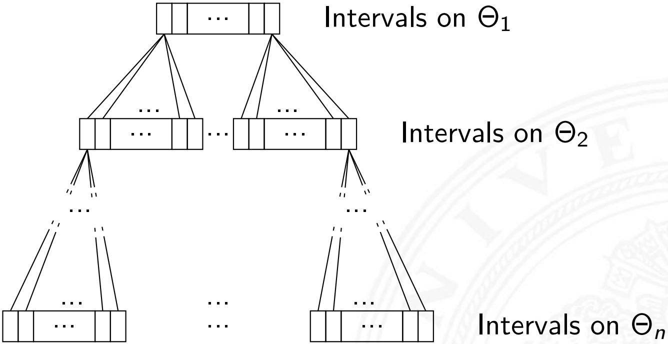
C-obstacles of a pole



C-obstacles of a 2-DOF Chain of Poles

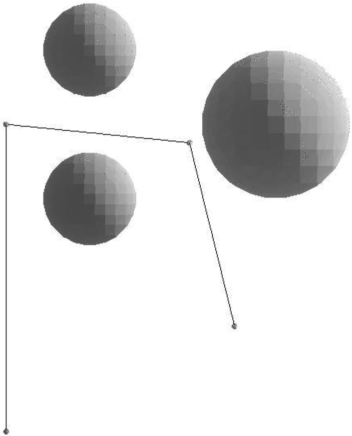


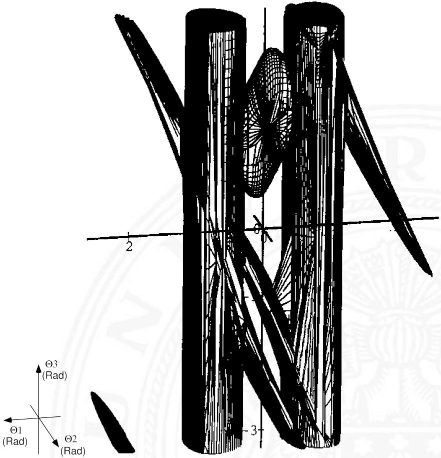
Tree-structure for Configuration Space partitioning



Curse of dimensionality

Configuration Space of a 3-DOF Chain of Poles





Partition Representation of C-Space

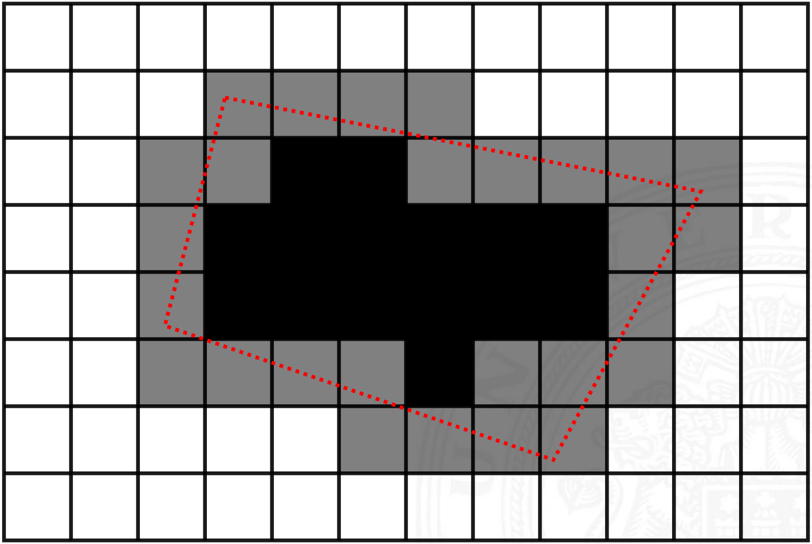
The free space is partioned into cells using

- Geometrical partition
  - uniform cubes
  - a hierarchical tree-structure (Quad-tree, Oct-tree, etc.)
  - slices and scanlines
  - `bubbles` of variable size

  The union of the non-overlapping cells is part of the free space. Neighborship graphs represent the connectivity of free space.
- Topological partition
  - overlapping generalized cones
  - critical points of the C-obstacle connection graph

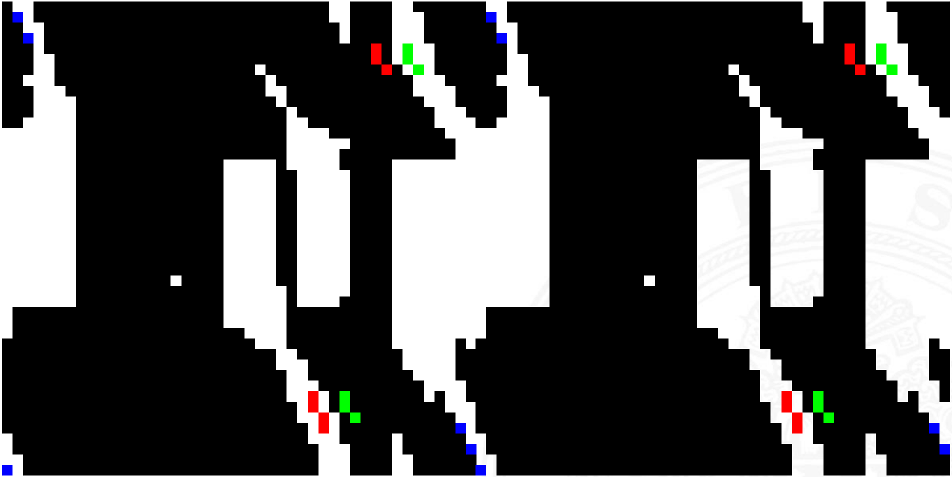
  The union of the overlapping cells is equal to the free space.

Squares-Partitioning of Configuration Space



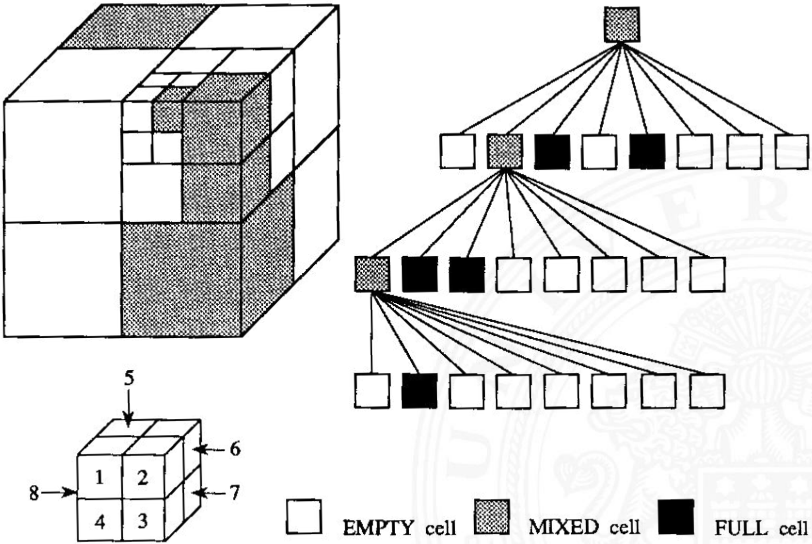
Resulting bitmap of configuration space using squares partitioning

Squares-Partitioning of Configuration Space (cont.)

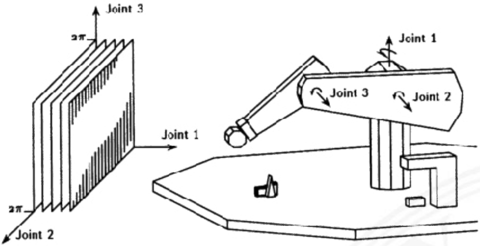


Bitmap of configuration space

Partitioning of the configuration space using Octrees



Partitioning of the configuration space using Slices

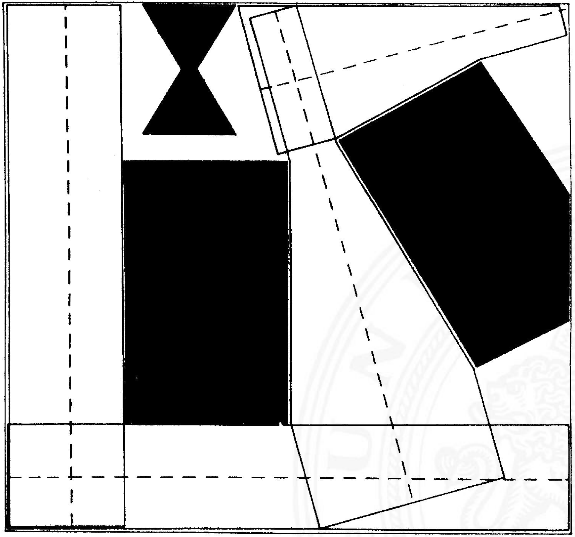


Complexity regarding the transformation of the C-obstacles

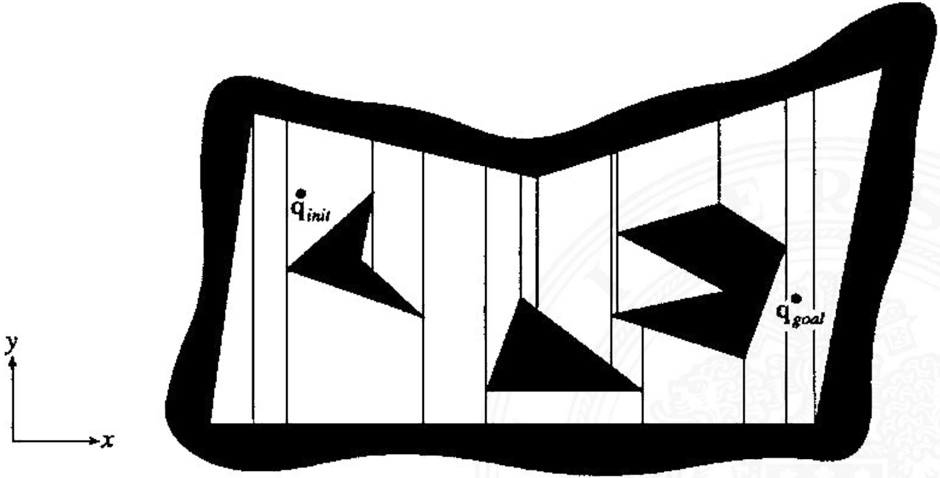
$$r^{d-1} f(m)$$

where r: the number of discretization steps for each DOF,
d: DOF of the robot arm
$f(m)$: the computing time of one slice
m: the number of edges of all obstacles

Representation of free space with generalized cones

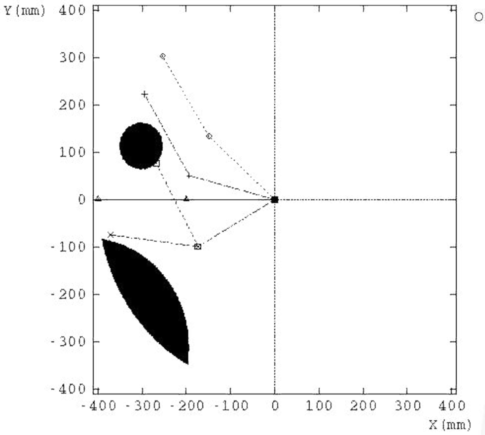


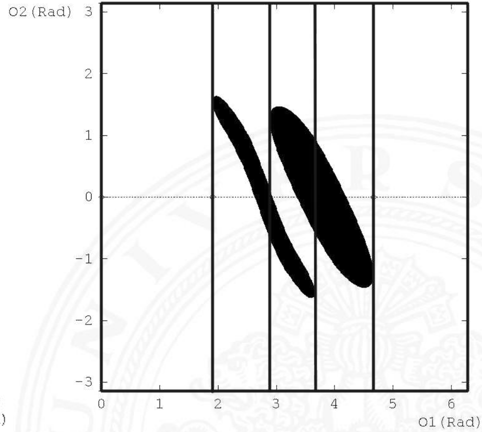
Exact Partition of Configuration Space



Trapezoidal partitioning of the configuration space

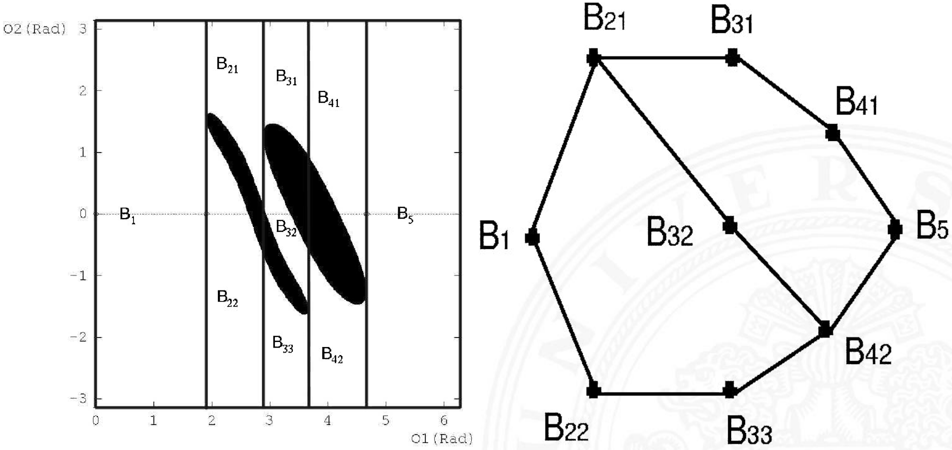
Exact Partition of Configuration Space (cont.)





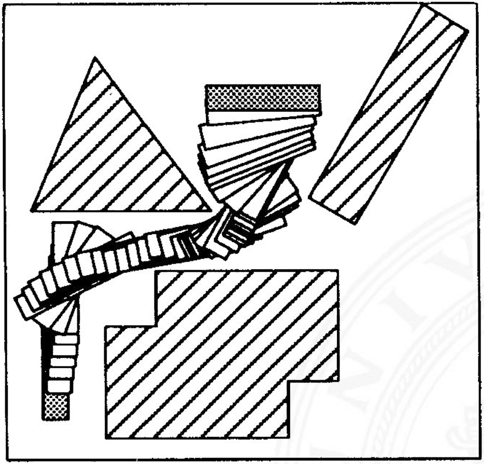
Cylindrical partitioning using critical points

Exact Partition of Configuration Space (cont.)



Cylindrical partitioning and connectivity graph

Planning Results



[12]

Serial computing: 3-DOF C-space

Massive-parallel computing: up to 6-DOF C-Space

Partition based Path Planning

Advantages:

- Complete in case of sufficient resolution
- Global overview

Disadvantages:

- High demand for RAM
  - `Curse of Dimensionality`
- Complex to implement
- Practically implementable only for few degrees of freedom

$$\Downarrow$$

Path planning without explicit representation of free space?

$\Longrightarrow$ next Lecture!

Bibliography

[1] K. Fu, R. González, and C. Lee, *Robotics: Control, Sensing, Vision, and Intelligence*.
McGraw-Hill series in CAD/CAM robotics and computer vision, McGraw-Hill, 1987.

[2] R. Paul, *Robot Manipulators: Mathematics, Programming, and Control: the Computer Control of Robot Manipulators*.
Artificial Intelligence Series, MIT Press, 1981.

[3] J. Craig, *Introduction to Robotics: Pearson New International Edition: Mechanics and Control*.
Always learning, Pearson Education, Limited, 2013.

[4] J. F. Engelberger, *Robotics in service*.
MIT Press, 1989.

[5] W. Böhm, G. Farin, and J. Kahmann, “A Survey of Curve and Surface Methods in CAGD,” *Comput. Aided Geom. Des.*, vol. 1, pp. 1–60, July 1984.

[6] J. Zhang and A. Knoll, "Constructing Fuzzy Controllers with B-spline Models - Principles and Applications," *International Journal of Intelligent Systems*, vol. 13, no. 2-3, pp. 257–285, 1998.

[7] M. Eck and H. Hoppe, "Automatic Reconstruction of B-spline Surfaces of Arbitrary Topological Type," in *Proceedings of the 23rd Annual Conference on Computer Graphics and Interactive Techniques*, SIGGRAPH '96, (New York, NY, USA), pp. 325–334, ACM, 1996.

[8] M. C. Ferch, *Lernen von Montagestrategien in einer verteilten Multiroboterumgebung*.
PhD thesis, Bielefeld University, 2001.

[9] J. H. Reif, "Complexity of the Mover's Problem and Generalizations - Extended Abstract," *Proceedings of the 20th Annual IEEE Conference on Foundations of Computer Science*, pp. 421–427, 1979.

[10] J. T. Schwartz and M. Sharir, "A Survey of Motion Planning and Related Geometric Algorithms," *Artificial Intelligence*, vol. 37, no. 1, pp. 157–169, 1988.

[11] J. Canny, *The Complexity of Robot Motion Planning*. MIT press, 1988.

[12] T. Lozano-Pérez, J. L. Jones, P. A. O'Donnell, and E. Mazer, *Handey: A Robot Task Planner*. Cambridge, MA, USA: MIT Press, 1992.

[13] O. Khatib, "The Potential Field Approach and Operational Space Formulation in Robot Control," in *Adaptive and Learning Systems*, pp. 367–377, Springer, 1986.

[14] J. Barraquand, L. Kavraki, R. Motwani, J.-C. Latombe, T.-Y. Li, and P. Raghavan, "A Random Sampling Scheme for Path Planning," in *Robotics Research* (G. Giralt and G. Hirzinger, eds.), pp. 249–264, Springer London, 1996.

Bibliography (cont.)

[15] R. Geraerts and M. H. Overmars, "A Comparative Study of Probabilistic Roadmap Planners," in *Algorithmic Foundations of Robotics V*, pp. 43–57, Springer, 2004.

[16] K. Nishiwaki, J. Kuffner, S. Kagami, M. Inaba, and H. Inoue, "The Experimental Humanoid Robot H7: A Research Platform for Autonomous Behaviour," *Philosophical Transactions of the Royal Society of London A: Mathematical, Physical and Engineering Sciences*, vol. 365, no. 1850, pp. 79–107, 2007.

[17] R. Brooks, "A robust layered control system for a mobile robot," *Robotics and Automation, IEEE Journal of*, vol. 2, pp. 14–23, Mar 1986.

[18] M. J. Mataric, "Interaction and intelligent behavior.," tech. rep., DTIC Document, 1994.

[19] M. P. Georgeff and A. L. Lansky, "Reactive reasoning and planning.," in *AAAI*, vol. 87, pp. 677–682, 1987.

[20] J. Zhang and A. Knoll, *Integrating Deliberative and Reactive Strategies via Fuzzy Modular Control*, pp. 367–385. Heidelberg: Physica-Verlag HD, 2001.

[21] J. S. Albus, "The nist real-time control system (rcs): an approach to intelligent systems research," *Journal of Experimental & Theoretical Artificial Intelligence*, vol. 9, no. 2-3, pp. 157–174, 1997.

[22] A. Meystel, "Nested hierarchical control," 1993.

[23] G. Saridis, "Machine-intelligent robots: A hierarchical control approach," in *Machine Intelligence and Knowledge Engineering for Robotic Applications* (A. Wong and A. Pugh, eds.), vol. 33 of *NATO ASI Series*, pp. 221–234, Springer Berlin Heidelberg, 1987.

[24] T. Fukuda and T. Shibata, "Hierarchical intelligent control for robotic motion by using fuzzy, artificial intelligence, and neural network," in *Neural Networks, 1992. IJCNN., International Joint Conference on*, vol. 1, pp. 269–274 vol.1, Jun 1992.

Bibliography (cont.)

[25] R. C. Arkin and T. Balch, "Aura: principles and practice in review," *Journal of Experimental & Theoretical Artificial Intelligence*, vol. 9, no. 2-3, pp. 175–189, 1997.

[26] E. Gat, "Integrating reaction and planning in a heterogeneous asynchronous architecture for mobile robot navigation," *ACM SIGART Bulletin*, vol. 2, no. 4, pp. 70–74, 1991.

[27] L. Einig, *Hierarchical Plan Generation and Selection for Shortest Plans based on Experienced Execution Duration.*
Master thesis, Universität Hamburg, 2015.

[28] J. Craig, *Introduction to Robotics: Mechanics & Control. Solutions Manual.*
Addison-Wesley Pub. Co., 1986.

[29] H. Siegert and S. Bocionek, *Robotik: Programmierung intelligenter Roboter: Programmierung intelligenter Roboter.*
Springer-Lehrbuch, Springer Berlin Heidelberg, 2013.

Bibliography (cont.)

[30] R. Schilling, *Fundamentals of robotics: analysis and control*. Prentice Hall, 1990.

[31] T. Yoshikawa, *Foundations of Robotics: Analysis and Control*. Cambridge, MA, USA: MIT Press, 1990.

[32] M. Spong, *Robot Dynamics And Control*. Wiley India Pvt. Limited, 2008.