Algorithmic Robotics and Motion Planning

Introduction

Dan Halperin
School of Computer Science
Tel Aviv University

Fall 2020-2021

[Saildrone, bathymetry, c|net 9/2021](#)

2:50 – 5:30

[Dolce & Gabbana 2018 handbag collection](#)

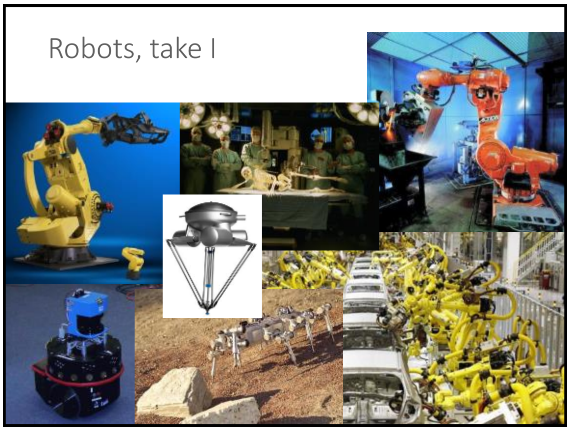
Today's lesson

Introduction, Part I
- basic terminology
- fundamental problems

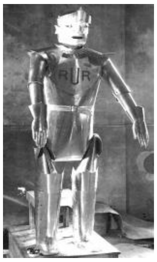
About the course
- bird's eye view of the course's topics
- course mechanics

As time permits
- the Roomba in the café, combinatorics and algorithms

Robots, take I



An extremely brief history of robotics

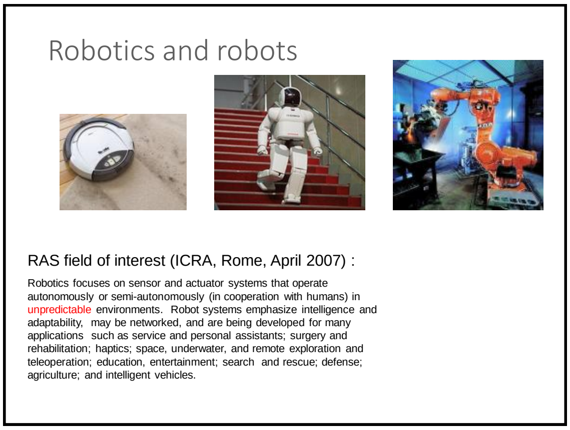


The RUR robot which appeared in an adaption of Czech author Karel Capek's *Rossum's Universal Robots.*
Circa 1930's.

UNIMATE becomes the first industrial robot in use. It was used at the General Motors factory in New Jersey. 1961.

NASA's Curiosity, 2011 →

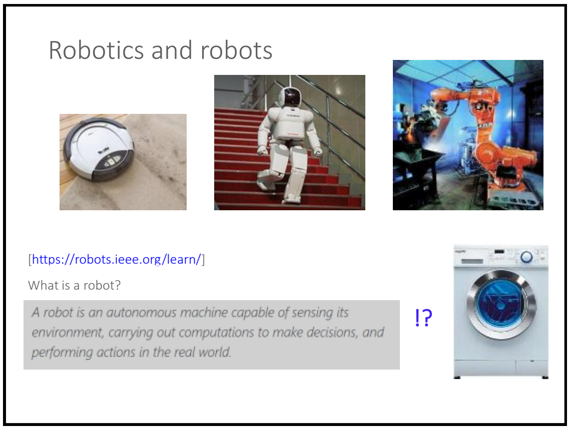
Honda's ASIMO, 2002



Robotics and robots

RAS field of interest (ICRA, Rome, April 2007) :

Robotics focuses on sensor and actuator systems that operate autonomously or semi-autonomously (in cooperation with humans) in unpredictable environments. Robot systems emphasize intelligence and adaptability, may be networked, and are being developed for many applications such as service and personal assistants; surgery and rehabilitation; haptics; space, underwater, and remote exploration and teleoperation; education, entertainment; search and rescue; defense; agriculture; and intelligent vehicles.



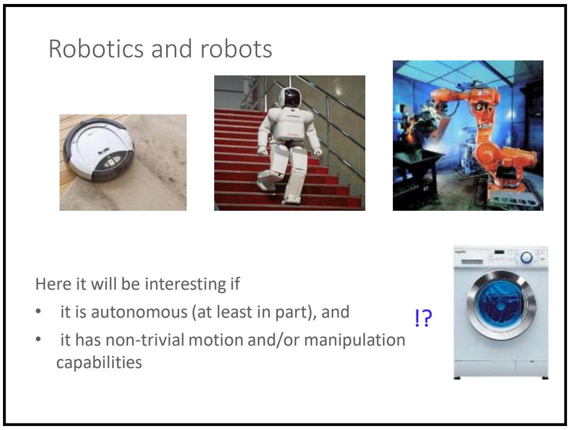
Robotics and robots

[https://robots.ieee.org/learn/]

What is a robot?

> *A robot is an autonomous machine capable of sensing its environment, carrying out computations to make decisions, and performing actions in the real world.*

!?

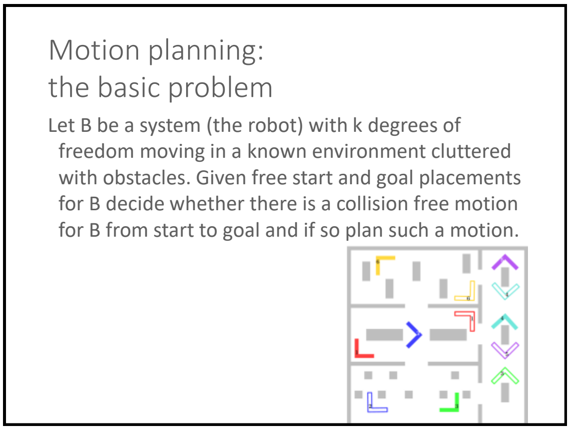


Robotics and robots

Here it will be interesting if

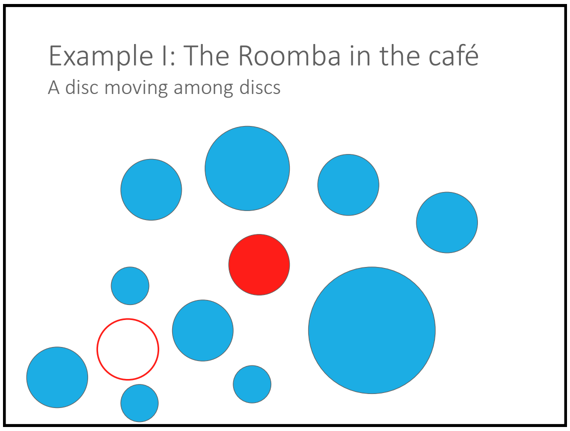
- it is autonomous (at least in part), and
- it has non-trivial motion and/or manipulation capabilities

!?



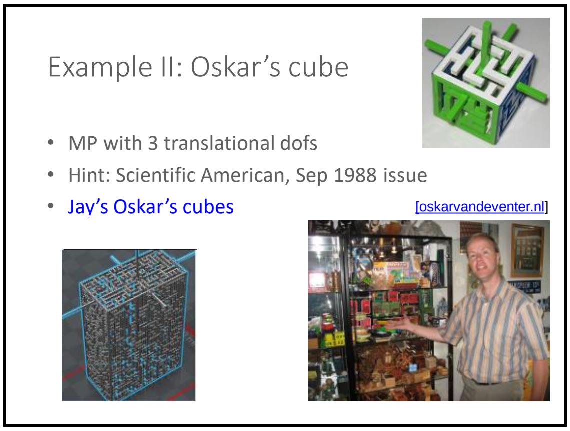
Motion planning:
the basic problem

Let B be a system (the robot) with k degrees of freedom moving in a known environment cluttered with obstacles. Given free start and goal placements for B decide whether there is a collision free motion for B from start to goal and if so plan such a motion.



Example I: The Roomba in the café

A disc moving among discs



Example II: Oskar's cube

- MP with 3 translational dofs
- Hint: Scientific American, Sep 1988 issue
- Jay's Oskar's cubes

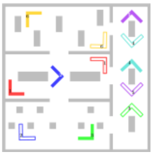
[oskarvandeventer.nl]

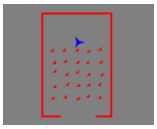
Terminology

- Workspace
- Configuration space (state space)
- Degrees of freedom (dofs)

Degrees of freedom

- a polygon robot translating in the plane
- a polygon robot translating and rotating
- a spatial robot translating and rotating
- industrial robot arms
- many robots

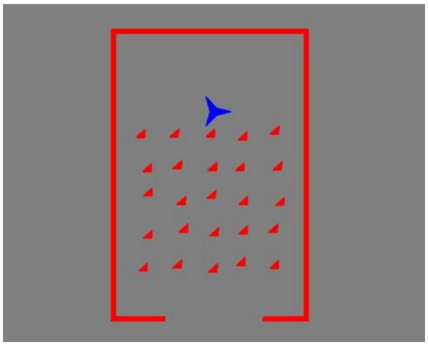


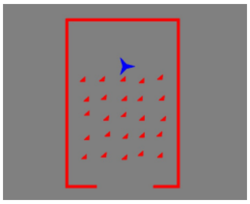


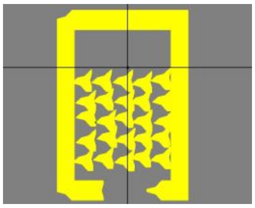
Configuration space

of a robot system with k degrees of freedom

- C-space, for short
- also known as state space
- the space of parametric representation of all possible robot configurations
- C-obstacles: the expanded obstacles
- the robot -> a point
- k-dimensional space
- point in configuration space: free, forbidden (, semi-free)
- path -> curve





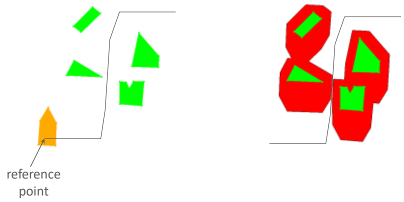


MOVE

C-obstacles

Q - a polygonal object that moves by translation

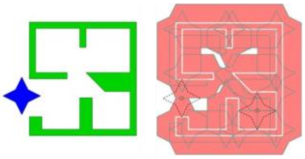
P - a set of polygonal obstacles



Minkowski sums

and translational C-obstacles

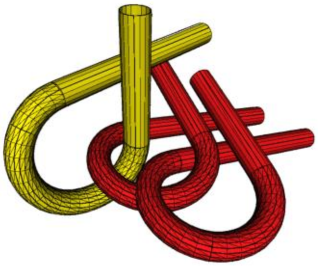
a central tool in geometric computing applicable to motion planning and other domains



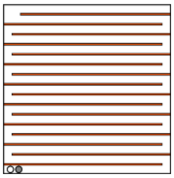
More complex systems

new designs, multi-robot systems, and other moving artifacts have many more dofs

Example III: the α puzzle



Types of solutions



- exact
- probabilistic
- hybrid
- heuristic

- major components in practical solutions: nearest-neighbor search, collision detection

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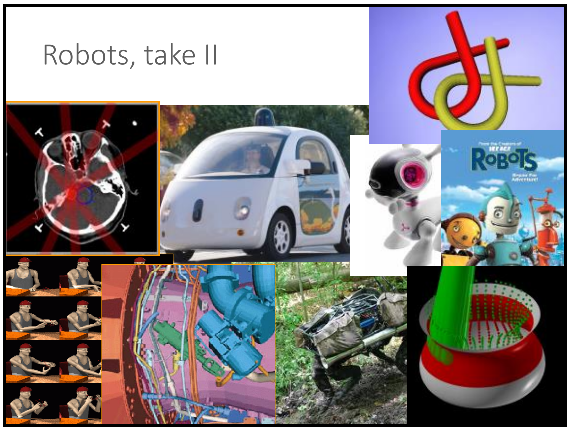
Robots, take II



Beyond the basic MP problem

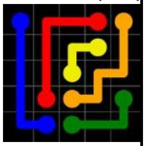
- moving obstacles
- multiple robots
- movable objects
- uncertainty
- nonholonomic constraints
- dynamic constraints
- ...

Multiple robots

[home.ustc.edu.cn/~hxiangli]

[cbsnew]

[flow free]

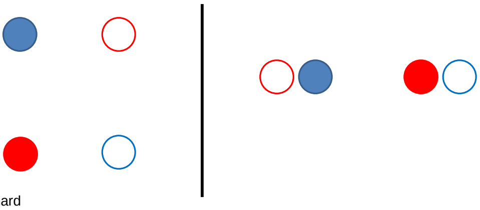


[lccRobotics.com]

[autonomy.cs.sfu.ca]

Exercise* (thought experiment)

Given two Roomba's, each has to move from given start to goal positions, no obstacles. What are the joint shortest paths (minimum total length)?

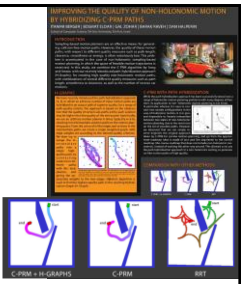


* hard

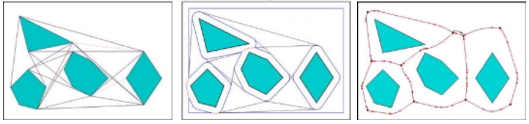
- The Introduction will be continued next week
- Move to About the course

Path quality

- length
- clearance
- combined measures
- minimum energy
- Minimum time
- …
- hard even in simple settings

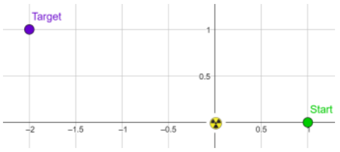


IMPROVING THE QUALITY OF NON-HOLONOMIC MOTION BY HYBRIDIZING C-PRM PATHS



Exercise* (thought experiment)

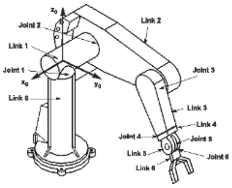
- A (point) robot is moving in the plane in the vicinity of a (point) source of nuclear radiation. It has to move from start to target. The cots per unit distance is inversely proportional to the clearance from the source of radiation. What is the minimum cost path for the robot?



typical in robotics: multi-objective optimization

Kinematics

- link
- joint
- base
- tcp
- kinematic chain
- direct kinematics
- inverse kinematics

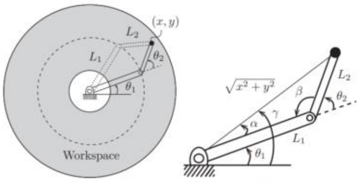


Inverse kinematics

[Fanuc Iberia]

Denavit-Hartenberg 1955, Pieper-Roth 1969

Inverse kinematics, a simple example



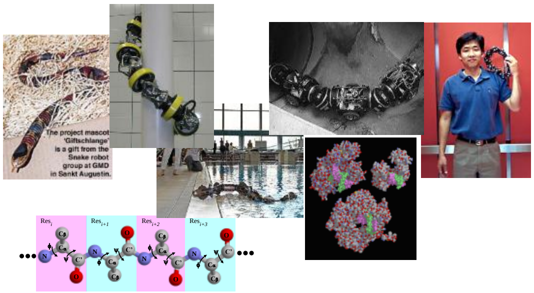
(a) A workspace, and lefty and righty configurations.

(b) Geometric solution.

Figure 6.1: Inverse kinematics of a 2R planar open chain.

[Modern Robotics, Lynch-Park, Cambridge UP]

Large kinematic structures



SWIMMING SNAKE ROBOT

Algorithmic robotics and automation

typically structured
predictable environment

looking toward unpredictable environments; lifelong planning

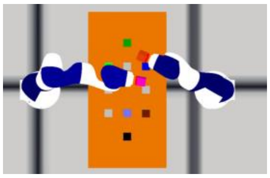
slightly less structured
environment

Q: is the cloth always below the line through the two fingers?

Cluttered environments

Algorithmic robotics and automation

Packaging: collision detection in tight settings



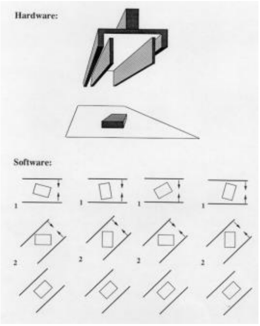
Dual arm object rearrangement

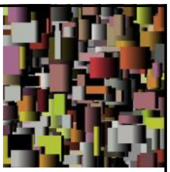
Algorithmic robotics, sensorless manipulation

Example:

the parallel jaw gripper [Goldberg]

VIDEO





About the course

Setting your expectations

The course at a glance

The main themes

Algorithmic foundations

- Part I: Complete (exact) methods
- Part II: Sampling-based methods
- Part III: Multi-robot motion planning

Robotics at large

- Guest lectures
- Students mini talks

Algorithmic foundations

- Part I: Complete (exact) methods
  - Arrangements, Minkowski sums, visibility graphs, Voronoi diagrams, Collins decomposition
- Part II: Sampling-based methods
  - Roadmaps, single vs. multi-query structures, probabilistic completeness, asymptotic optimality, collision detection
- Part III: Multi-robot motion planning
  - Hardness, labeled vs. unlabeled, separation assumptions, exact algorithms, SB planners

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Guest lectures

- David Zarrouk, BGU, 01.11.21:
Minimally Actuated Reconfigurable Robots

- Aviv Tamar, Technion, 22.11.21:
Reinforcement Learning in Robotics

- Oren Salzman, Technion, 06.12.21:
Algorithmic Motion Planning Meets Minimally-Invasive Robotic Surgery
1:03:30 – 1:09:15 - 10.10.21 שלושה שיודעים

- More guests if time permits

The course at a glance

Additional topics, as time permits/mini talks

- SLAM
- ROS
- Large kinematic structures

The course at a glance
Setting your expectations, I

Algorithmic foundations

- Part I: Complete (exact) methods
- Part II: Sampling-based methods
- Part III: Multi-robot motion planning

Robotics at large

- Guest lectures
- Students mini-talks

Course mechanics

- requirements (% of the final grade):
  - assignments (50%; 40% if you speak)
  - mini talk (10%) optional
  - final project (50%)
- assignment types:
  - () theory
  - (p) programming, solo
  - (p2) programming, you can work and submit in pairs
- office hours: by appointment

Tailor the tasks to your interests (in part)

- 40% fixed: the assignments
- 60% adaptable: mini talk and final project

Course team

- Instructor: Dan Halperin
- Teaching assistant: Michal Kleinbort
- Software assistance: Michal Kleinbort, Michael Bilevich

Background knowledge
Setting your expectations, II

- Basic assumed knowledge (informal prerequisites): Algorithms, Data Structures, Software1
- This course vs. Computational Geometry:
  - knowledge of some tools at the “API level”
  - basic reading (required):
    CG book by de Berg et al, Chapters 1&2
  - needed material will be discussed in the recitation

Background knowledge, cont’d
Setting your expectations, II

- Programming:
  - Python
  - some C++ might be unavoidable–we will provide Python bindings to C++ code, where possible
  - support will be provided in the recitation and in helpdesk

Main class vs recitation

- Main class, Monday 16-19, mandatory attendance
- Recitation, Monday 19-20, optional

topics of recitation: support, computational geometry tools, software tools

Mini talks

- 10-15 minutes
- or, 20-30 minutes for two students together
- topic of your choice; requires approval
- references to various up-to-date sources follow
- preferably involving more than one robot
- on a first-come, first-served basis
- deadline for selecting a topic: November 8th, 2021

Final project

- compact
- topic of your choice; requires approval
- algorithms+experiments, but other options possible
- various projects will be proposed by the course team
- preferably involving more than one robot
- deadline for selecting a topic: December 19th (Sunday!), 2021

Course site

- http://acg.cs.tau.ac.il/courses
- Algorithmic Robotics and Motion Planning Fall 2021-2022
- includes bibliography, lesson summary, assignments and more

Conferences and journals

- Conferences
  - ICRA
  - IROS
  - RSS
  - WAFR
  - …
  - MRS: conference on multi-robot systems
  - CoRL: conference on robot learning

Conferences and journals

- Journals
  - IJRR (International journal of Robotics Research)
  - IEEE TOR (Transactions on Robotics)
  - IEEE RA-L (Robotics and Automation Letters)
  - IEEE TASE (Transactions on Automation Science and Engineering)
  - Autonomous Robots,
  - …

Bibliography I
Books

Talk by Steve LaValle in our seminar, Wednesday 20/10/21 16:10:
Goldilocks and the Robot Brains

- Planning Algorithms, Steve LaValle, Cambridge University Press, 2006 (free online)
- Robot Motion Planning, Jean-Claude Latombe, Kluwer, 1991, later Springer
- Modern Robotics, Kevin Lynch and Frank Park, Cambridge University Press, 2017 (free online)
- Principles of Robot Motion: Theory, Algorithms, and Implementations, Choset et al, MIT Press, 2005

  in particular Chapter 7
- Computational Geometry: Algorithms and Applications, de Berg et al, 3rd Edition, Springer, 2008

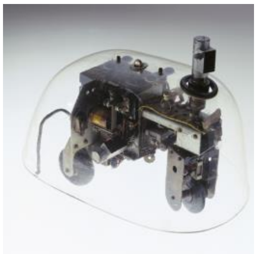
Bibliography II
Surveys

- Sampling-Based Robot Motion Planning, Oren Salzman, Communications of the ACM, October 2019
- Sampling-Based Robot Motion Planning: A Review, Elbanhawi and Simic, IEEE Access, 2014 (free online)
- Robotics, Halperin, Kavraki, Solovey, in Handbook of Discrete and Computational Geometry, 3rd Edition, 2018
- Algorithmic Motion Planning, Halperin, Salzman, Sharir, Handbook of Discrete and Computational Geometry, 3rd Edition, 2018

Why study robot algorithms?

- Robotics is fast expanding, posing new and challenging algorithmic questions
- Robot algorithms connect with many areas of mathematics and computer science
- Solutions to algorithmic questions in robotics have repeatedly proved useful in many other domains

Before the end,
a little more history



- Grey Walter's tortoises ~1948
- Turing’s visit to the Science Museum 1951

THE END