Robotics

Erwin M. Bakker| LIACS Media Lab

28-2 2019

Universiteit Leiden

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Organization and Overview

Period: February 15th - May 10th 2019
Time: Friday 09.00 – 10.45
Place: LIACS, Room 401 (Workshops Room 303)
Lecturer: Dr Erwin M. Bakker (erwin@liacs.nl)
Assistant: Andrius Bernatavicius

NB E-mail your name and student number to erwin@liacs.nl

Schedule:

15-2	Introduction and Overview
22-2	Control Space, Locomotion and Kinematics
1-3	Inverse Kinematics and Sensors
8-3	***Yetiborg Introduction*** *and SLAM Workshop I*
15-3	*Project Proposals (presentation by students)*
22-3	***Yetiborg Qualification*** and *ROS Workshop II*
29-3	Robotics Image Processing
5-4	***Yetiborg Race*** *and/or Nao Workshop III*
12-4	Robotics Image Processing and Understanding
19-4	No Class
26-4	Robotics Reinforcement Learning.
3-5	Robotics Reinforcement Learning Workshop IV
10-5	***Project Demos*** *(by students)*

Website: http://liacs.leidenuniv.nl/~bakkerem2/robotics/

Grading (6 ECTS): Presentations and Robotics Project (60% of grade). Class discussions, attendance, workshops and assignments (40% of grade). It is necessary to be at every class and to complete every workshop.

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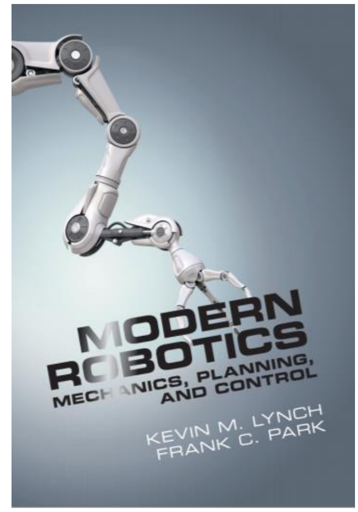
Overview

- Configuration Space
- Rigid Body Motion
- Forward Kinematics
- Inverse Kinematics
- Sensors

- Link: http://modernrobotics.org



K.M. Lynch, F.C. Park, Modern Robotics: Mechanics, Planning and Control, Cambridge University Press, 2017

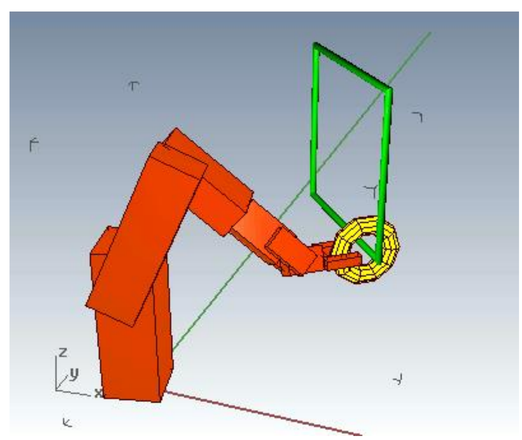
How to move to a goal?

Problem: How to move to a goal?

- Grasp, Walk, Stand, Dance, Follow, etc.

Solution:

1. *Program step by step*
   - *Computer Numerical Control (CNC), Automation.*
2. *Inverse kinematics*:
   - take end-points and move them to designated points.
3. *Tracing movements*
   - by specialist, human, etc.
4. ***Learn the right movements***
   - **Reinforcement Learning**, give a reward when the movement resembles the designated movement.



Configuration Space

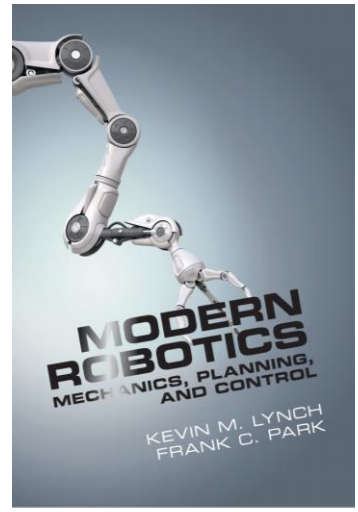
Robot Question: Where am I?

Answer:

The robot's configuration: a specification of the positions of all points of a robot.

Here we assume:

Robot links and bodies are rigid and of known shape => only a few variables needed to describe it's configuration.



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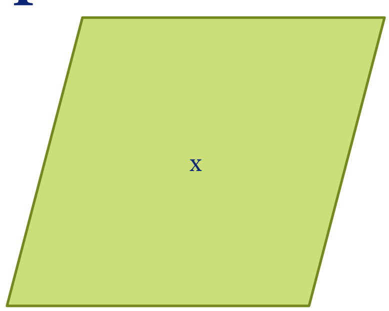
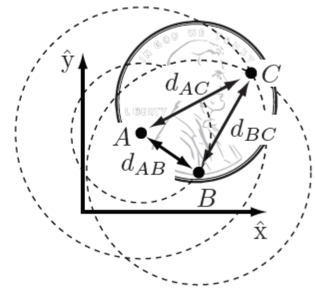
Configuration Space



- Degrees of Freedom of a Rigid Body: the smallest number of real-valued coordinates needed to represent its configuration

Configuration Space



Assume we have a coin with 3 points A, B, C on it.

In the plane A,B,C have 6 degrees of freedom:
(x_A,y_A) , (x_B,y_B) , (x_C,y_C)
A coin is rigid => 3 extra constraints on distances: d_{AB}, d_{AC}, d_{BC} are fixed, wherever the location of the coin would be.

1. The coin and hence A can be placed everywhere => (x_A,y_A) free to choose.
2. B can only be placed under the constraint that its distance to A would be equal to d_{AB}. => freedom to turn the coin around A with angle φ_{AB} => (x_A, y_A, φ_{AB}) are free to choose.
3. C should be placed at distance d_{AC}, d_{BC} from A and B, respectively => only 1 possibility, hence no degree of freedom added.

Degrees of Freedom (DOF) of a Coin
= sum of freedoms of the points – number of independent constraints
= number of variables – number of independent equations = 6 – 3 = 3

Configuration Space

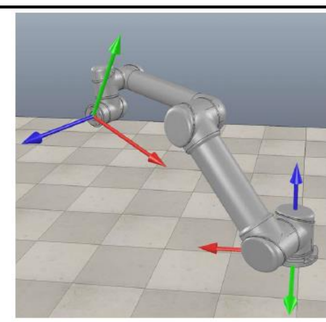
[1] Definition 2.1.

The **configuration** of a robot is a complete specification of the position of every point of the robot.

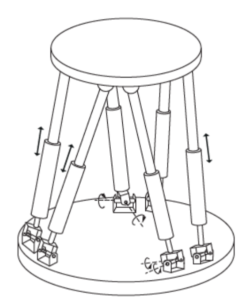
The minimum number *n* of real-valued coordinates needed to represent the configuration is the number of **degrees of freedom (dof)** of the robot.

The *n*-dimensional space containing all possible configurations of the robot is called the **Configuration Space (C-space)**.

The configuration of a robot is represented by a point in its C-space.



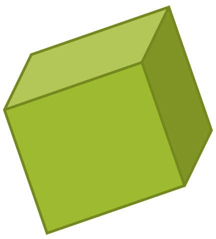
Open-chain robot: Manipulator (in V-REP). [1]



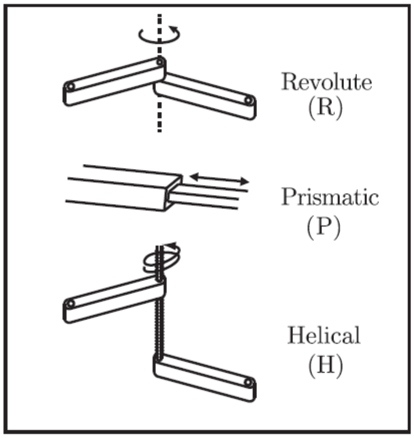
Closed-chain robot: Stewart-Gough platform. [1]

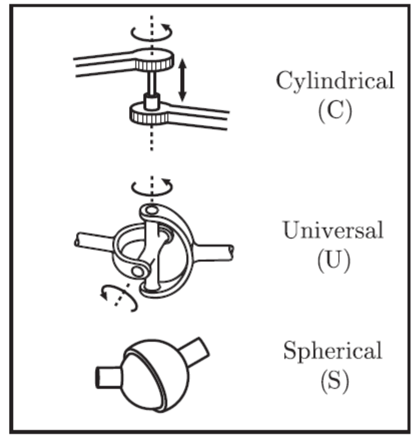
Degrees of Freedom of a Robot

- A rigid body in 3D Space has **6 DOF**



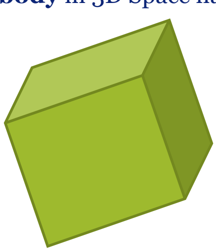
- A joint can be seen to put constraints on the rigid bodies it connects
- It also allows freedom to move relative to the body it is attached to.





Degrees of Freedom of a Robot

- A **rigid body** in 3D Space has 6 DOF



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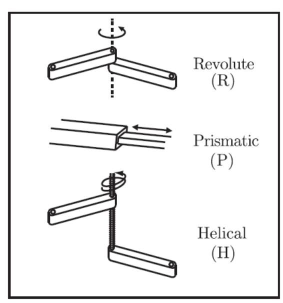

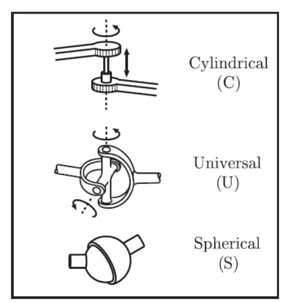

Joint type	dof f	Constraints c between two planar rigid bodies	Constraints c between two spatial rigid bodies
Revolute (R)	1	2	5
Prismatic (P)	1	2	5
Helical (H)	1	N/A	5
Cylindrical (C)	2	N/A	4
Universal (U)	2	N/A	4
Spherical (S)	3	N/A	3

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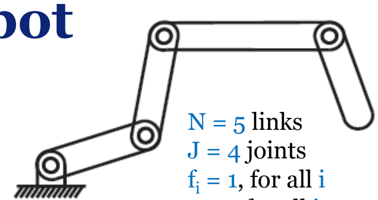
Degrees of Freedom of a Robot

Planar Mechanism DOF = 4



N = 5 links
J = 4 joints
$f_i = 1$, for all i
$c_i = 2$, for all i

Proposition (Grübler's formula)

Consider a mechanism consisting of

- N links, where ground is also regarded as a link.
- J number of joints,
- m number of degrees of freedom of a rigid body (m = 3 for planar mechanisms and m = 6 for spatial mechanisms),
- f_i the number of freedoms provided by joint i, and
- c_i the number of constraints provided by joint i, where $f_i + c_i = m$ for all i.

Then *Grübler's formula* for the number of degrees of freedom of the robot is

$$dof = m(N-1) - \sum_{i=1}^{J} c_i = m(N-1-J) + \sum_{i=1}^{J} f_i$$

This formula holds only if all joint constraints are independent. If they are not independent then the formula provides a lower bound on the number of degrees of freedom.

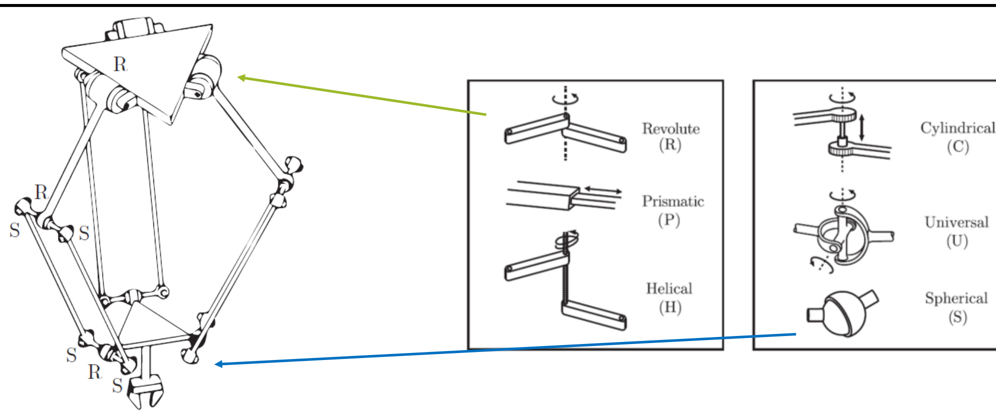


Figure 2.8: The Delta robot.

Example 2.7 (Delta robot). The Delta robot of Figure 2.8 consists of two platforms – the lower one mobile, the upper one stationary – connected by three legs. Each leg contains a parallelogram closed chain and consists of three revolute joints, four spherical joints, and five links. Adding the two platforms, there are $N = 17$ links and $J = 21$ joints (nine revolute and 12 spherical). By Grübler's formula,

$$\text{dof} = 6(17 - 1 - 21) + 9(1) + 12(3) = 15.$$

- Links: 1 + 3 + 3 + 6 + 3 + 1 = 17
- Joints: 21: 9x R(1 dof) and 12 x S(3 dof)
- m= 6

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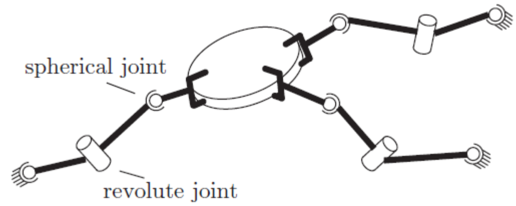
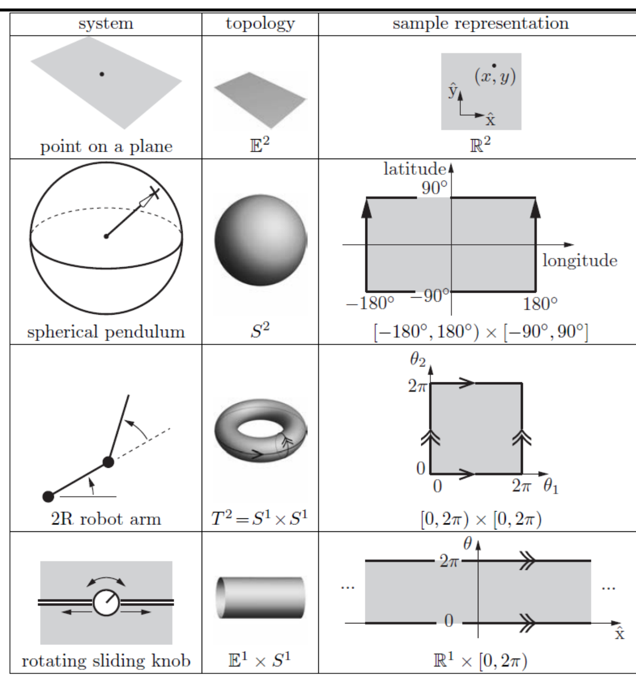
Assignments

- 3x SRS
- M=6, N = 1 + 3 x 3 = 10, J = 3 x 3, dof per leg 3 + 1 + 3
  => dof = 6 (10 – 1 – 9) + 3 x 7 = 21



Topologies

Note: $S^1 \times S^1 = T^2$ (not S^2)



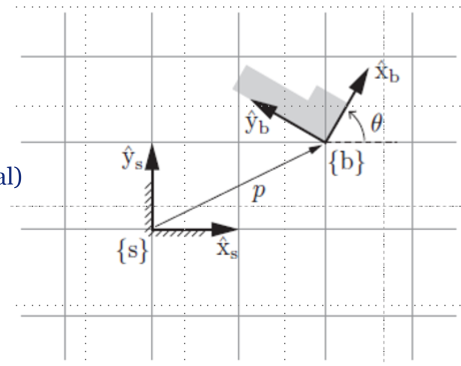
Coordinates

Explicit Coordinates
- Euclidean (x,y)
- Polar (r,φ)
- Combined (x,y) x (r, φ)

Implicit Coordinates
- $\{ (x,y,z) \mid x^2+y^2+z^2=1 \}$

C-Space (Configuration Space)

How to describe a rigid body's position and orientation in C-Space?



Fixed reference frame {s}

Reference fame attached to body {b}

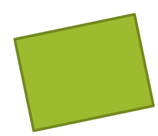
Described by 4x4 matrix with 10 constraints (unit-length, orthogonal)

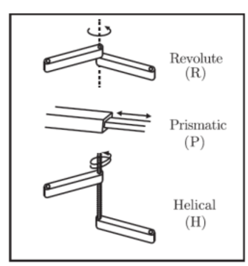
Matrix can be used to:

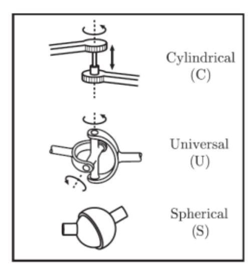
1. Translate or rotate a vector or a frame
2. Change the representation of a vector or a frame
   - for example from relative to {s} to relative to {b}

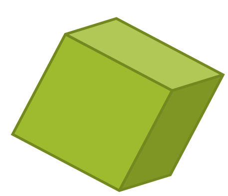
C-Spaces

- The C-space of a rigid body in the plane can be written as $\mathbb{R}^2 \times S^1$, since the configuration can be represented as the concatenation of the coordinates (x, y) representing $\mathbb{R}^2$ and an angle θ representing S^1.
- The C-space of a PR robot arm can be written $\mathbb{R}^1 \times S^1$. (We will occasionally ignore joint limits, i.e., bounds on the travel of the joints, when expressing the topology of the C-space; with joint limits, the C-space is the Cartesian product of two closed intervals of the line.)
- The C-space of a 2R robot arm can be written $S^1 \times S^1 = T^2$, where T^n is the n-dimensional surface of a torus in an $(n+1)$-dimensional space. (See Table 2.2.) Note that $S^1 \times S^1 \times \cdots \times S^1$ (n copies of S^1) is equal to T^n, not S^n; for example, a sphere S^2 is not topologically equivalent to a torus T^2.
- The C-space of a planar rigid body (e.g., the chassis of a mobile robot) with a 2R robot arm can be written as $\mathbb{R}^2 \times S^1 \times T^2 = \mathbb{R}^2 \times T^3$.
- As we saw in Section 2.1 when we counted the degrees of freedom of a rigid body in three dimensions, the configuration of a rigid body can be described by a point in $\mathbb{R}^3$, plus a point on a two-dimensional sphere S^2, plus a point on a one-dimensional circle S^1, giving a total C-space of $\mathbb{R}^3 \times S^2 \times S^1$.









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Task Space and Work Space

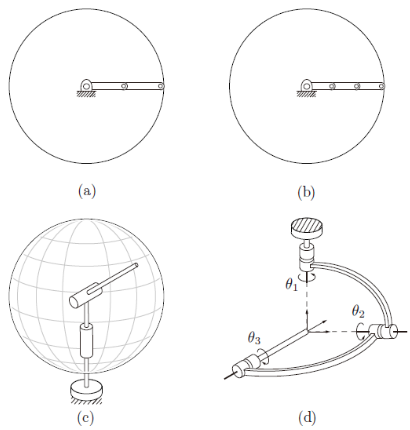
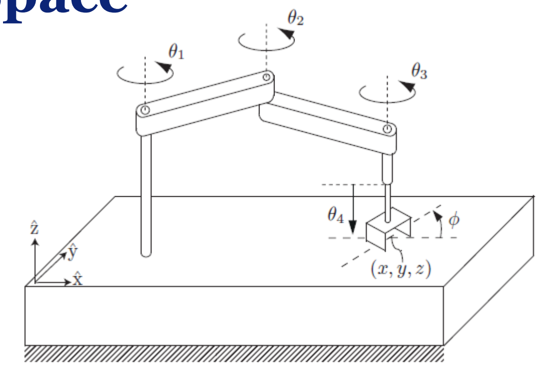


Figure 2.12: Examples of workspaces for various robots: (a) a planar 2R open chain; (b) a planar 3R open chain; (c) a spherical 2R open chain; (d) a 3R orienting mechanism.

The **workspace** is a specification of the configurations that the end-effector of the robot can reach.



The SCARA robot is an RRRP open chain that is widely used for tabletop pick-and-place tasks. The end-effector configuration is completely described by (x, y, z, φ)

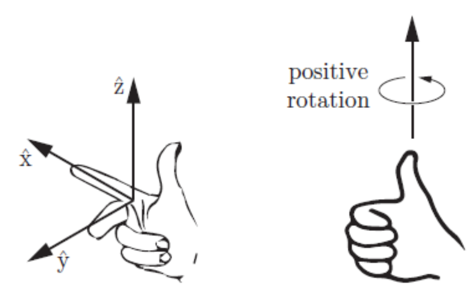
⇒ **task space** $R^3 \times S^1$ and

⇒ **workspace** as the reachable points in (x, y, z), since all orientations φ can be achieved at all reachable points.

Rigid Body Motion

Rigid-body position and orientation (x, y, z, φ, θ, ψ)

- Can also be described by 4x4 matrix with 10 constraints.
- In general 4x4 matrices can be used for
  - Location
  - Translation + rotation of a vector or frame
  - Transformation of coordinates between frames

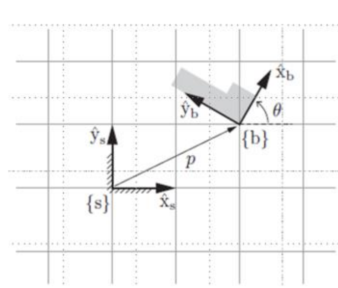


- Velocity of a rigid body: $(\partial x/\partial t,\ \partial y/\partial t,\ \partial z/\partial t,\ \partial \phi/\partial t,\ \partial \theta/\partial t,\ \partial \psi/\partial t)$

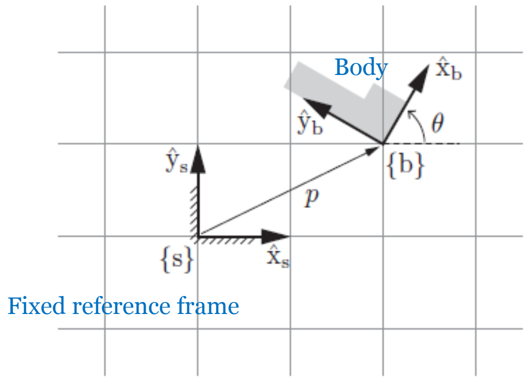
Exponential coordinates:

Every rigid-body configuration can be achieved by:

- Starting in the fixed home frame and integrating a constant twist for a specified time.
- Direction of a screw axis and scalar to indicate how far the screw axis must be followed



Rigid Body Motions in the Plane



$$p = p_x\hat{x}_s + p_y\hat{y}_s.$$

$$\hat{x}_b = \cos\theta\,\hat{x}_s + \sin\theta\,\hat{y}_s,$$
$$\hat{y}_b = -\sin\theta\,\hat{x}_s + \cos\theta\,\hat{y}_s.$$

Figure 3.3: The body frame {b} is expressed in the fixed-frame coordinates {s} by the vector p and the directions of the unit axes $\hat{x}_b$ and $\hat{y}_b$. In this example, $p = (2, 1)$ and $\theta = 60°$, so $\hat{x}_b = (\cos\theta, \sin\theta) = (0.5, 1/\sqrt{2})$ and $\hat{y}_b = (-\sin\theta, \cos\theta) = (-1/\sqrt{2}, 0.5)$.

Rigid Body Motions in the Plane

Previously:

$$p = p_x\hat{x}_s + p_y\hat{y}_s.$$

$$\hat{x}_b = \cos\theta\,\hat{x}_s + \sin\theta\,\hat{y}_s,$$
$$\hat{y}_b = -\sin\theta\,\hat{x}_s + \cos\theta\,\hat{y}_s.$$

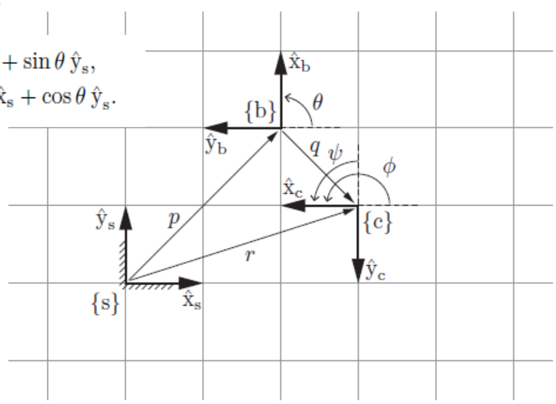


Figure 3.4: The frame {b} in {s} is given by (P, p), and the frame {c} in {b} is given by (Q, q). From these we can derive the frame {c} in {s}, described by (R, r). The numerical values of the vectors p, q, and r and the coordinate-axis directions of the three frames are evident from the grid of unit squares.

{b} relative to {s}

$$p = \begin{bmatrix} p_x \\ p_y \end{bmatrix}$$

$$P = [\hat{x}_b \;\; \hat{y}_b] = \begin{bmatrix} \cos\theta & -\sin\theta \\ \sin\theta & \cos\theta \end{bmatrix}$$

{c} relative to {s}

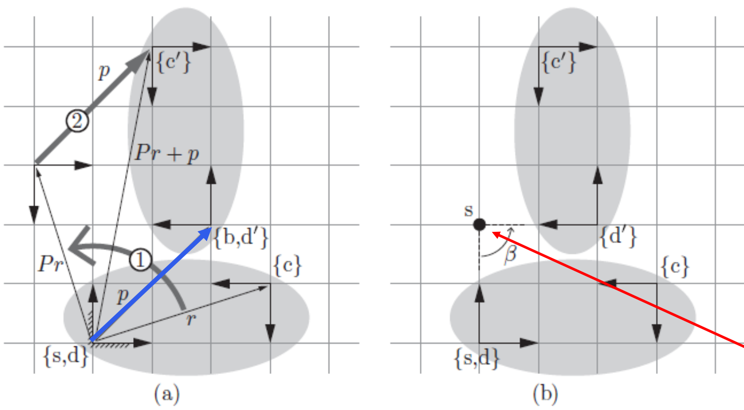
$$r = \begin{bmatrix} r_x \\ r_y \end{bmatrix}, \qquad R = \begin{bmatrix} \cos\phi & -\sin\phi \\ \sin\phi & \cos\phi \end{bmatrix}$$

{c} relative to {b}

$$q = \begin{bmatrix} q_x \\ q_y \end{bmatrix}, \qquad Q = \begin{bmatrix} \cos\psi & -\sin\psi \\ \sin\psi & \cos\psi \end{bmatrix}$$

Note and verify: R = PQ, and r = Pq+p

Rigid Body Motions in the Plane



{c} described by (R,r)

$$r = \begin{bmatrix} r_x \\ r_y \end{bmatrix}, \qquad R = \begin{bmatrix} \cos\phi & -\sin\phi \\ \sin\phi & \cos\phi \end{bmatrix}$$

Move rigid body such that {d} coincides with {d'}.

$$p = \begin{bmatrix} p_x \\ p_y \end{bmatrix} \qquad P = [\hat{x}_b \;\; \hat{y}_b] = \begin{bmatrix} \cos\theta & -\sin\theta \\ \sin\theta & \cos\theta \end{bmatrix}$$

Then {c'} described by (R',r'):

$$R' = PR,$$
$$r' = Pr + p,$$

Note: SCREW MOTION
The above rotation followed by a translation can also be expressed as a rotation of the rigid-body about a fixed point s by an angle β

(P, p) can be used to

1. Represent a configuration of a rigid body in {s}
2. Change the reference frame for vector representation.
3. **Displace a vector or a frame.**

Rigid Body Motions in the Plane

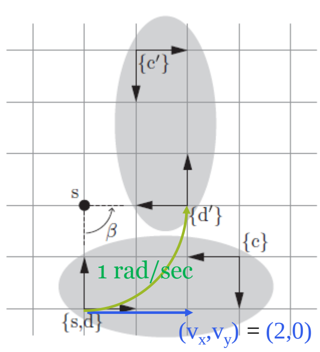
Note: SCREW MOTION
The above rotation followed by a translation can also be expressed as a rotation of the rigid-body about a fixed point s by an angle β

(β, s_x, s_y) , where $(s_x, s_y) = (0, 2)$

In the {s}-frame rotate 1 rad/sec with speed $(v_x,v_y) = (2, 0)$ is denoted as:
$S = (\omega, v_x, v_y) = (1, 2, 0)$

Following the screw-axis for an angle $\theta = \pi/2$ gives the displacement we want:
$S\theta = (\pi/2, \pi, 0)$

These are called the **exponential coordinates** for the planar rigid-body displacement.



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$$p = \begin{bmatrix} p_x \\ p_y \end{bmatrix} \qquad P = [\hat{x}_b \;\; \hat{y}_b] = \begin{bmatrix} \cos\theta & -\sin\theta \\ \sin\theta & \cos\theta \end{bmatrix}$$

Then {c'} described by (R',r'):

$$R' = PR,$$
$$r' = Pr + p,$$

Note:
- distance = vt
- distance along quarter circle with radius 2 equals π.

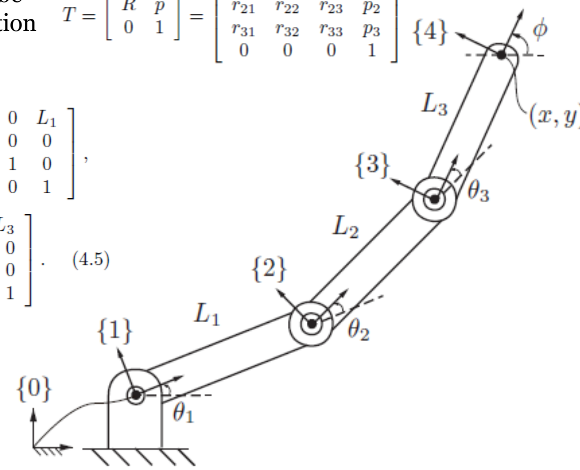
Forward Kinematics

The forward kinematics of 3R Planar Open Chain can be written as a product of four homogeneous transformation matrices: $T_{04} = T_{01}T_{12}T_{23}T_{34}$, where

$$T = \begin{bmatrix} R & p \\ 0 & 1 \end{bmatrix} = \begin{bmatrix} r_{11} & r_{12} & r_{13} & p_1 \\ r_{21} & r_{22} & r_{23} & p_2 \\ r_{31} & r_{32} & r_{33} & p_3 \\ 0 & 0 & 0 & 1 \end{bmatrix}$$

$$T_{01} = \begin{bmatrix} \cos\theta_1 & -\sin\theta_1 & 0 & 0 \\ \sin\theta_1 & \cos\theta_1 & 0 & 0 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix}, \quad T_{12} = \begin{bmatrix} \cos\theta_2 & -\sin\theta_2 & 0 & L_1 \\ \sin\theta_2 & \cos\theta_2 & 0 & 0 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix},$$

$$T_{23} = \begin{bmatrix} \cos\theta_3 & -\sin\theta_3 & 0 & L_2 \\ \sin\theta_3 & \cos\theta_3 & 0 & 0 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix}, \quad T_{34} = \begin{bmatrix} 1 & 0 & 0 & L_3 \\ 0 & 1 & 0 & 0 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix}. \quad (4.5)$$



Home position M:

$$M = \begin{bmatrix} 1 & 0 & 0 & L_1 + L_2 + L_3 \\ 0 & 1 & 0 & 0 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix}$$

Forward Kinematics: Product of Exponentials

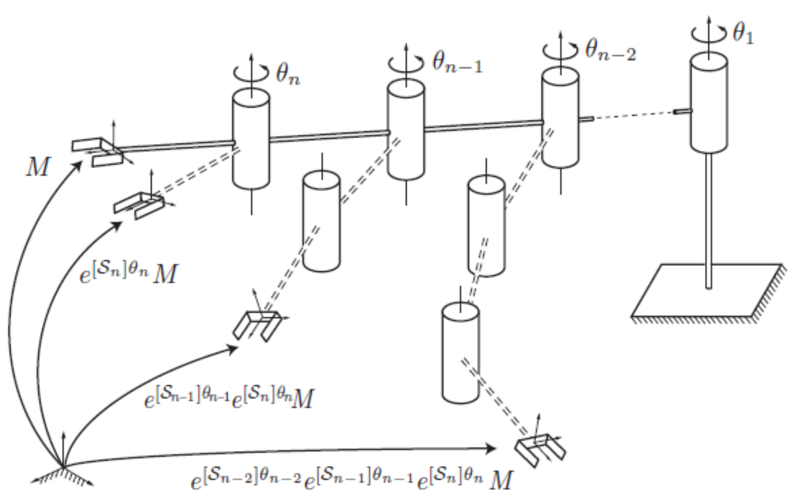


Figure 4.2: Illustration of the PoE formula for an n-link spatial open chain.

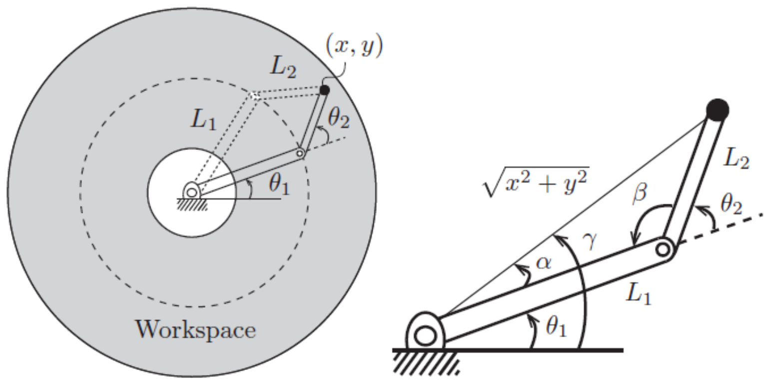
PoE parameters also known as Euler-Rodrigues parameters.

There are many other representations:
- for example Denavit-Hartenberg (1955) representation is very popular, but can be cumbersome

In velocity kinematics Jacobians are used.

Inverse Kinematics

Which angles θ_1, and θ_1 will lead to location (x,y)?



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

(b) Geometric solution.

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

Law of cosines gives:

$$L_1^2 + L_2^2 - 2L_1L_2\cos\beta = x^2 + y^2$$

, hence

$$\beta = \cos^{-1}\left(\frac{L_1^2 + L_2^2 - x^2 - y^2}{2L_1L_2}\right)$$

,and similarly

$$\alpha = \cos^{-1}\left(\frac{x^2 + y^2 + L_1^2 - L_2^2}{2L_1\sqrt{x^2 + y^2}}\right)$$

γ= atan2(y,x)

Answer:

$$\theta_1 = \gamma - \alpha, \qquad \theta_2 = \pi - \beta$$

In general: IK-Solvers

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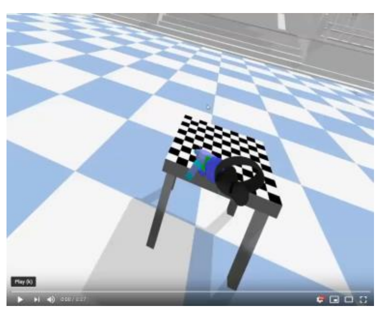
Real Time Physics Modelling

https://pybullet.org/wordpress/



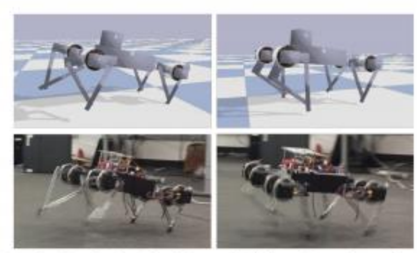
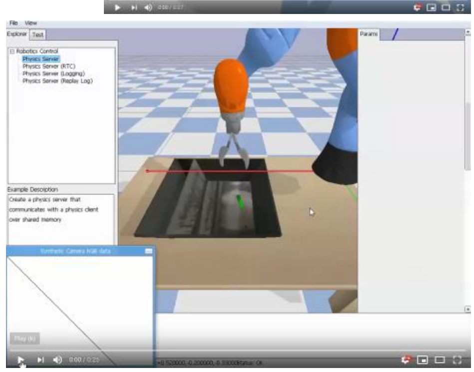
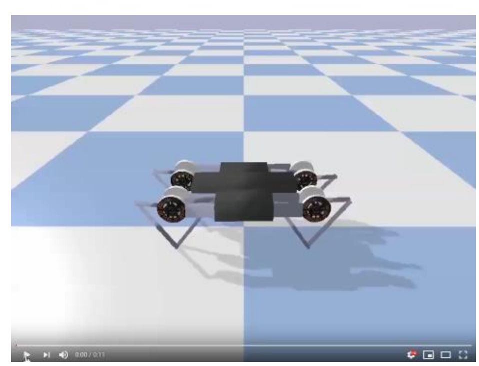


Fig. 1: The simulated and the real Minitaurs learned to gallop using deep reinforcement learning.

pybullet KUKA
grasp training

Using Tensorflow
OpenAI gym
Baselines
DeepQNetworks (DQNs)





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Robotics Preparations

1) Form YetiBorg Racing Teams of 3 to 4 people
Appoint one person who will be responsible for the robot.

Email your teams to erwin@liacs.nl with subject 'Robotics YetiBorg Racing Team'.
Due: Thursday 7-3 at 14.00 PM.

2) **Project Proposal Title and Abstract**
Give the title and abstract of the project proposal you will present on March 15th.
Also mention the number of people that will cooperate on the project (1-4).

Email your proposal to erwin@liacs.nl with subject 'Robotics Project Proposal'.
Due: Thursday 7-3 at 14.00 PM.

References

1. K.M. Lynch, F.C. Park, Modern Robotics: Mechanics, Planning and Control, Cambridge University Press, 2017. (DOI: 10.1017/9781316661239)
2. https://pybullet.org/wordpress/

Robotics

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