Configuration Space

CS 6301 Special Topics: Introduction to Robot Manipulation and Navigation

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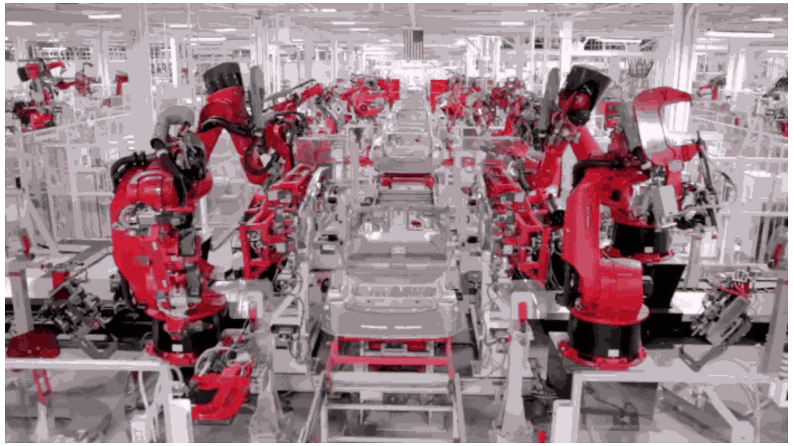
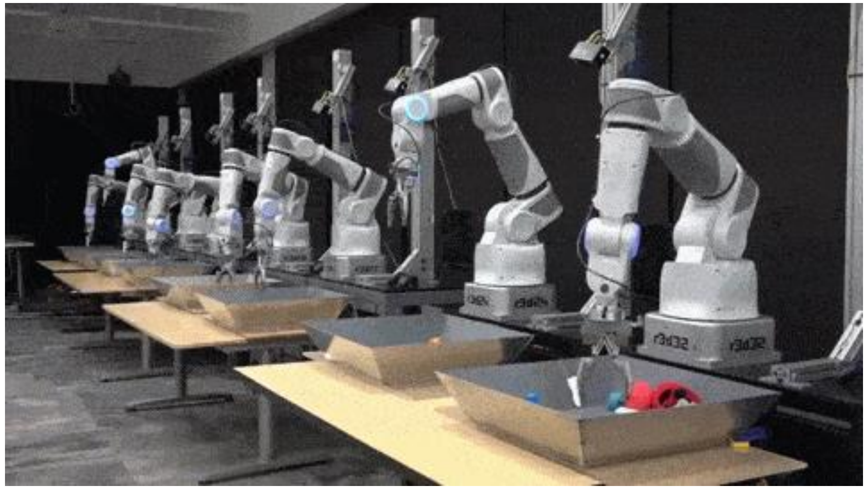
The University of Texas at Dallas

Robotics

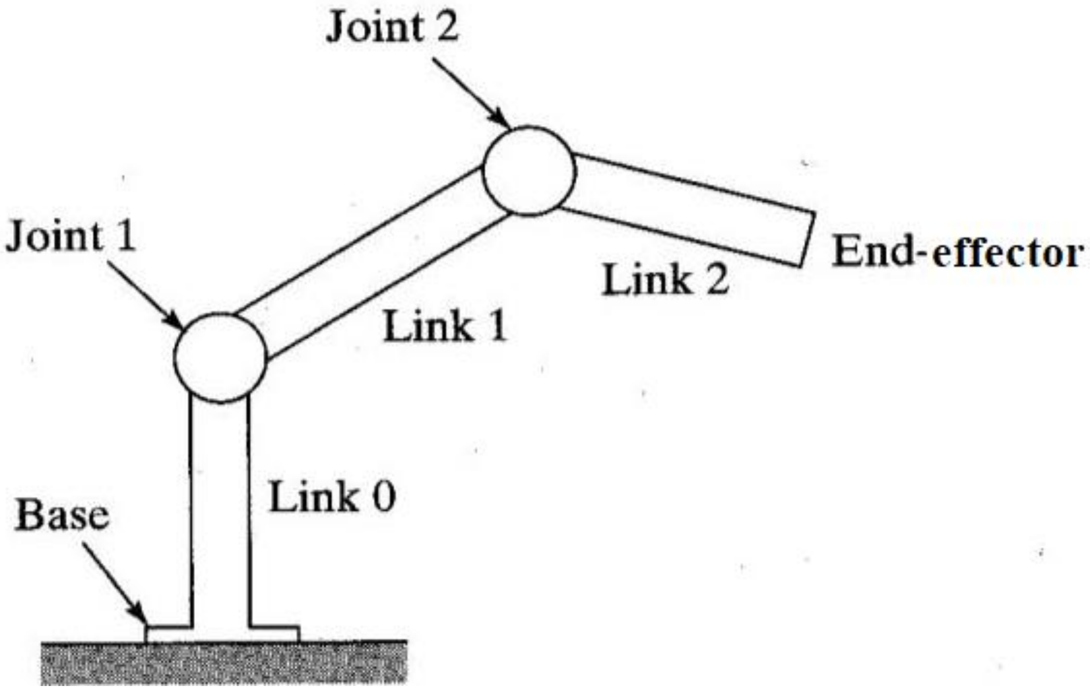


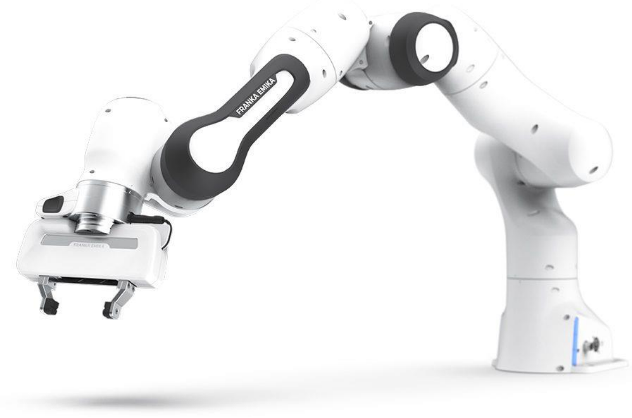


What is the common phenomenon in these robots? Motion

Robot Mechanisms

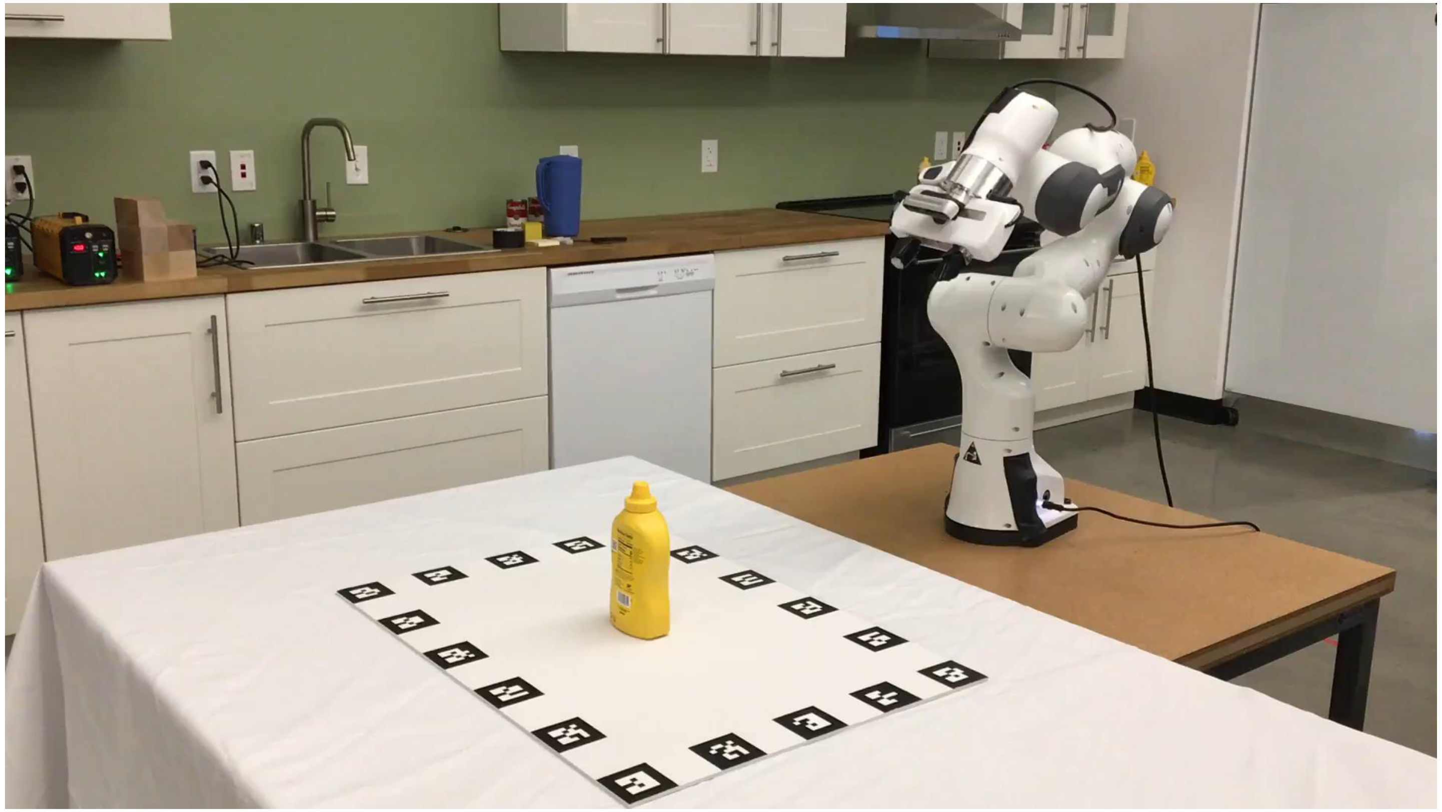
- Links and Joints





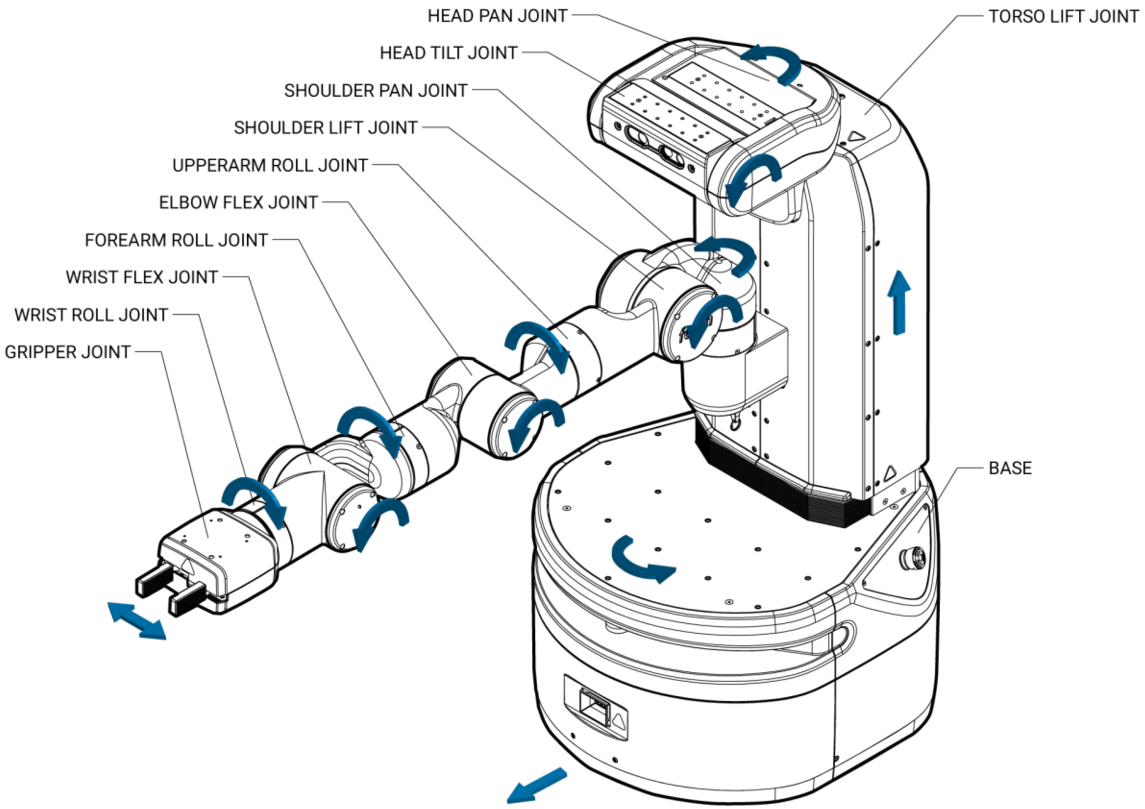
Franka Emika

Franka Movement



Robot Mechanisms

- Links and Joints

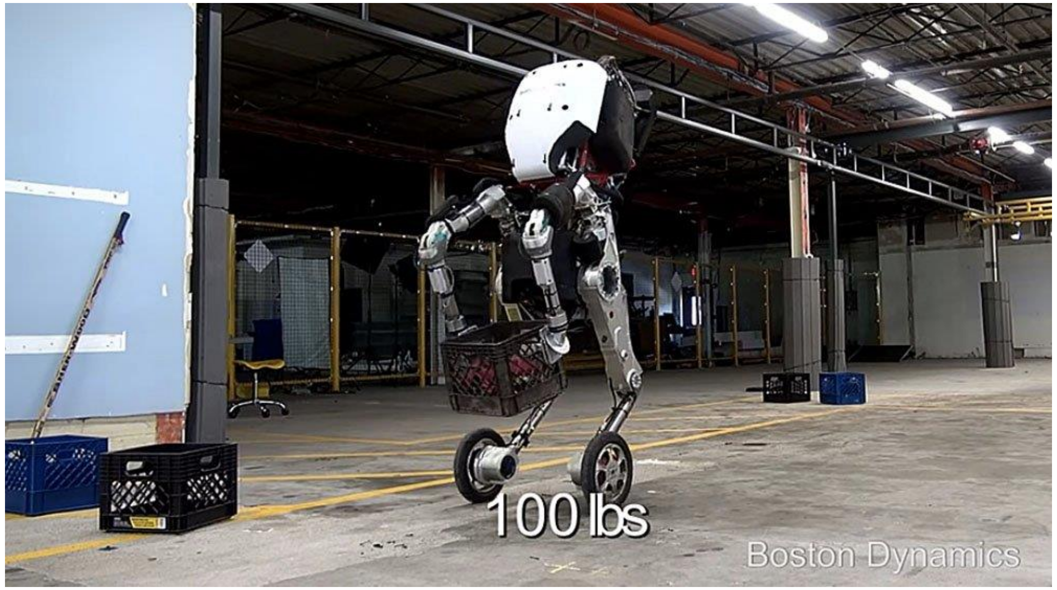


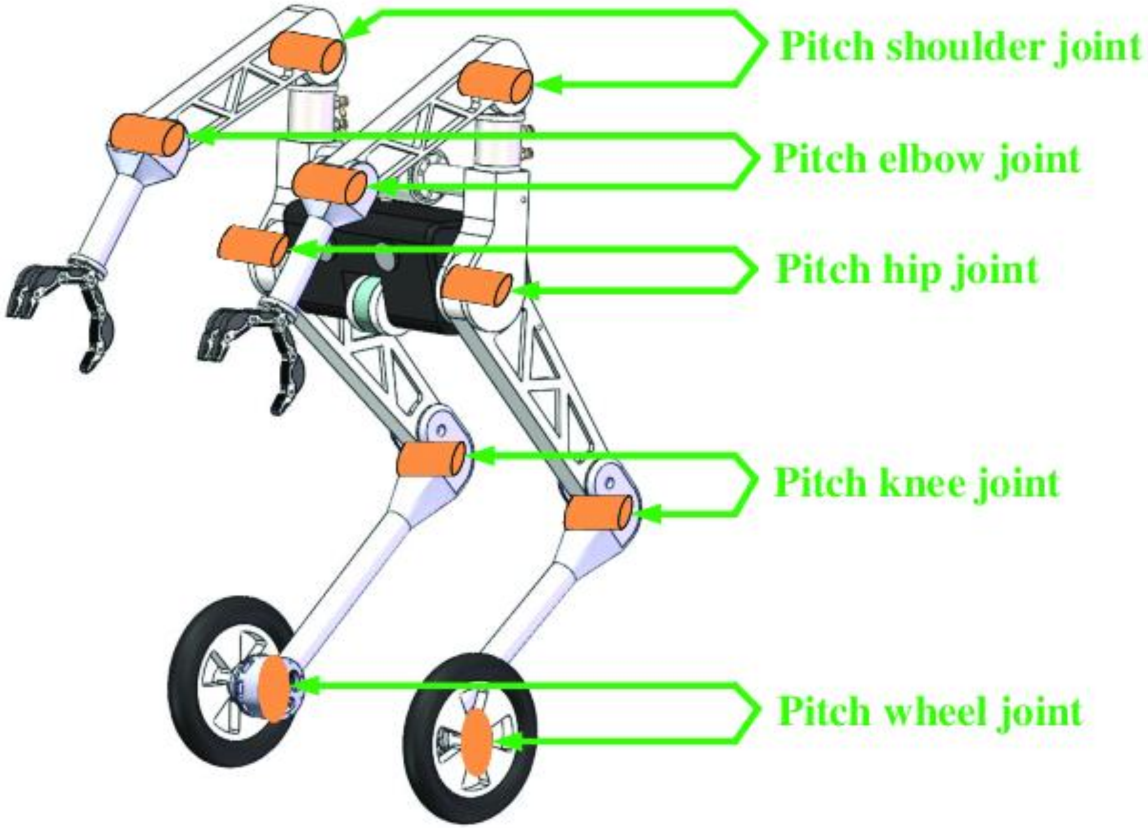
Fetch Mobile Manipulator

Fetch Movement

Robot Mechanisms

- Links and Joints

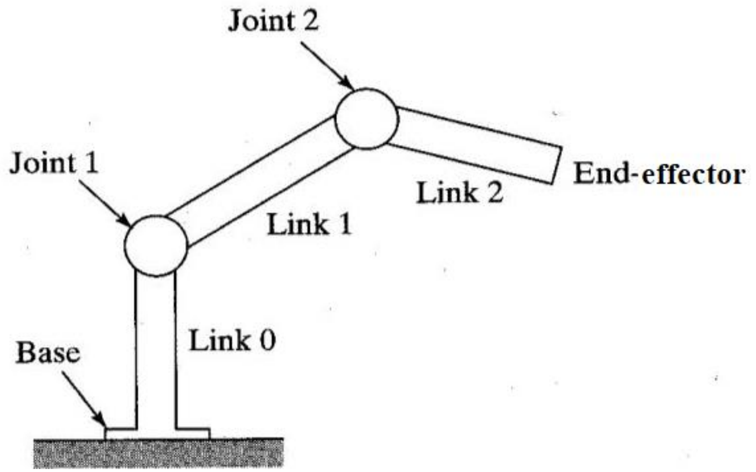




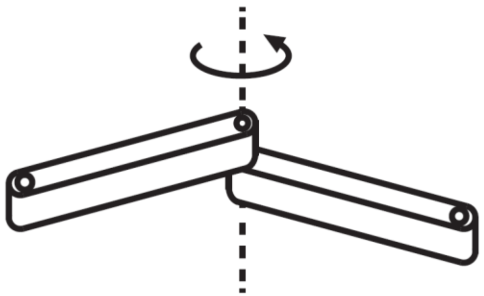
https://thenewstack.io/boston-dynamics-agile-wheel-legged-humanoid-robot-performs-incredible-stunts/

Robot Joints

- Every joint connects exactly two links

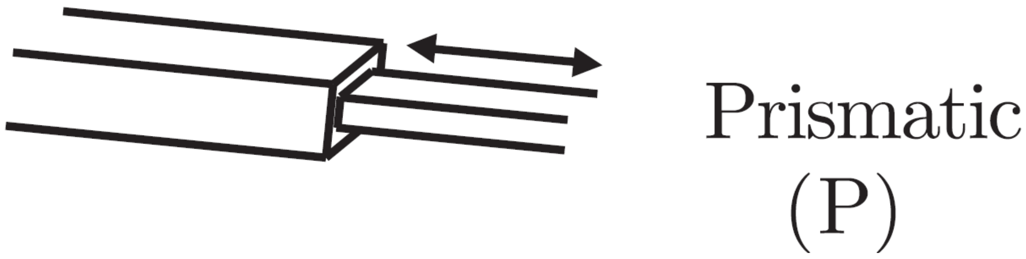


- Revolute joint (R)
  - Hinge joint
  - Allows rotation motion about the joint axis

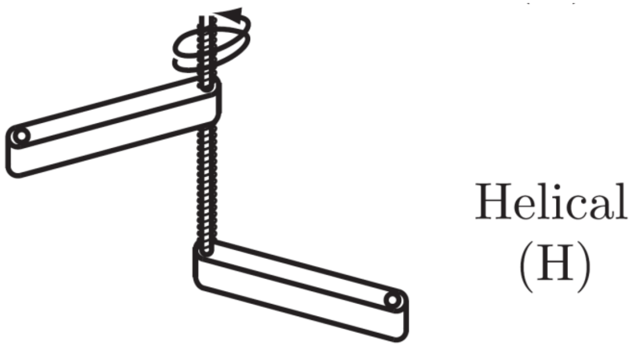


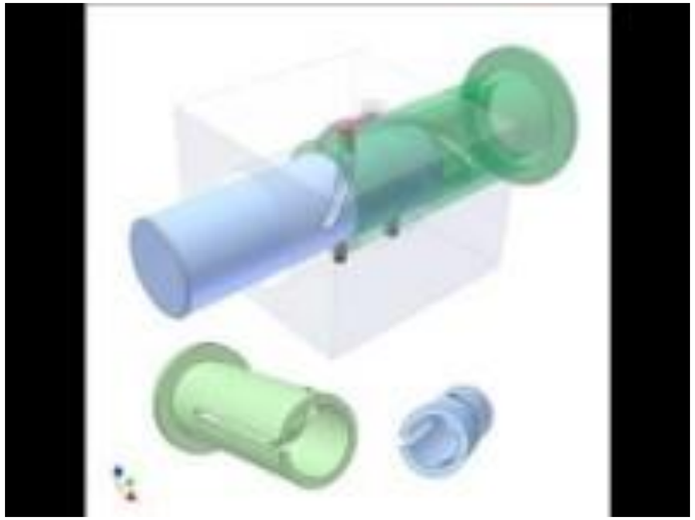
Robot Joints

- Prismatic Joint (P)
  - Sliding joint or linear joint
  - Allows translational motion along the direction of the joint axis



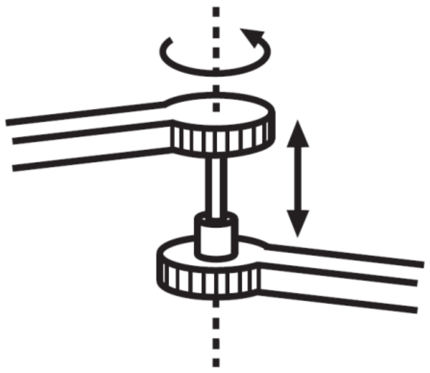
- Helical Joint (H)
  - Screw joint
  - Allows rotation and translation about a screw axis



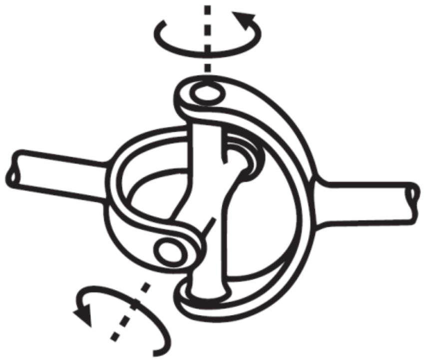


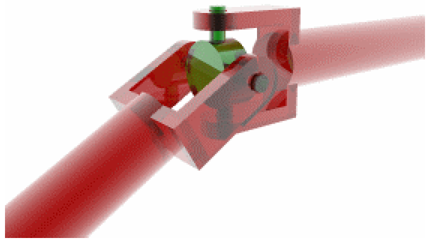
Robot Joints

- Cylindrical joint (C)
  - Allows independent translations and rotations about a single fixed joint axis



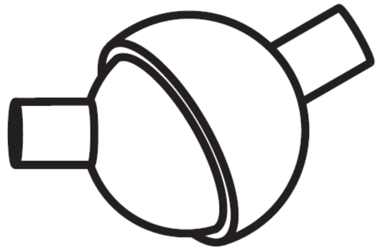
- Universal joint (U)
  - A pair of revolute joints with orthogonal joint axes





Robot Joints

- Spherical joint (S)
  - Ball-and-socket joint

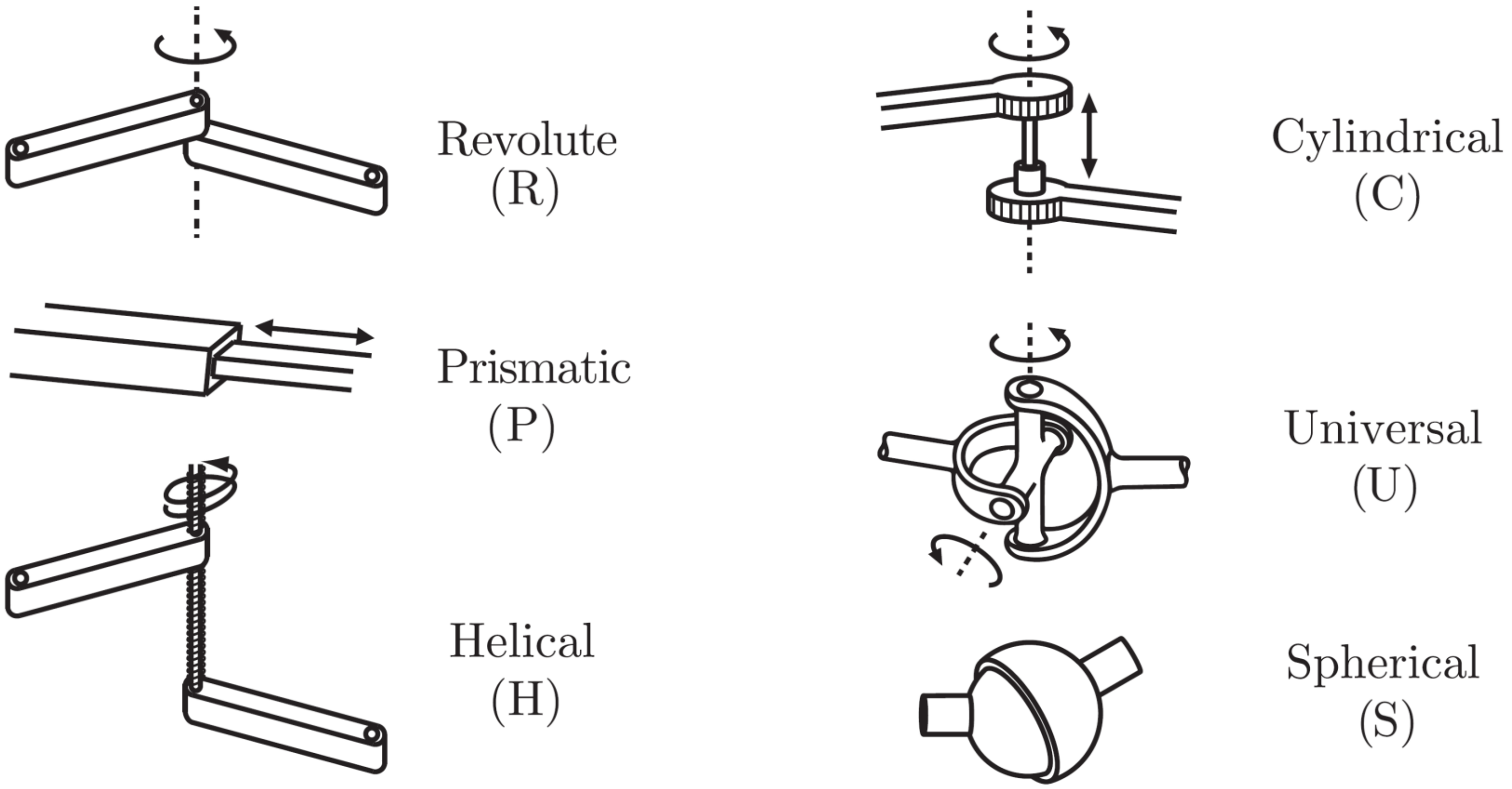


Spherical
(S)

https://youtu.be/kztZu3uTyvM

Robot Joints

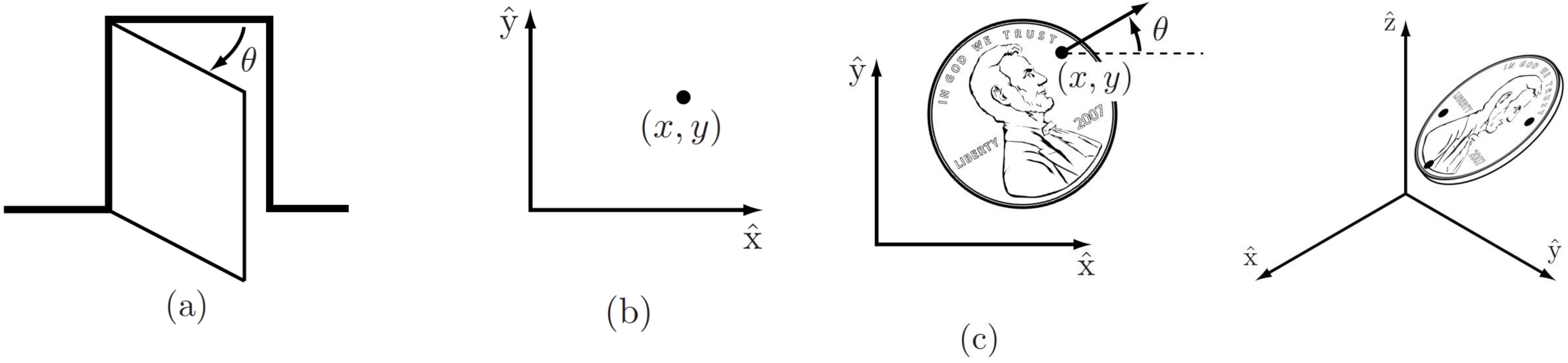
- **Every joint connects exactly two links**



Degrees of Freedom

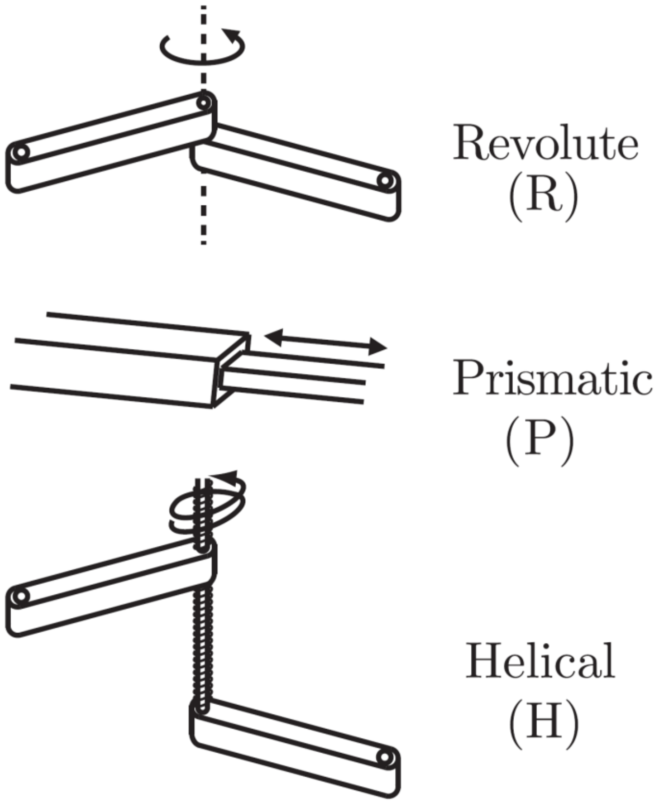
- Maximum number of logically independent values

- Specify the position of a rigid body



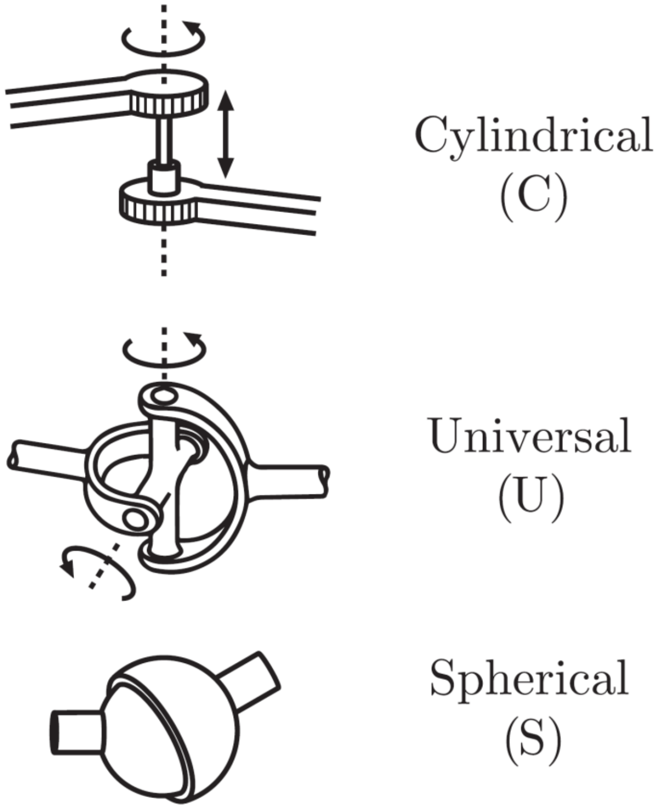
Degrees of Freedom of Robot Joints

- Revolute joint
  - 1 DOF
- Prismatic joint
  - 1 DOF
- Helical joint
  - 1 DOF

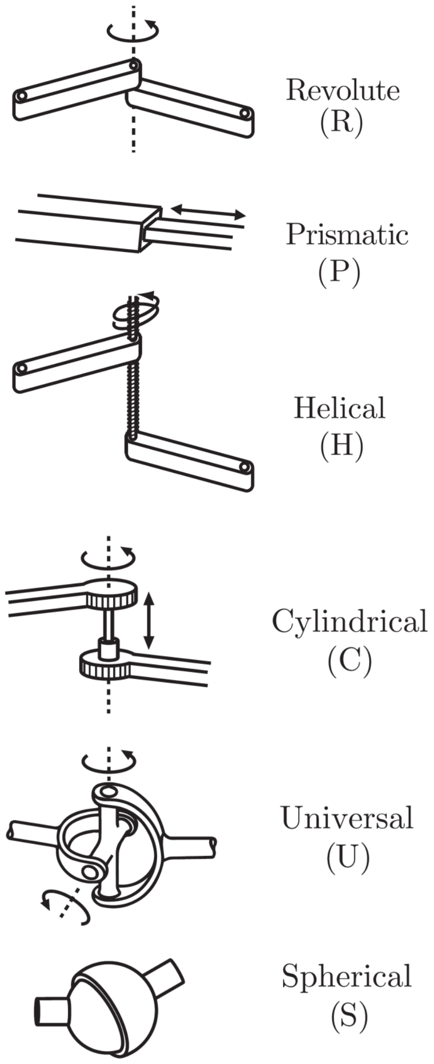


Degrees of Freedom of Robot Joints

- Cylindrical joint
    - 2 DOF
- Universal joint
    - 2 DOF
- Spherical joint
    - 3 DOF

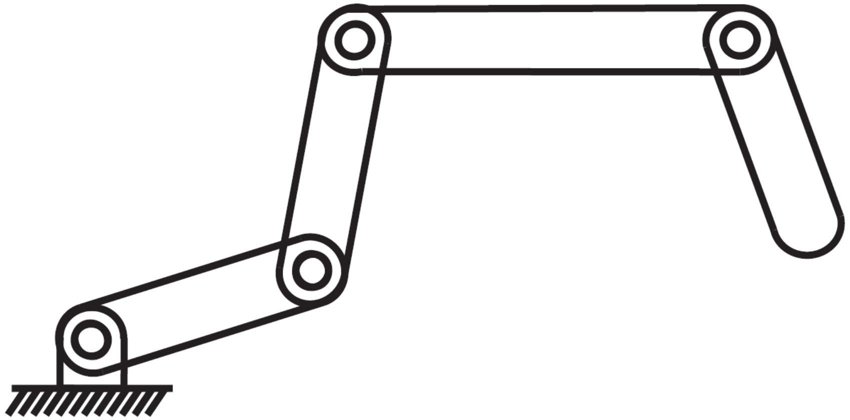


Degrees of Freedom of Robot Joints

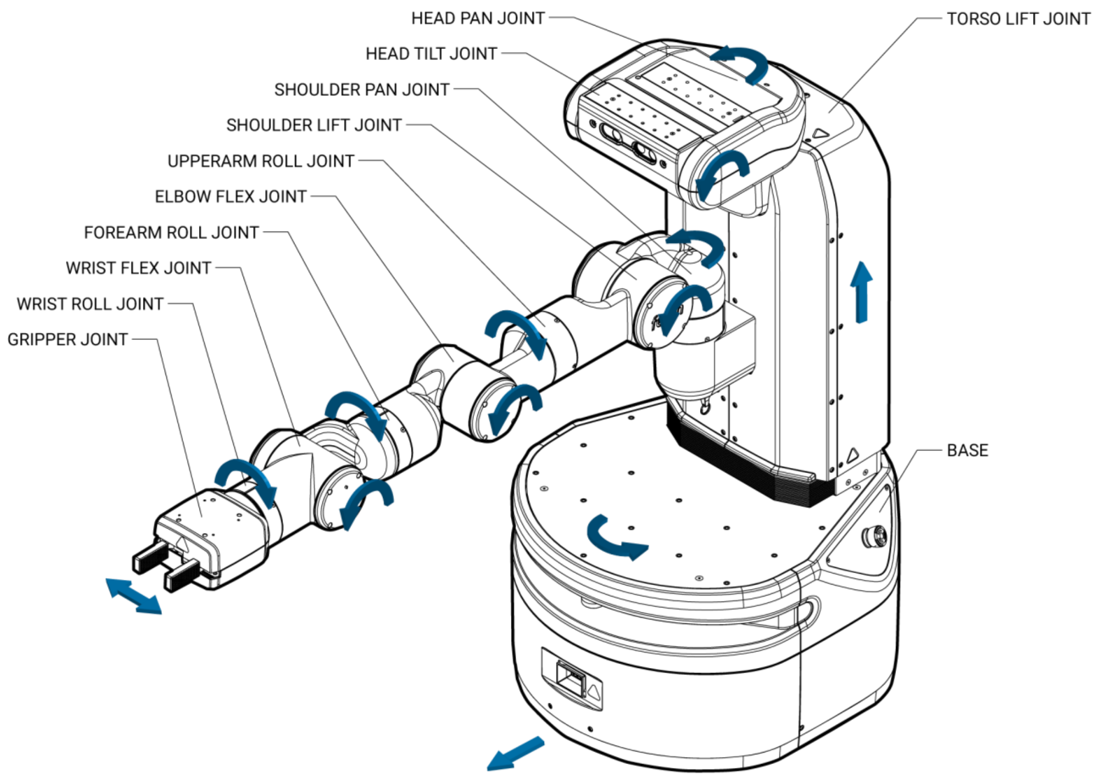


Joint type	dof f	Constraints c between two planar rigid bodies	Constraints c between two spatial rigid bodies
Revolute (R)	1	2	5
Prismatic (P)	1	2	5
Helical (H)	1	N/A	5
Cylindrical (C)	2	N/A	4
Universal (U)	2	N/A	4
Spherical (S)	3	N/A	3

Degrees of Freedom of a Robot



- 4 revolute joints
- 4 DOFs



- 7 revolute joints for the arm
- 7 DOFs

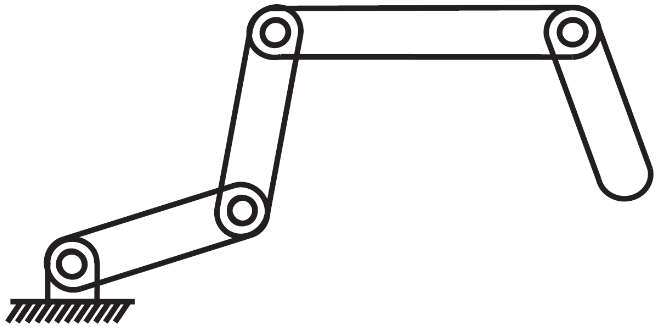
Configuration Space of a Robot

- 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).

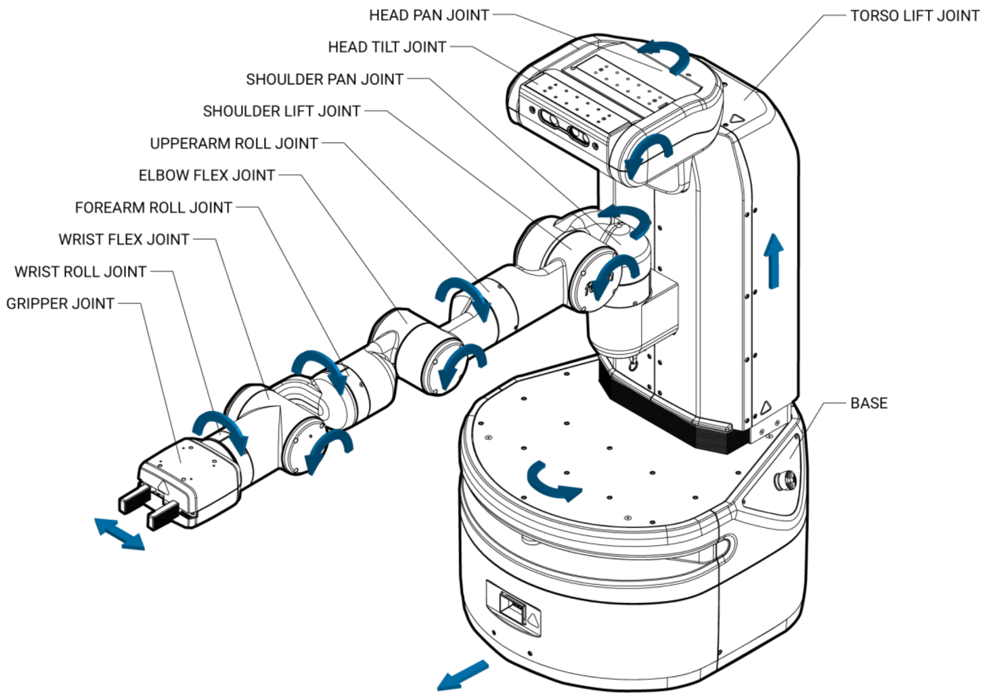
- The configuration of a robot is represented by a point in its C-space.



- 4 revolute joints
- 4 DOFs

Configuration Space of a Robot

- The configuration space of the Fetch arm is a 7D space
- Each value in the 7D vector indicates the value of the revolute joint



Grübler’s Formula

- The number of degrees of freedom of a mechanism with links and joints can be calculated using Grübler's formula

$$\begin{aligned}\text{degrees of freedom} = {} & (\text{sum of freedoms of the bodies}) - \\ & (\text{number of independent constraints})\end{aligned}$$

- Consider the following setting
  - A robot with N links, J joints (consider ground as one link)
  - Each link has m DOF (planar link? spatial link?)
  - Number of freedoms by joint i f_i
  - Number of constraints by joint i c_i

$$f_i + c_i = m$$

Grübler's Formula

$$\text{dof} = \underbrace{m(N-1)}_{\text{rigid body freedoms}} - \underbrace{\sum_{i=1}^{J} c_i}_{\text{joint constraints}}$$

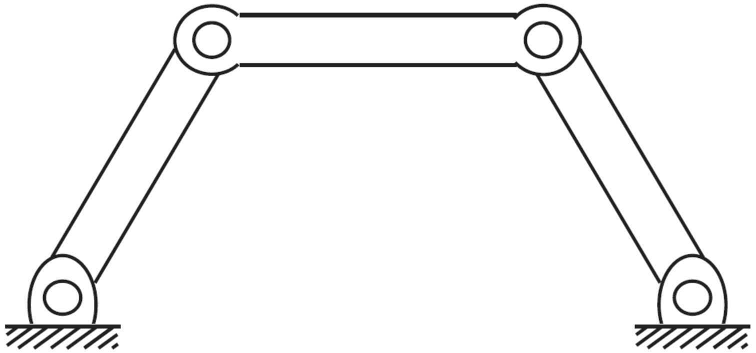
Ground is regarded as a link

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

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

Assume all joint constraints are independent.

Grübler’s Formula



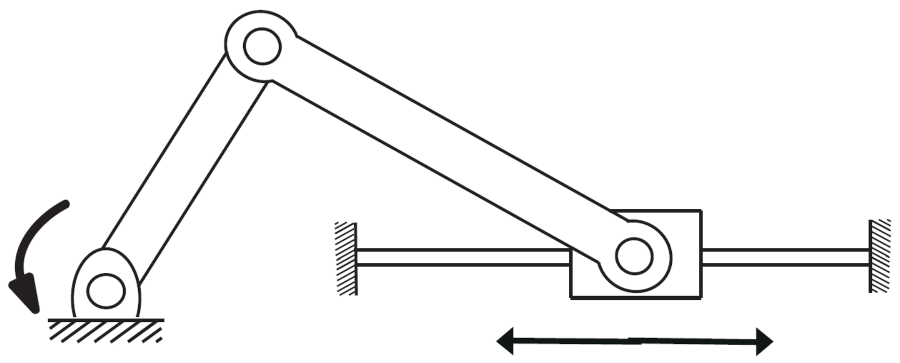
The planar four-bar linkage

- How many links?
  - 4 (one is ground)
- Each link has m DOF. What is m?
  - m=3

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

$$= 3(4 - 1 - 4) + \sum_{i=1}^{4} 1$$

Grübler's Formula

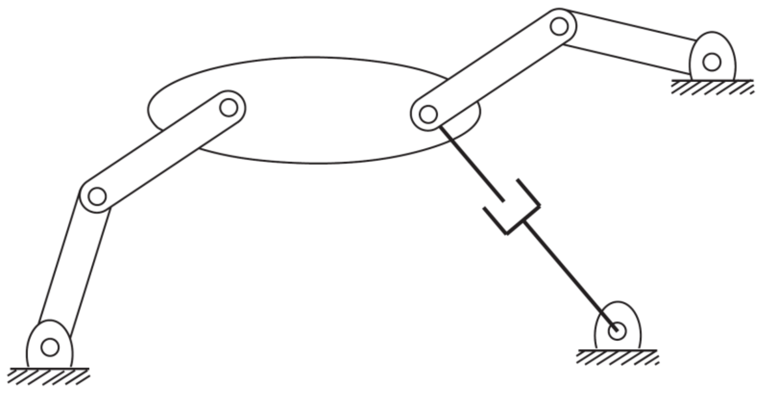


Slider-crank mechanism
(planar)

- How many links?
  - 4 (one is ground)
- Each link has m DOF. What is m?
  - m=3
- How many joints?
  - 3 revolute joints, 1 prismatic joint

$$\text{DOF} = m(N-1-J) + \sum_{i=1}^{J} f_i$$
$$= 3(4-1-4) + \sum_{i=1}^{4} 1$$

Grübler's Formula



A planar mechanism with two overlapping joints

- How many links?
  - 8 (one is ground)
- Each link has m DOF. What is m?
  - m=3
- How many joints?
  - 8 revolute joints, 1 prismatic joint

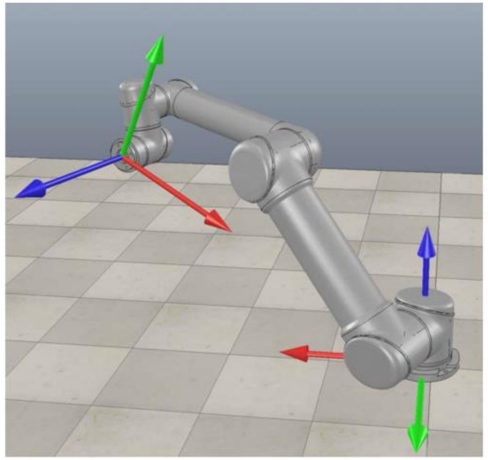
$$\text{dof} = 3(8 - 1 - 9) + 9(1) = 3$$

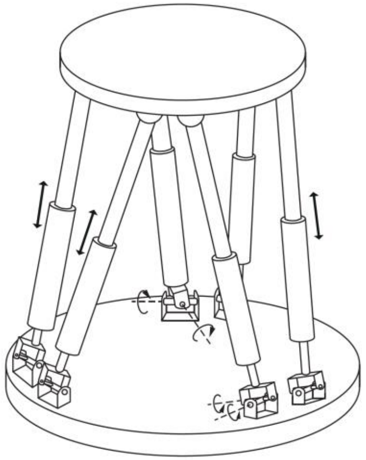
Read more examples in the textbook Lynch & Park

Open-Chain vs. Closed-Chain

- Open-chain mechanisms: without a closed loop
- Closed-chain mechanisms: with a closed loop

- Examples
  - A person standing with both feet





Stewart-Gough platform

Configuration Space Topology

- Configuration specifies the position of a robot
- For a robot with n joints, the configuration is a vector in $\mathbb{R}^n$
  - C-space
- Joints may have limits, upper bound and lower bound
- Topology: shape of the space
  - Consider all the feasible points in the configuration space

Configuration Space Topology

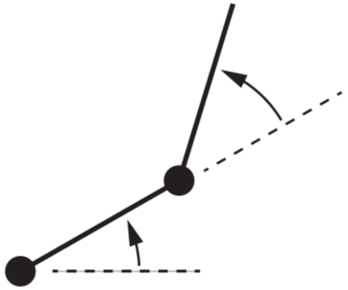
- n-dimensional Euclidean space $\mathbb{R}^n$
- n-dimensional sphere in a (n+1)-dimensional Euclidean space S^n
  - Two-dimensional surface of a sphere in three-dimensional space S^2

S^2

- The C-space can have different representations, but its shape is the same
  - A point on a circle, angle θ, coordinates (x, y) $x^2 + y^2 = 1$

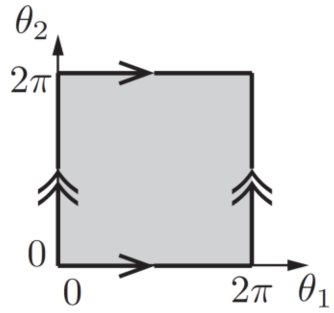
Configuration Space Topology

- C-space as Cartesian product (all ordered pairs)
  - A rigid body in the plane $\mathbb{R}^2 \times S^1$
  - A PR robot (Prismatic-Revolute) $\mathbb{R}^1 \times S^1$
    - Ignore joint limits
  - A 2R robot $S^1 \times S^1 = T^2$ n-dimensional surface of a torus in an (n+1)-dimensional space



2R robot arm

$T^2 = S^1 \times S^1$



$[0, 2\pi) \times [0, 2\pi)$

sample representation

Configuration Space Topology

- C-space of a planar rigid body (chassis of a mobile robot) with a 2R robot arm

$$\mathbb{R}^2 \times S^1 \times T^2 = \mathbb{R}^2 \times T^3$$

- C-space of a rigid body in 3D space
    - 3D translation
    - 3D rotation

$$\mathbb{R}^3 \times S^2 \times S^1$$

Summary

- Robot links and joints
- Degrees of freedom of joints and robots
- Grübler's Formula
- Configuration space

Further Reading

- Chapter 2 in Kevin M. Lynch and Frank C. Park. Modern Robotics: Mechanics, Planning, and Control. 1st Edition, 2017 http://hades.mech.northwestern.edu/images/7/7f/MR.pdf
- T. Lozano-Perez. Spatial planning: a configuration space approach. A.I. Memo 605, MIT Artificial Intelligence Laboratory, 1980. http://people.csail.mit.edu/tlp/
- W. M. Boothby. An Introduction to Differentiable Manifolds and Riemannian Geometry. Academic Press, 2002.