8. Manipulator Mechanism Design

① Basing the Design on Task Requirements

- Number of Degrees of Freedom: DoF of the robot should match DoFs required by the task.
  - Some tasks don't require 6 DoF, for instance tasks that use end-effectors with a symmetry axis; in those cases, we have a redundant robot for that task.

- Workspace: we need to be able to reach objects without singularities and collisions in the robot's workspace

- Load capacity: load/weight to pick must be enough for our purposes
  - That property is given by: size of links, power of actuators
  - Load can be static & dynamic; dynamic load takes into account the inertial and velocity-related forces

- Speed: Cycle time or operation speed determine the required speed
  - Note that higher speeds mean higher inertia and velocity related forces, thus if high speed is required, weight and workspace size might need to be smaller

- As important as speed is acceleration time, because most of the time is spent during acceleration/deceleration.

– Repeatability and accuracy: they depend on the application
  - High accuracy means having good knowledge of robot parameters and careful attention to tolerances during manufacturing

Note: a closed-form solution of the inv. kin is seeked!!

② Kinematic Configuration

Most common manipulators:

Cartesian

– 3 DoF, decoupled

– X, Y, Z, prismatic

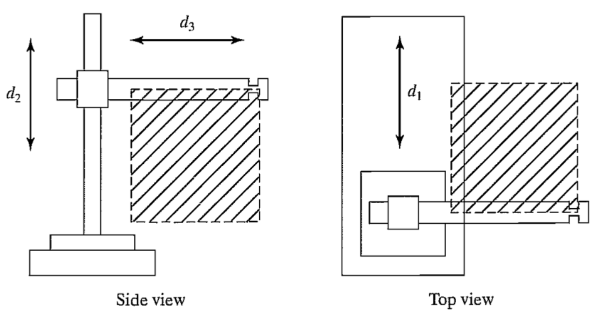


FIGURE 8.3: A Cartesian manipulator.
Craig, 3rd Ed., Sec. 8.3

Articulated

– 5 or 6 DoF

– robot arms

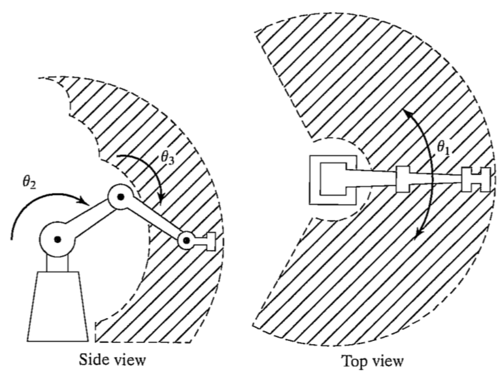


FIGURE 8.4: An articulated manipulator.
Craig, 3rd Ed., Sec. 8.3

SCARA = Selectively Compliant Assembly Robot Arm

– 4 DoF: 1 P + 3 parallel R

– Very fast, because first 2 joints can have large actuators

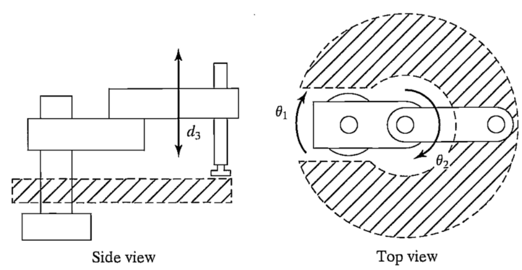


FIGURE 8.5: A SCARA manipulator.
Craig, 3rd Ed., Sec. 8.3

Cylindrical

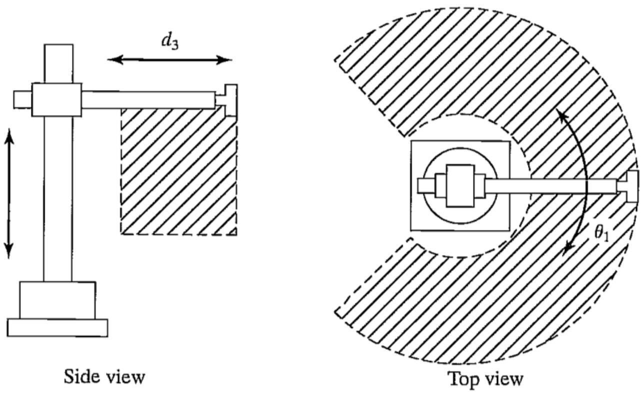


FIGURE 8.7: A cylindrical manipulator.

Craig, 3rd Ed., Sec. 8.3

Spherical

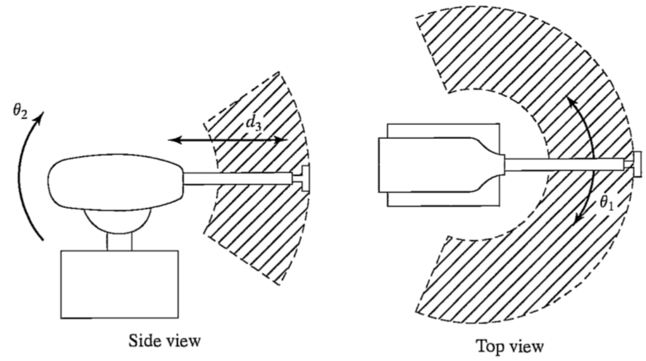


FIGURE 8.6: A spherical manipulator.

Craig, 3rd Ed., Sec. 8.3

3 Quantitative Measures of Workspace Attributes

- **Length sum**: $L = \sum_{i=1}^{n} \left(\overbrace{a_{i-1} + d_i}^{\text{DH parameters}} \right)$
- **Structural length index**: $Q_L = L / \sqrt[3]{\underbrace{V_W}_{\text{workspace volume}}}$

  good designs have ↓Q_L, because for the same L they cover larger W
- **Manipulability measure**: $w(\theta) = \sqrt{\det\left(\underset{\sim}{J}(\theta)\, \underset{\sim}{J}^T(\theta) \right)}$

  A good manipulator has larger areas with high $w(\theta)$ values

  When we have singularities $w = 0$.

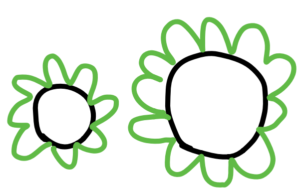
- Inertia ellipsoids: the eigenvalues of the Cartesian mass matrix account for the acceleration capabilities: the more spherical, the better, because same acceleration capabilities in all directions

$$\underset{\sim}{M}_x(\theta) = \underset{\sim}{J}^{-T}(\theta)\,\underset{\sim}{M}(\theta)\,\underset{\sim}{J}^{-1}(\theta)$$

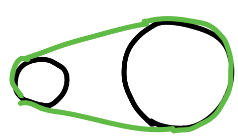
④ Actuation Schemes

- Actuator location can be: direct / indirect
  - Direct drive: actuator on joint; the joint is then as controllable as the actuator, more fidelity
  - Indirect: many actuators are unfortunately better suited for high speeds, thus, speed reduction is needed, in addition to a transmission system.

- Reduction and transmission systems: two common systems: gears / belts



r_1 r_2



r_1 r_2

$$\boxed{\eta = \frac{r_2}{r_1}, \quad \dot{\theta}_2 = \frac{1}{\eta}\dot{\theta}_1, \quad \tau_2 = \eta\,\tau_1}$$

- If we want to minimize the backlash in gears, we usually increase their friction
- Belts are flexible, deform, and need preload

- Lead screws and ball bearings reduce rotational velocity and transform rotational motion to linear movement

5 Stiffness and Deflections

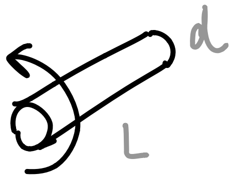
- Ideally, we want to have an infinitely stiff robot to
  - predict the position of the endeffector with its DH params precisely
  - avoid resonances that appear under flexible structures
- However, all elements have a limited stiffness and the overall stiffness is computed summing the element stiffness values in parallel or series:
  - Parallel: $K = K_1 + K_2$
  - Series: $\frac{1}{K} = \frac{1}{K_1} + \frac{1}{K_2}$

$K_{output} = \eta^2 K_{input}$

gear reduction increases by η^2 the stiffness of the drive

- Elements stiffness formulas:

Shafts



$$K = \frac{G \pi d^4}{32 L}$$

shear modulus of elasticity: steel: $7.5\ 10^{10}\ N/m^2$
Aluminium: 1/3 steel

Gears

$$K = C_g b r^2$$

output gear

face width of the gears

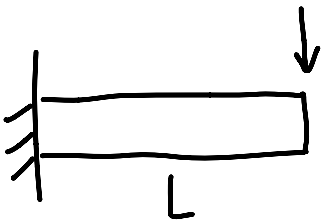
$1.34\ 10^{10}\ N/m^2$ for steel

Belts

$$k = \frac{AE}{L}$$

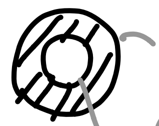
A: cross-sectional area
E: Young
L: length of free belt + 1/3 of belt in contact

Links



$$k = \frac{3\pi E(d_o^4 - d_i^4)}{64L}$$

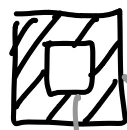
Circular section



$$k = \frac{E(W_o^4 - W_i^4)}{4L^3}$$

Young Elasticity modulus: $2 \cdot 10^{11}$ N/m²

Square section



6 Actuators and Sensors

- Actuators are commonly:
  - Pneumatic: with air, but difficult to control accurately, due to the compressibility of air
  - Electric motors, most commonly
    - They have a lower power-to-weight ratio than pneumatic ones, but are more controllable
    - Usually, DC motors are used, with brushless configurations to avoid wear and friction

Position Sensing

Manipulators are servo-controlled mechanisms

↳ force/torque commands are based on the error between the sensed/measured position and the desired

↳ therefore, we need sensing!

Most common technologies:

- Photoelectric sensors that send pulses, located on the shaft, assuming no backlash
- Potentiometers that produce voltage proportional to the rotation/angle; they have resolution issues
- Tachometers can be used to measure shaft rotation velocity. But, it is possible to differentiate the rotation, although it introduces noise...

Force Sensing

- Strain gauges are typically used: structures built of metal foil or semiconductor that produce an output proportional to the strain that acts on them.
- Posible locations: joints, wrist (before endeffector), fingertips
- Issues:
  - Flexibility is necessary to produce output, which reduces stiffness!
  - Hysteresis might appear