CHAPTER 8. MANIPULATOR MECHANISM DESIGN

- Elements of a robot system
  - Manipulator, including its internal or proprioceptive sensors
  - End-effector or end-of-arm tooling
  - External sensors and effectors (e.g., vision systems, part feeders, etc.)
  - Controller

Basing the Design on Task Requirements

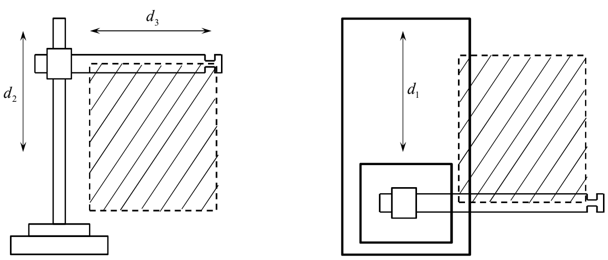
- Number of degrees of freedom (DOF) in a manipulator should match the number required by the task.
- Workspace (= work volume = work envelope)
- Load capacity
- Speed: maximum end-effector speed and overall cycle time for a particular task
  (Often, the acceleration and deceleration phases take up most of the cycle time.)
- Repeatability and accuracy

Kinematic Configuration

- For serial kinematic linkages, [# of joints] = [# DOFs]

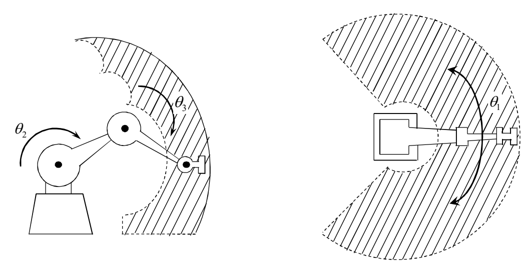
- Wrist-partitioned mechanism: Usually, the last n–3 joints orient the end-effector and have axes that intersect at the wrist point (orienting structure or wrist), and the first three joints position this wrist point (positioning structure).

- Manipulator classifications according to the design of the first three joints (positioning structure):
  Cartesian, Articulated, SCARA, Spherical, Cylindrical, Wrists



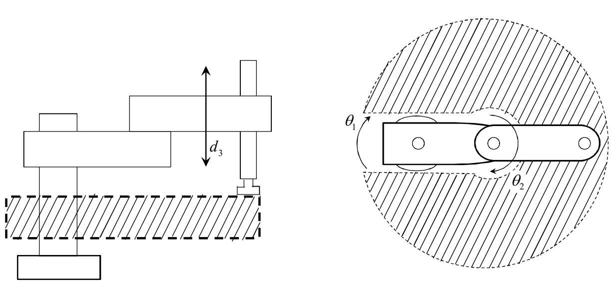
Side view Top view

A Cartesian manipulator



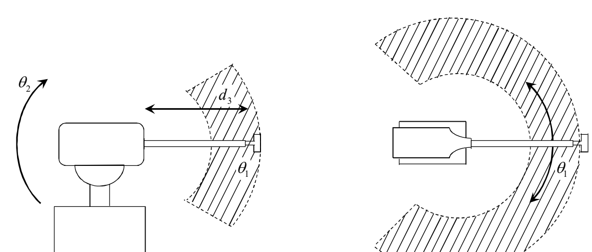
Side view Top view

An Articulated manipulator



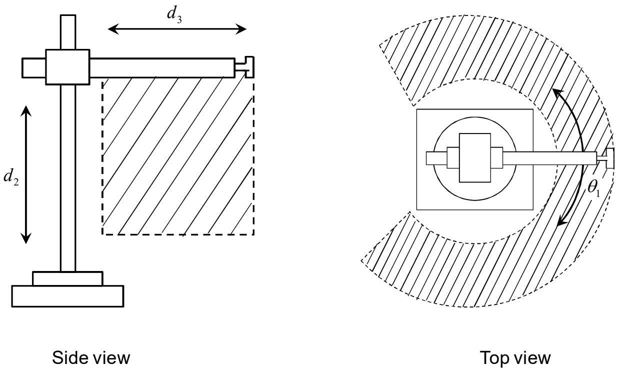
Side view Top view

A SCARA manipulator



Side view Top view

A spherical manipulator



A cylindrical manipulator

Efficiency of Design in terms of Generating Workspace

- Length sum of a manipulator: $L = \sum_{i=1}^{N} \left(a_i + d_i \right)$
  → Rough measure of the length of the complete linkage

- Structural length index: $Q_L = L / \sqrt[3]{W}$
  → Ratio of the manipulator length sum to the cube root of the workspace volume W
  → Relative amount of structure (linkage length) required by different configurations to generate a given work volume (good design: Q_L ↓)

Designing Well-Conditioned Workspaces

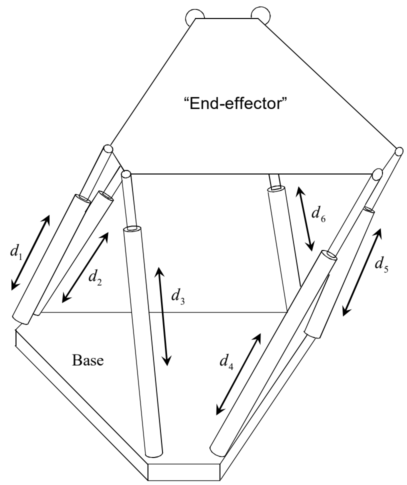
- Singularity: $\det(J(\mathbf{q})) = 0$
  → Manipulator effectively loses one or more DOFs → Certain tasks cannot be performed at that point
- In the neighborhood of singular points (including workspace-boundary singularities), actions of the manipulator may no longer be well-conditioned.

- Manipulability measure: $w = \sqrt{\det(J(\mathbf{q}) J^T(\mathbf{q}))}$ (good design: w ↑)
  For non-redundant manipulator: $w = |\det(J(\mathbf{q}))|$

Redundant and Closed Chain Structures

- Redundancy: singularity avoidance, obstacle/collision avoidance, and infinite ways of reaching
- Closed loop structures: increased stiffness, but reduced joint ranges of motion (decreased workspace)

- Stewart mechanism (Stewart manipulator): closed-loop alternative to the serial 6-DOF manipulator
  Parallel mechanism
  End-effector position/orientation are controlled by six linear actuators' length connected to base.
  At base, each actuator is connected by a two-DOF universal joint.
  At end-effector, each actuator is attached with a three-DOF ball-and-socket joint.
  Stiff with limited ranges of motion than do serial linkages.



- Grubler's formula (in 3-D space): $F = 6(l - n - 1) + \sum_{i=1}^{n} f_i$

  F: total number of DOFs
  l: number of links (including the base)
  n: total number of (physical) joints
  f_i: number of DOFs for ith (physical) joint

- Example 8.2: Verify that the Stewart mechanism has six DOFs.
  The number of joints is 18 (6 universal, 6 ball-and-socket, and 6 prismatic in the actuators). The number of links is 14 (2 parts for each actuator, the end-effector, and the base). The sum of all the joint freedoms is 36. $\therefore$ $F = 6(14 - 18 - 1) + 36 = 6$

Actuator Location

- Direct-drive configuration: output attached directly to the joint (no transmission or reduction elements between the actuator and the joint)
  → Design simplicity and superior controllability (joint motions can be controlled with same fidelity as actuator)

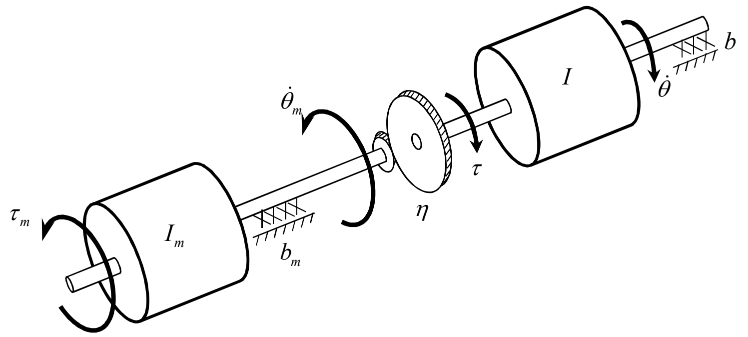
- Many actuators are best suited to relatively high speeds and low torques.
  → Requires speed-reduction system

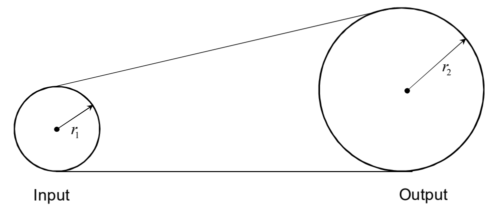
- Actuators are heavy.
  → Locate remotely from joint and toward manipulator base (to reduce inertia and sizes).
  → Requires transmission system (transfer motion from actuator to joint)

Reduction and Transmission Systems

- Gears: reduction element (large reductions in compact configurations)
  Backlash: maximum angular motion of output gear when input gear remains fixed
  → arises from imperfect meshing of gears
  If gear teeth are meshed tightly to eliminate backlash, there can be excessive amounts of friction.
  Gear ratio: speed-reducing, torque-increasing effects ($\eta > 1$) → $\dot{\theta}_o = (1/\eta)\dot{\theta}_i$, $\tau_o = \eta \tau_i$

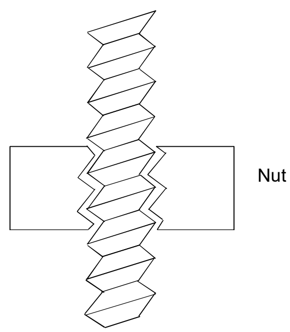
- Flexible bands, cables, belts, roller chains → Ratio of the transmission system: $\eta = r_2 / r_1$

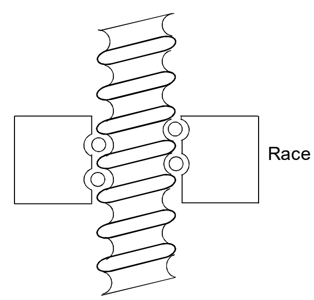




- Lead screws: large reduction in a compact package; transform rotary motion into linear motion
  → Very stiff and can support very large loads

- Ball-bearing screws: similar to lead screws, but recirculating circuit of ball bearings rolls between the sets of threads
  → Very low friction and are usually back-drivable

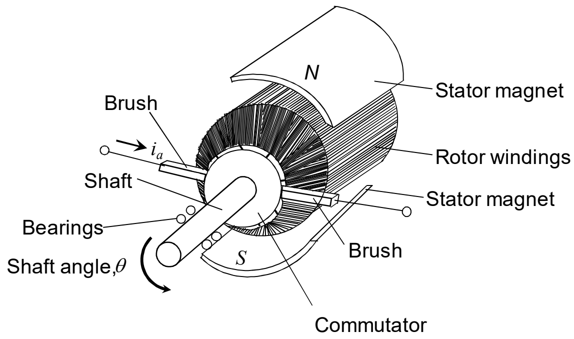


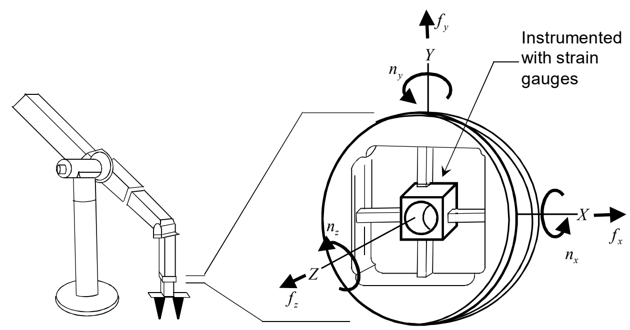


<u>Stiffness and Deflections</u>
(Do it yourself.)

<u>Actuators</u>
- Hydraulic cylinders (or vane actuators)
- Pneumatic cylinders
- Electric motors – controllability and easy interface
  - Direct current (DC) brush motors: Current is conducted to the windings of the rotor via brushes, which make contact with the revolving commutator.
  - Brushless motors: Windings remain stationary and the magnetic field piece rotates; winding is on the outside attached to the motor case.
  - Alternating current (AC) motors
  - Stepper motors

  ➔ The electric motor's stator is attached to one link, while the rotor is attached to another link, usually through a gear train.





Position Sensing

- Servo-controlled mechanisms: Force or torque command to an actuator is calculated based on the error between the sensed position of the joint and the desired position.
- Co-located sensor and actuator pairs: position sensor located directly on the shaft of the actuator

- Incremental rotary optical encoder: As the encoder shaft turns, the device outputs two square wave pulse trains 90 degrees out of phase. The shaft angle is determined by counting the number of pulses, and the direction of rotation is determined by the relative phase of the two square waves.

- Resolvers: output analog signals of sine and cosine of the shaft angle
  → Shaft angle is determined from the relative magnitude of the two signals.

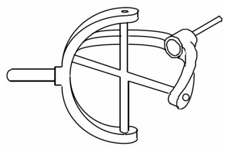
- Potentiometers: Connected in a bridge configuration, they produce a voltage proportional to the shaft position

- Tachometers: provide analog signal proportional to the shaft velocity

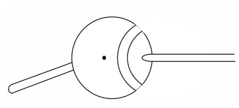
Force Sensing
(Do it yourself.)

APPENDIX: OTHER MECHANISMS

- Universal Joint

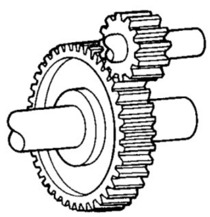


- Spherical Joint



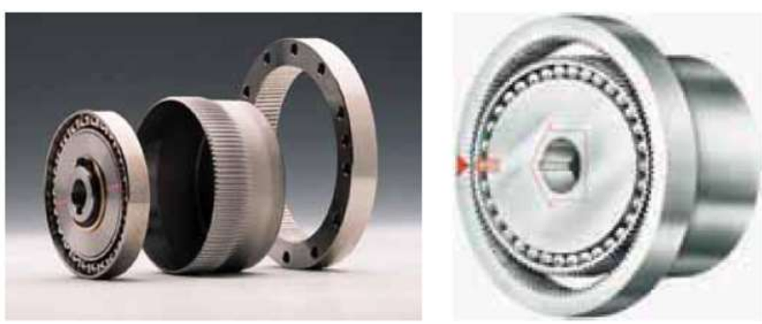
- Spur Gears

  Modify the characteristics of the rotational motion of the motor by changing the axis of rotation and/or by translating the application point.
  Usually constructed with wide cross-section teeth and squat shafts.



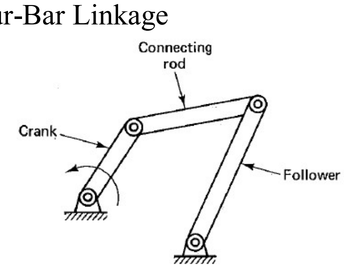
- Harmonic Drive

  Speed-reduction system
  Three fundamental elements: wave generator, flexspline, circular spline

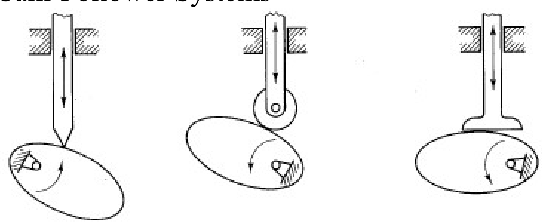


(Spong et al., 2006)

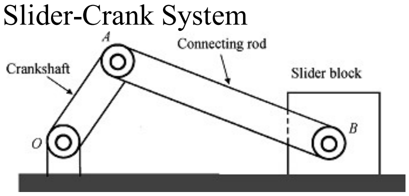
- Four-Bar Linkage



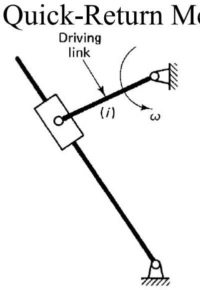
- Cam-Follower Systems



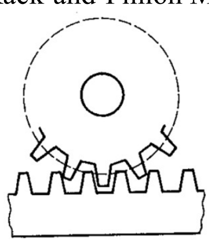
- Slider-Crank System



- Quick-Return Mechanism



- Rack-and-Pinion Mechanism



- Geneva-Wheel Mechanism