End Effectors and Grip Planning

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Contents

Gripper/End Effectors

- Manipulation is the result of the interaction between the end effector and the handled object
  - In industrial robots essentially transport tasks
- Change the position of an object by applying forces and moments
- Gripping systems for industrial robots
  - Mechanical gripper
  - Gripper with suction unit
  - Magnetic gripper

Foundations: Characterization of Technical End Effectors

- Mechanics and principles of action
- Number of fingers
- Number of finger joints
- Type of force and form fit
- Movement possibilities
- Actuator types
- Gripping force
- Sensors
- Size and weight

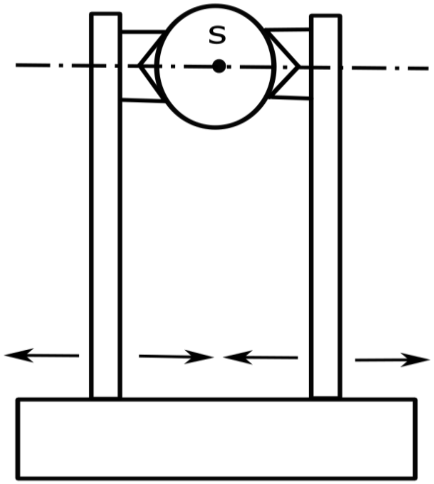
Control Parameter of Gripping Systems

- Position of the finger joints
- Gripping force
- Gripping path
- Gripping velocity
- Position of the object between the gripping plates
- Acting forces and moments

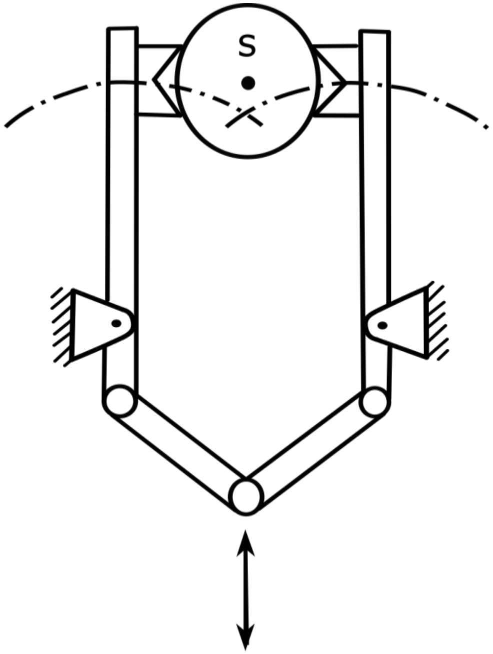
Gripping Force and Gripping Path Determination

- Work-piece weight
- Center of mass
- Geometry and position of the work-piece
- Grip points
- Positions of engagement

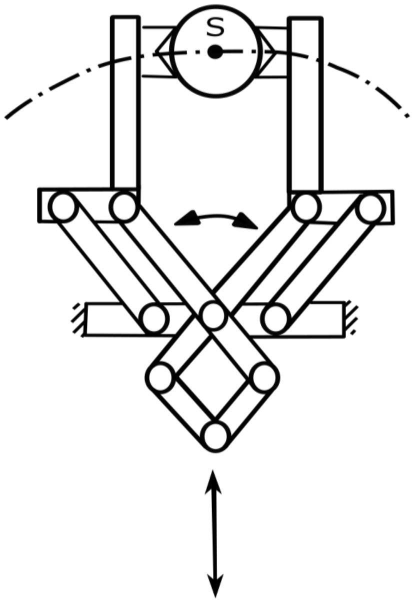
Mechanical Gripper



Translational



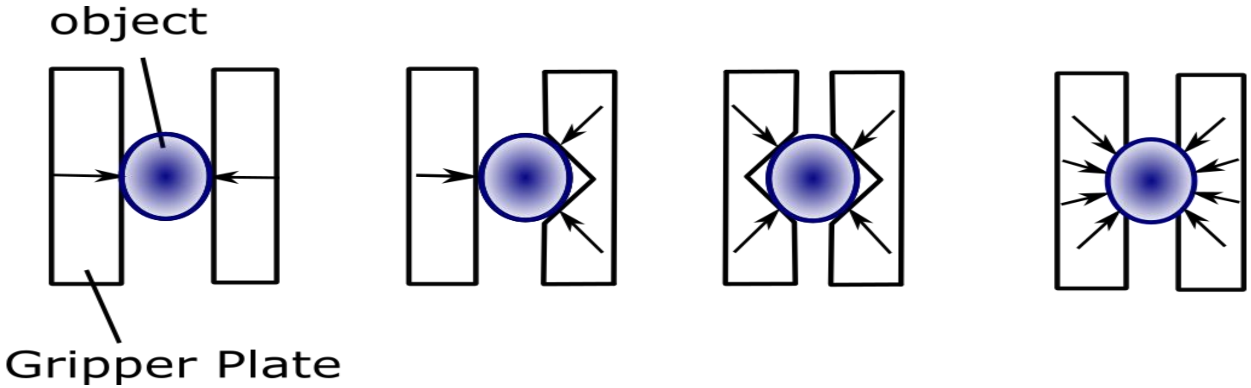
Rotational (toggle)



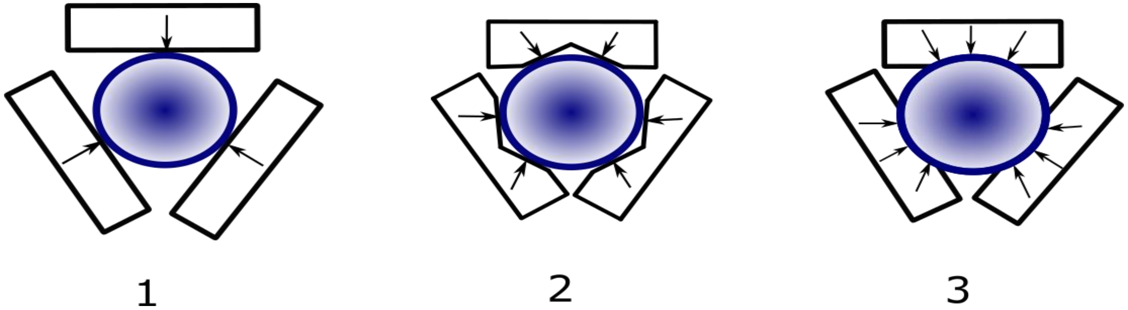
Rotational (scissors)

Enlargement of the Effective Surfaces

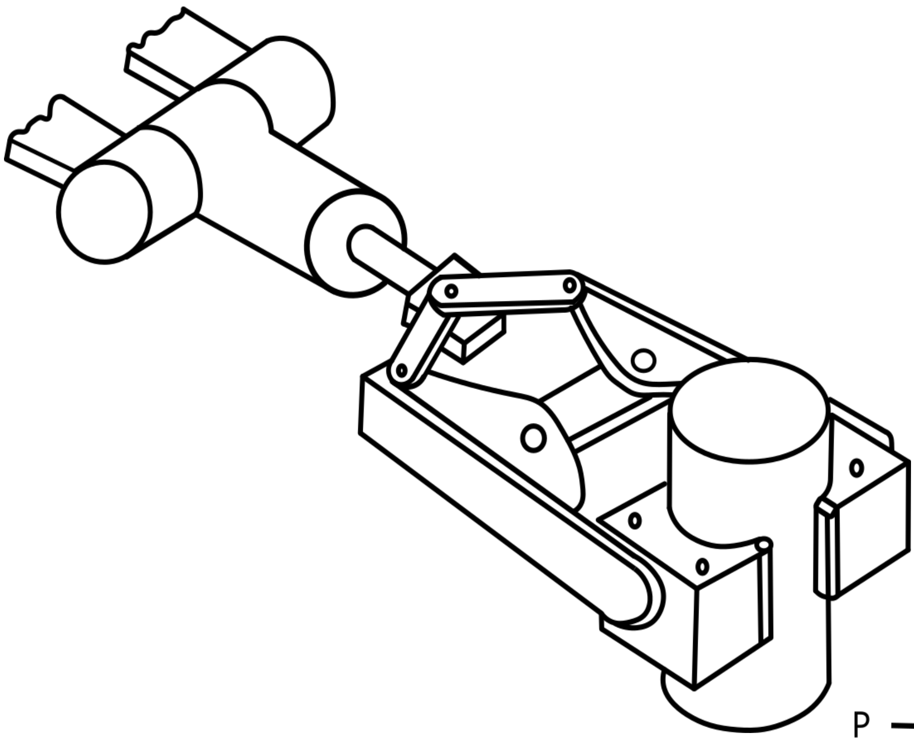
- Two finger gripping system: Slipping hazard, enlargement of effective area necessary

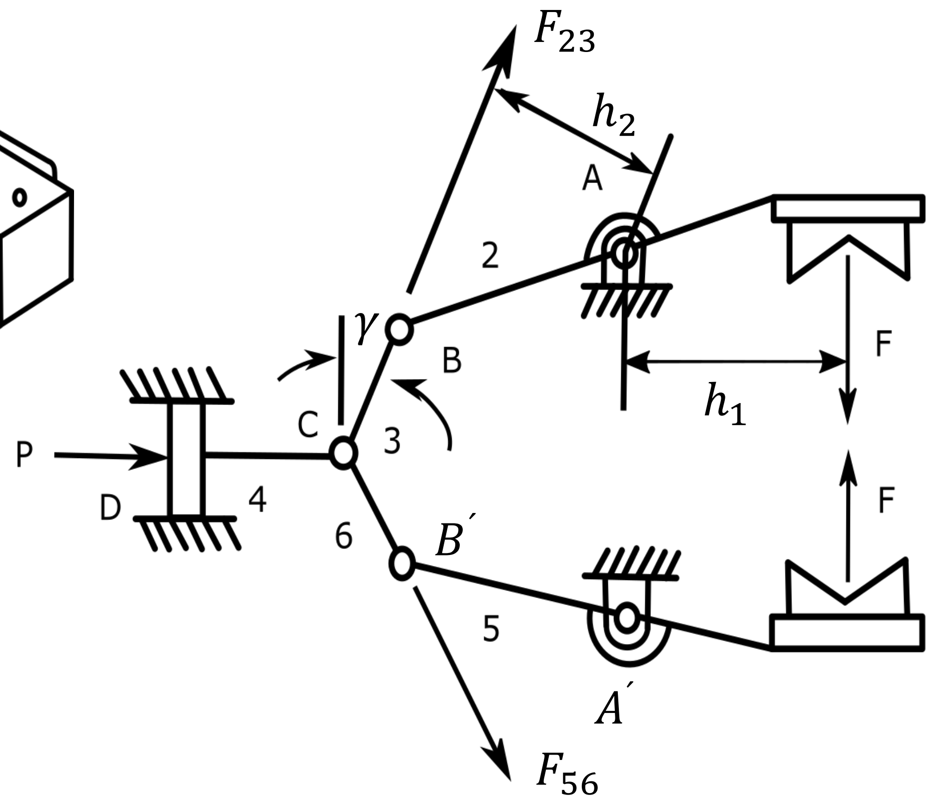


- Three finger system: Higher stability, optimum positive locking

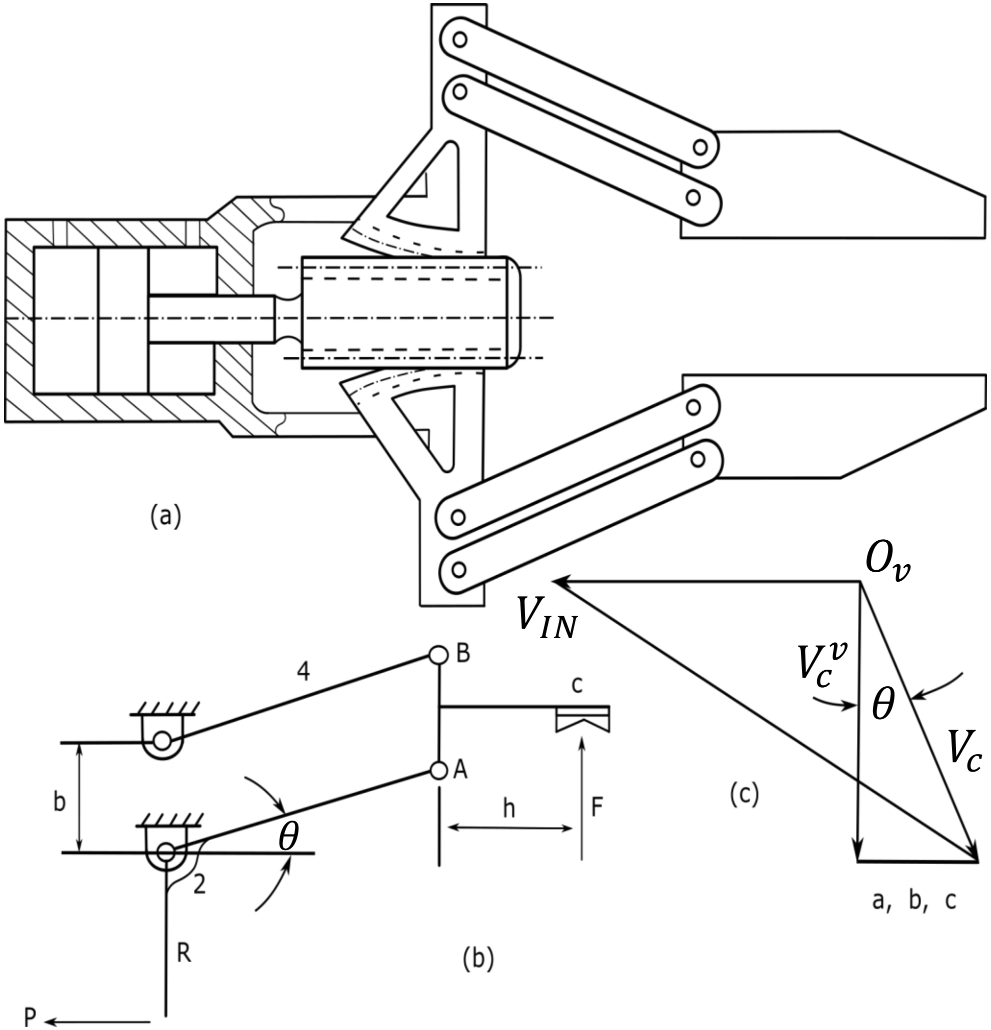


Scissor Gripper

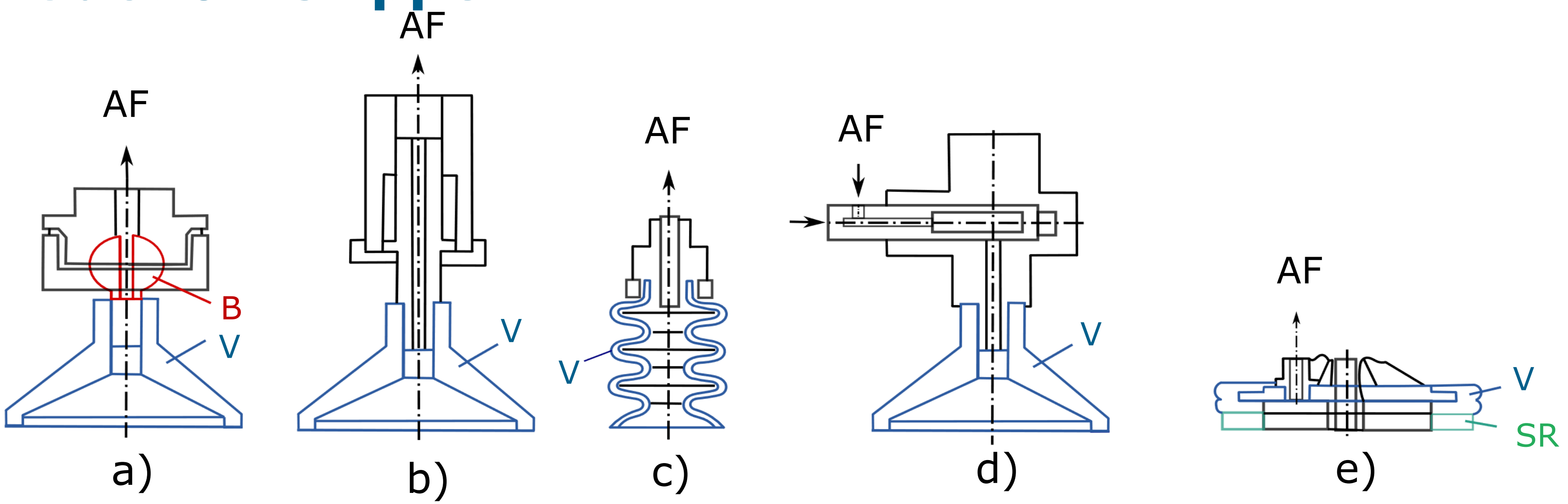




Pincer Gripper



Suction Gripper



a) Suction cup with ball joint
b) Spring-loaded suction cup
c) Sucker for sensitive objects
d) Adhesive suction cup with valve for releasing air
e) Suction cup for concrete slabs

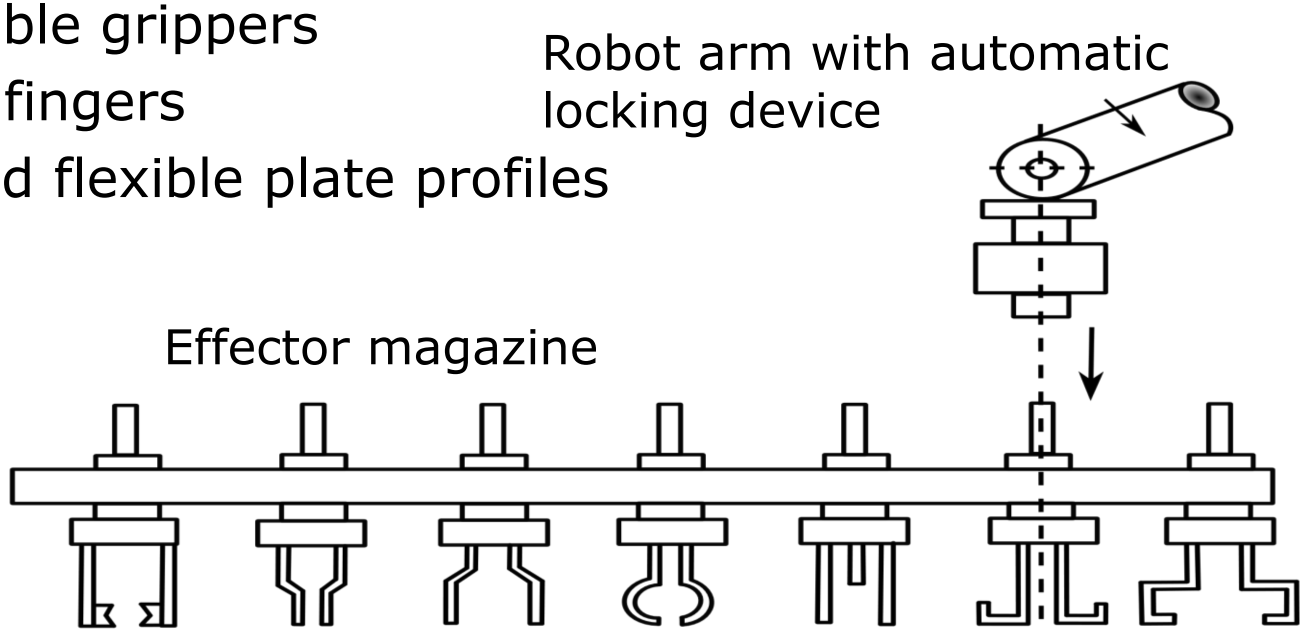
V = vacuum
B = ball joint
SR = Sponge Rubber
AF = airflow

Magnetic Gripper

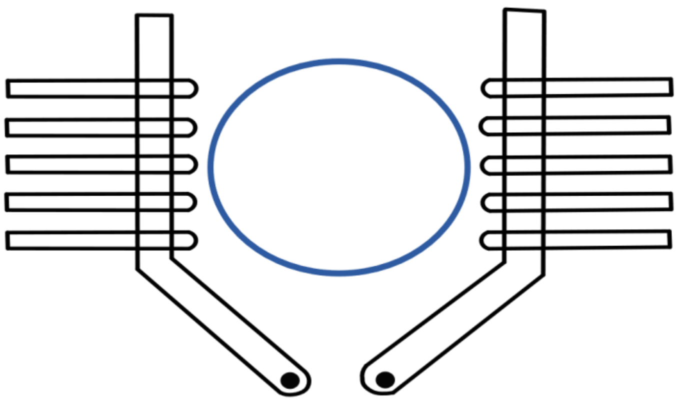
- Simple construction, no wear on any parts
- No moving elements, contact surface sufficient
- Ferromagnetic materials
- For thin materials, several can be gripped at once
- Electromagnetic grippers without power in case of power failure
- Gripping force $F_G = \frac{B^2 A}{2\mu_o}$
  - Magnetic field B
  - Area A
  - Vacuum permeability μ

Flexibility of Gripping Systems

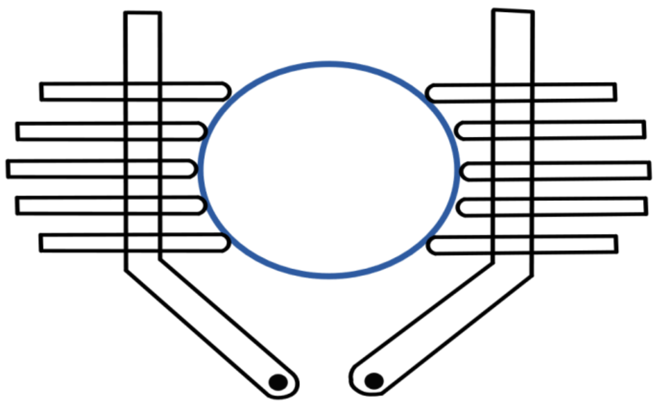
- Objective: Object-related adaptation with regard to force and form fit
- Possible solutions
  - Adjustable plate profiles
  - Adjustable operating points of the gripper
  - Interchangeable grippers
  - Multi-jointed fingers
  - Sensor-guided flexible plate profiles



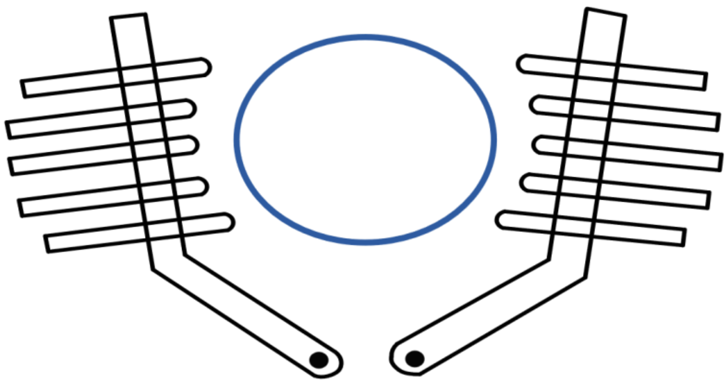
Improvement of the Form Fit



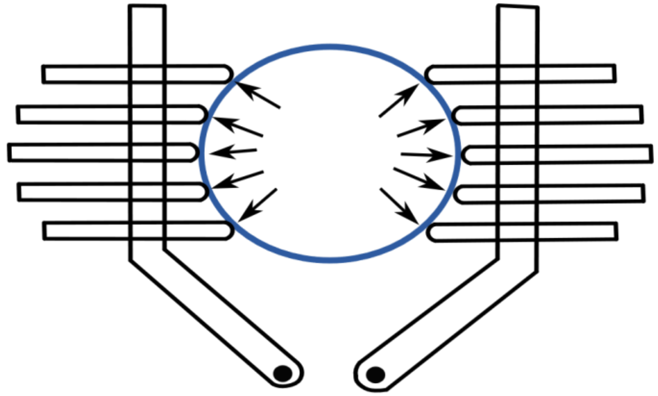
1- Initial State



2- Scan and Fix

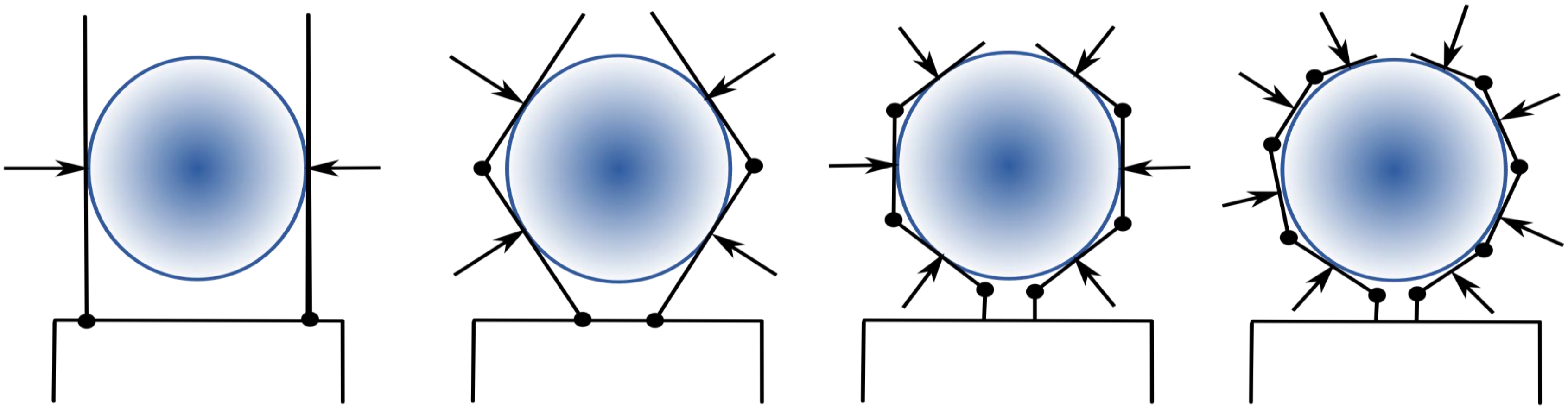


3- Scanned workpiece contour



4- Grip with form and frictional connected

Improvement of the Form Fit



1- 2 Fingers
   1 Finger joints

1- 2 Fingers
   2 Finger joints

3- 2 Fingers
   3 Finger joints

4- 2 Fingers
   4 Finger joints

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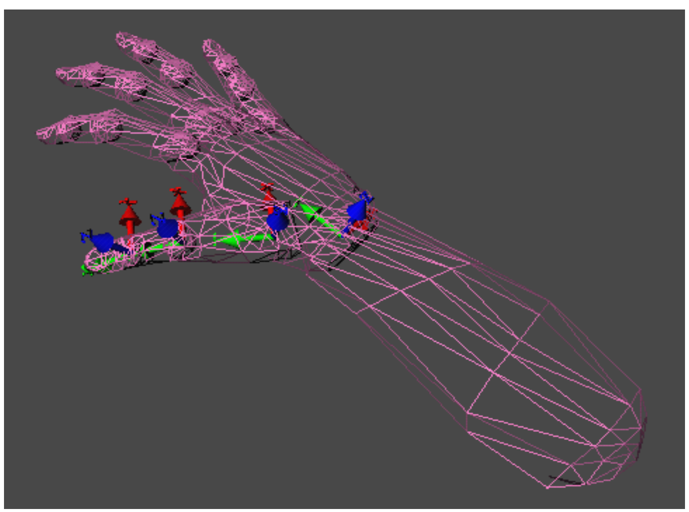
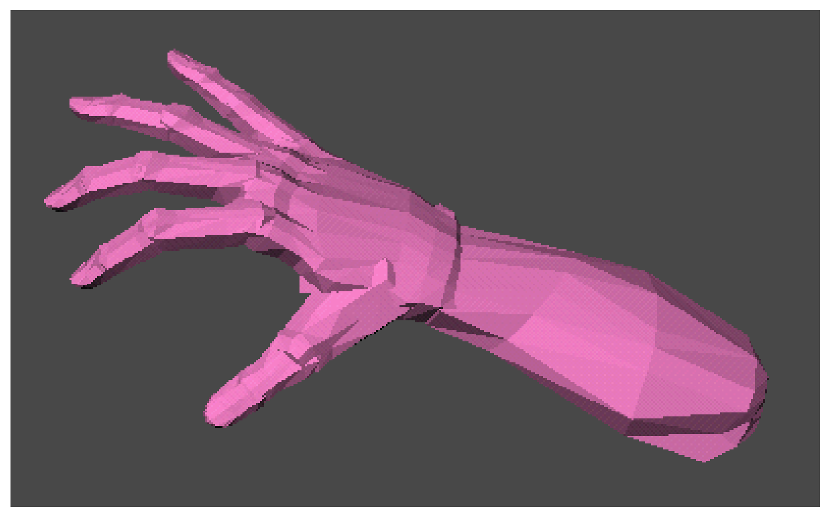
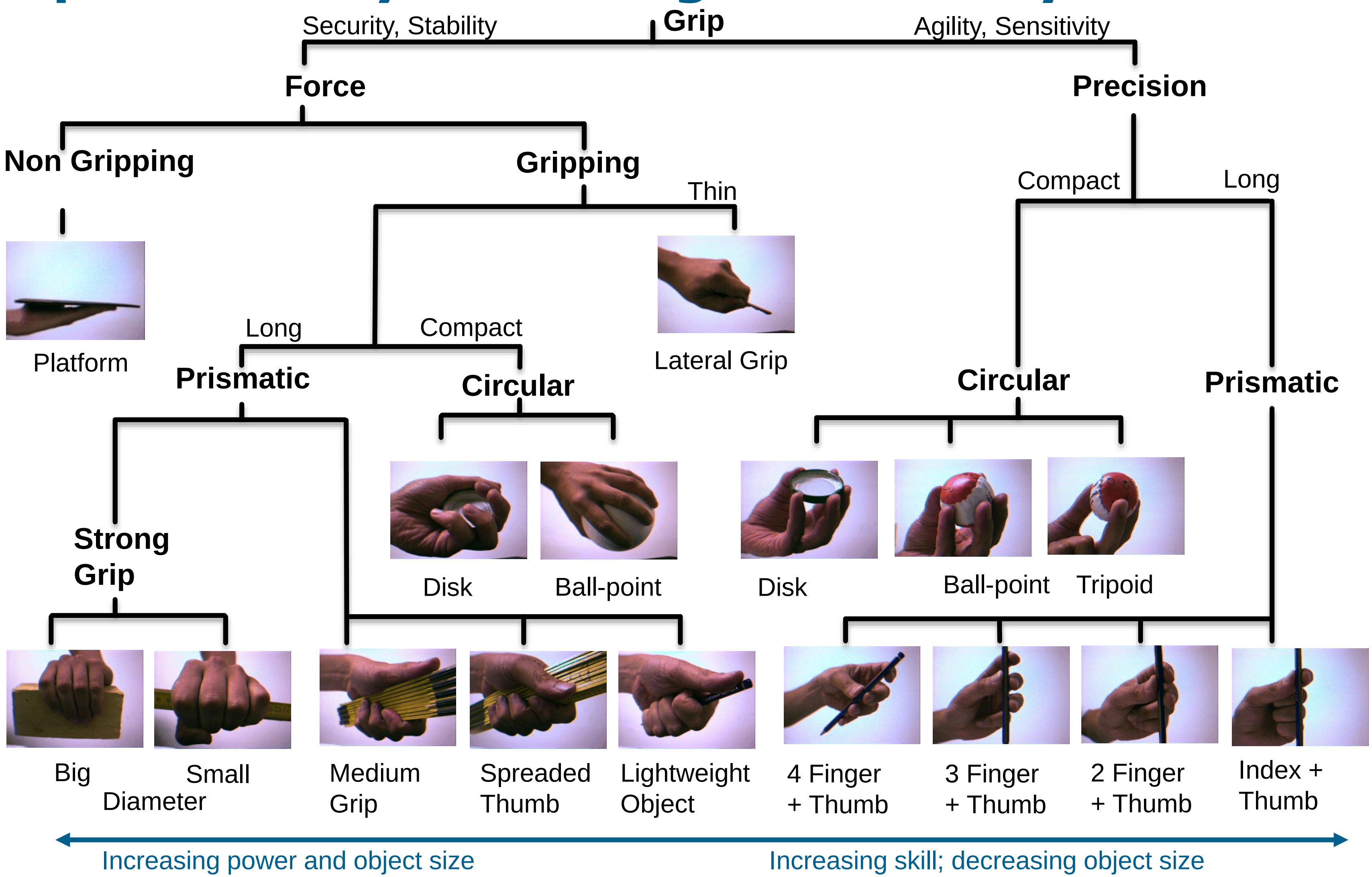
The Human Hand

- Universal gripper with 16 joints
- 22 degrees of freedom
- Common modeling
  - Kinematic model
  - Area-based geometry model





Grip Taxonomy According to Cutkosky



FZK–Hand (Forschungszentrum Karlsruhe) today KIT

Gripping Operations: Example Sequence

- Instruction: „Mount parts A, B according to installation plan P"
- Possible sequence (actions)
  1. Move robot hand in position of engagement of part A
  2. Move to the gripping position of part A
  3. Close claw fingers
  4. Drive with gripped part A into the repositioning position of part A
  5. Move hand with part A in position of engagement of part B
  6. Move hand with part A to mounting position of A and B
  7. Connect parts A, B according to the specification of P
  8. Open gripper fingers
  9. Move to the release position of part B

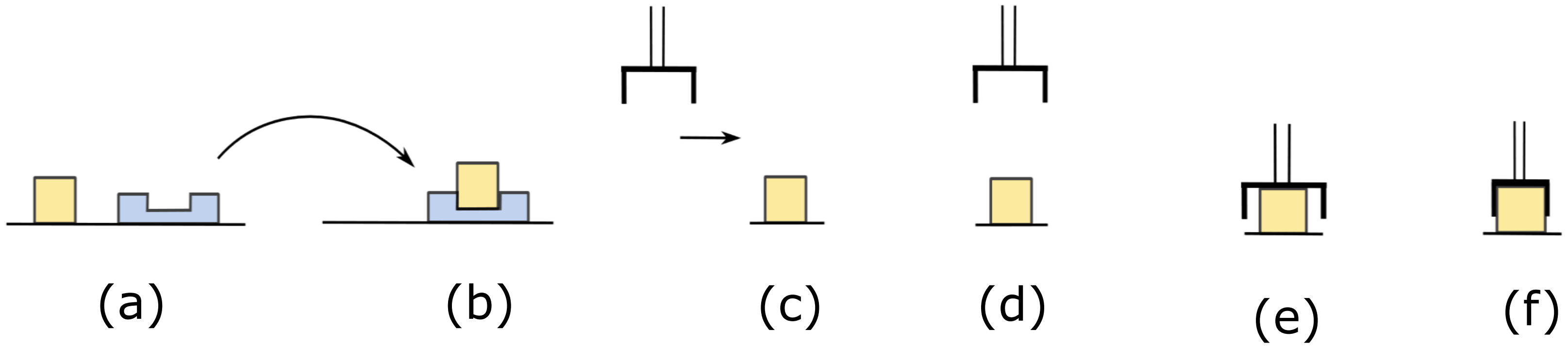
Gripping Operations: Movement Types

- Grasp/release object with mounted gripper
  - Selection of a secure grip, i.e. determination of a suitable geometric relation of the gripper fingers to the gripped object
  - Collision avoidance between gripper, object to be grabbed and objects of the environment (actions 3,8)
- Up/down movement of the gripper
  - Planning the movement (position and orientation)
  - Collision avoidance between gripper, object to be grabbed, robotic arm and objects of the environment (actions 2,9).

Gripping Operations: Movement Types

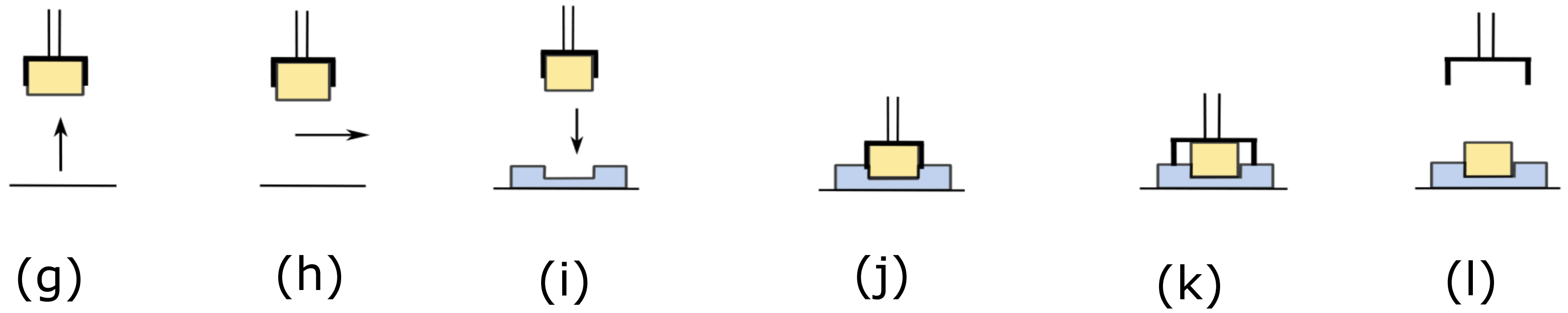
- Up/down movement of the gripper with gripped object
  - Motion planning of the gripper with gripped object
  - Collision avoidance between gripper, gripped object, robotic arm and objects of the environment (actions 4,6)
- Connecting the gripped object with other objects
  - Sensor-monitored and/or sensor-guided movements (action 7)
- Transfer movement of the gripper with/without a gripped object
  - Higher execution speeds and lower accuracy requirements compared to above movement types (actions 1,5)

Gripping Operations: Pick-and-Place



a) Picking configuration
b) Placing configuration
c) Transfer movement of the gripper
d) Movement of the gripper to position of engagement
e) Reaching the picking configuration
f) Gripping the object

Gripping Operations: Pick-and-Place



g) Upward movement of the gripper with the gripped object
h) Transfer movement of the gripper with gripped object
i) Downward movement of the gripper with the gripped object
j) Reaching the place configuration
k) Letting go of the object
l) Upward movement of the gripper

Gripping Operations: Internal Constraints

- $I1$ – Validity of a grip
  - Overlap between gripping features of the object to be gripped and the gripper fingers
- $I2$ – Collision free gripping
  - No collisions between gripper and gripped object
- $I3$ – Accessibility of a grip
  - Handle is reachable without collision for grippers

Gripping Operations: External Constraints

- $E1$ – Collision free movement of the gripper to position of engagement
  - No collisions between robot arm, gripper, adjacent objects and working plane
- $E2$ – Collision free movement of the gripper with the gripped object
  - See $E1$
- $E3$ – Consideration of the robot kinematics
  - Selected grip lies in the workspace of the robot
  - Corresponding trajectories of the up/down movement can be traversed by the robot

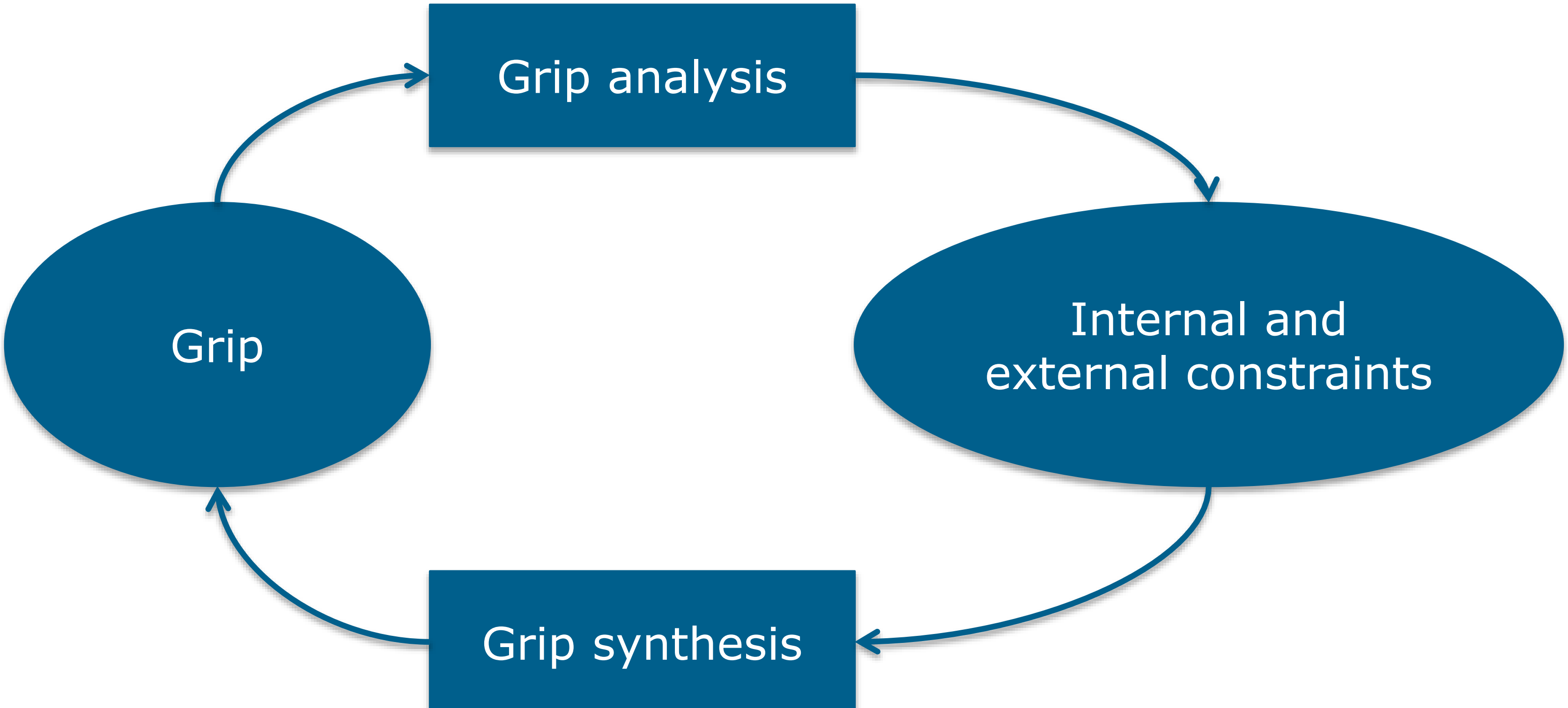
Gripping Operations: External Constraints

- $E4$ – Stability of a grip
  - Relative position and orientation of the object to be gripped or already gripped object to the gripper does not change (during gripping and transfer movement)
- $E5$ – Stability of the scene
  - No influence on the scene stability during the removal of the gripper with gripped object
- $E6$ – Task dependency of a gripper
  - Selection of a suitable handle for pick-and-place operations with regards to pick and place configuration

Gripping Operations: Planning Implications

- No grip can be determined (considering the constraints for pickup and tray configuration) → Determination of suitable recapturing sequence
- Execute a grip with special forces and torques on the gripped object → Determination of gripping position, required forces and torques

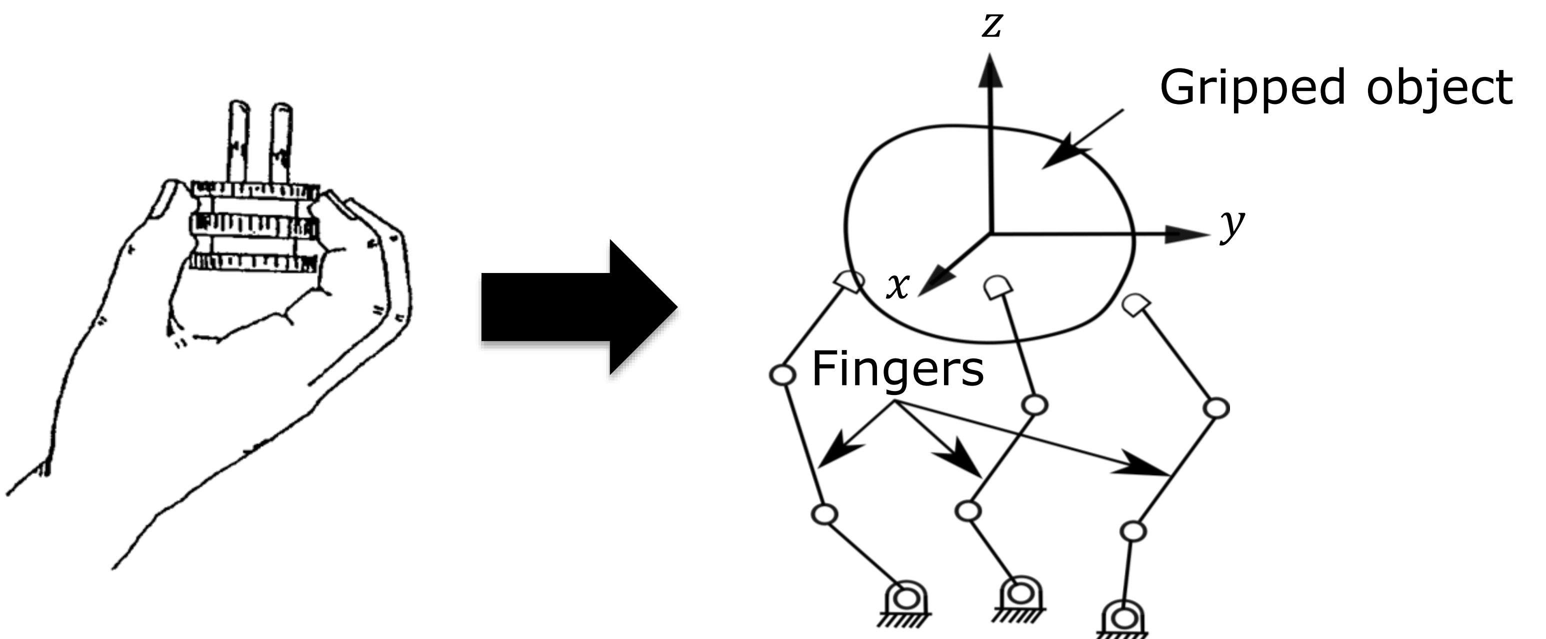
Gripping Operations: Planning Steps



Planning steps for generating gripping operations

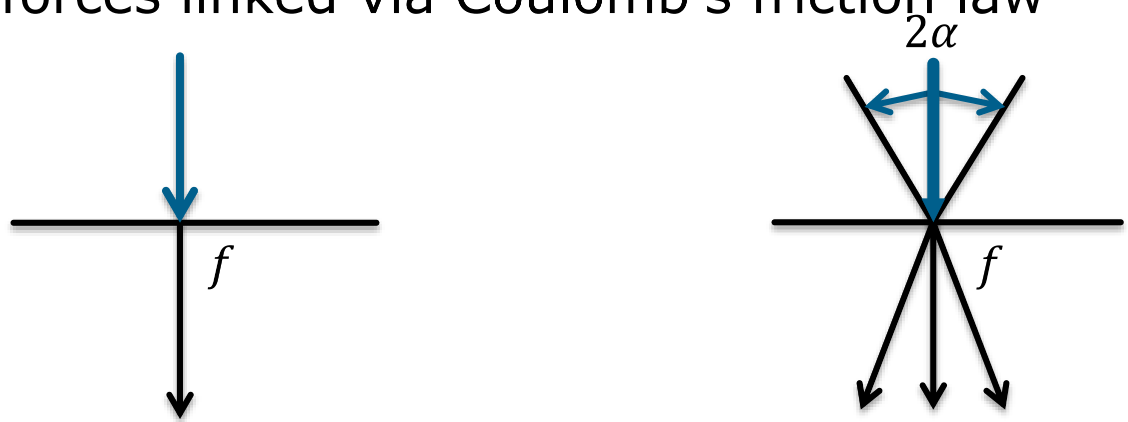
Fingertip Contact: Grip Model

- Simplification of the synthesis of possible grips by determining suitable contact points on the surface of the object to be gripped (constraint $I1$)
- Disadvantage: failure to observe fundamental constraints of the gripping process, such as collision freedom and accessibility of a handle (constraints $I2$ and $I3$)



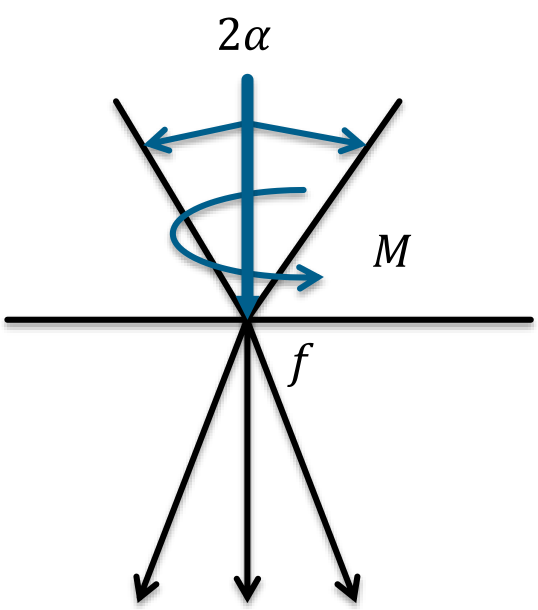
Fingertip Contact: Assumptions

- Point contact without friction
  - Force: point contact to the surface of the object without friction
  - Effect: Normal to the surface
- Rigid point contact with friction
  - Force: Rigid point contact on object surface with friction
  - Effect: Normal and tangential to the surface
  - Both forces linked via Coulomb's friction law



Fingertip Contact: Assumptions

- Non-rigid point contact with friction
  - Force: non-rigid contact on object surface with friction
  - Effect: Normal and tangential to the surface
  - Both forces linked via Coulomb's friction law



Grip Hierarchy: Wrench Vector $\vec{w}$

- Summary of forces f_i and torques τ_i acting on the contact point $\vec{p}$ with $i \in [x, y, z]$
  - Planar grip: $\vec{w} = \left(f_x, f_y, \tau_z\right)^T \in \mathbb{R}^3$
  - Spatial grip: $\vec{w} = \left(f_x, f_y, f_z, \tau_x, \tau_y, \tau_z\right)^T \in \mathbb{R}^6$
- Depending on the type of i-th contact point, wrench vectors describe the normal n and tangential forces t and the axial torque θ acting on the contact point
  - Identifier: ${}^i\vec{w}_n,\ {}^i\vec{w}_t,\ {}^i\vec{w}_\theta$
  - Corresponding scalars: ${}^ic_n,\ {}^ic_t,\ {}^ic_\theta$

Grip Hierarchy: Gripper Matrix

- Represents geometric and physical properties of a fingertip grip
- Wrench vectors can be represented as a spatial vector as column vectors of a $6 \times 3m$ matrix G.

$$G = \left[{}^{1}\overrightarrow{w}_{n},\ {}^{1}\overrightarrow{w}_{t},\ {}^{1}\overrightarrow{w}_{\theta}, \cdots {}^{m}\overrightarrow{w}_{n}, {}^{m}\overrightarrow{w}_{t}, {}^{m}\overrightarrow{w}_{\theta} \right]$$

- For the scalars we get the vector

$$\vec{c} = \left({}^{1}c_{n},\ {}^{1}c_{t},\ {}^{1}c_{\theta}, \cdots {}^{m}c_{n}, {}^{m}c_{t}, {}^{m}c_{\theta} \right)^{T} \in \mathbb{R}^{3m}$$

Equilibrium Grip

- A grip specified by gripping matrix G, to which an external force and an external torque $\vec{e} = \left(f_x, f_y, f_z, \tau_x, \tau_y, \tau_z\right)^T \in \mathbb{R}^6$ will be applied, if

$$\forall i \in [1, m]:\ {}^{i}c_n \geq 0,\quad {}^{i}\mu_t \cdot {}^{i}c_n \geq \left| {}^{i}c_t \right|,\quad {}^{i}\mu_\theta \cdot {}^{i}c_n \geq \left| {}^{i}c_\theta \right|$$

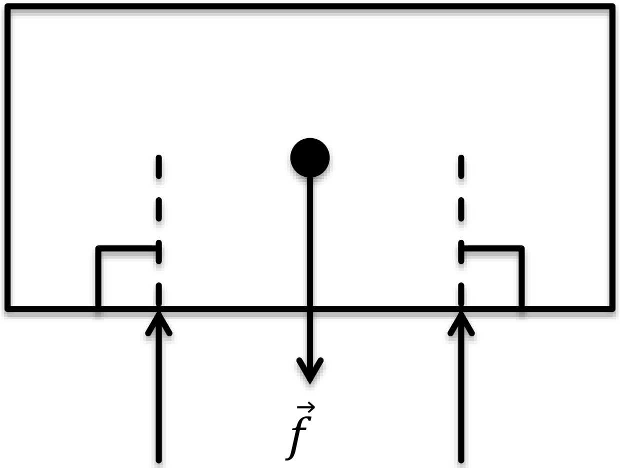
$$\exists \vec{c} \in \mathbb{R}^{3m}, \vec{c} \neq \vec{0}:\ G \cdot \vec{c} + \vec{e} = \vec{0}$$

- ${}^{i}\mu_t,\ {}^{i}\mu_\theta \in \mathbb{R}$ Coulomb friction coefficients at contact point i

- Limitation of the acting tangential forces t and axial moments θ with respect to the absolute value of the corresponding normal forces n

Equilibrium Grip

- Sum of all forces f_i and torques τ_i acting on the gripped object is equal to zero
- Equilibrium grip of an object is based on two rigid point-contacts without friction
  - An external force $\vec{f}$ acts on the object's center of gravity.



Force Closed Grips

- During transfer movement and assembly operation various previously unknown external forces and moments act on an object
- Solution
  - Stability of a grip through the balance of forces
  - Forces and moments exerted on objects by gripper fingers must compensate external forces and moments

- Grips specified by gripping matrix G, on which any external forces and moments $\vec{e} = \left(f_x, f_y, f_z, \tau_x, \tau_y, \tau_z\right)^T \in \mathbb{R}^6$ will be applied, if

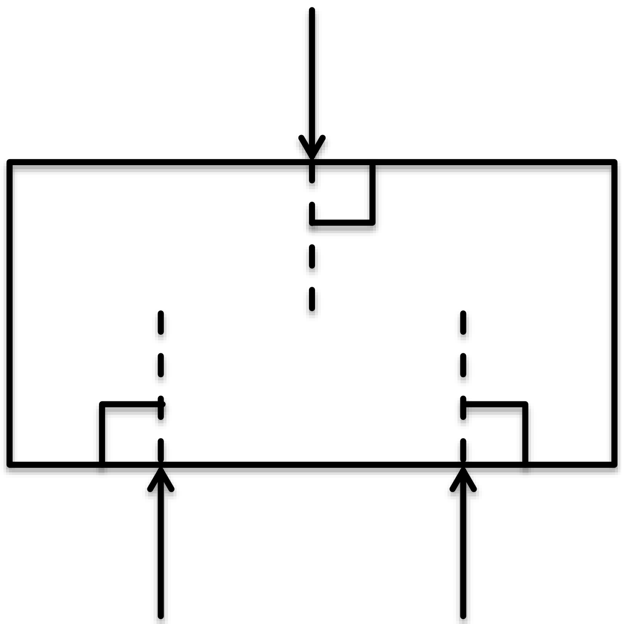
$$\forall \vec{e} = \left(f_x, f_y, f_z, \tau_x, \tau_y, \tau_z\right)^T \in \mathbb{R}^6 \; \exists \vec{c} \in \mathbb{R}^{3m}$$
$$\vec{c} \neq \vec{0}\colon \; G \cdot \vec{c} + \vec{e} = \vec{0}$$

Force Closed Grips: Contact Points

- Force closure with point contacts and without friction
  - Object to gripped without rotational symmetry: Planar force closed grip needs at least 4 contact points
  - Any 3D object: Max. 12 contact points required
  - Restriction on polyhedra: upper limit of 7 points
- Force closure with point contacts and friction
  - Planar objects: Fingertip grip with 3 contact points
  - Spatial case: Lower limit of 4 contact points

Form Closed Grips

Planar form closed grip of an object is based on three non-rigid point contacts with friction



Form Closed Grips

- For each contact point, consider only the non-penetrating properties co-linear to the corresponding external surface normal vector.

- Only dependent on the position of the contact points and the corresponding external surface normal vectors

- No consideration of normal or tangential forces and torques, which appear due to friction, among other things.

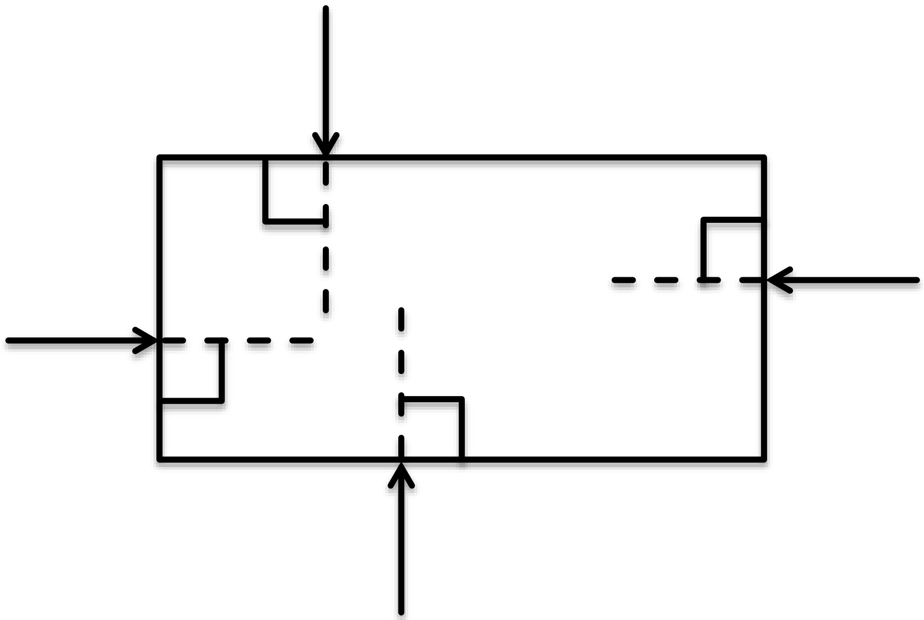
Form Closed Grips

- External surfaces normal vectors corresponding to the contact points specify the contact geometry of the fingertip grip
- Grip matrix $G' = \left[\, {}^{1}\overrightarrow{w}_n,\ {}^{2}\overrightarrow{w}_n, \cdots {}^{m}\overrightarrow{w}_n \right] \in \mathbb{R}^{6xm}$
- Contact points with form closed fingertip grip
  - Planar grip: Min. 4 contact points
  - Arbitrary 3D-object: Min. 7 contact points
- Grip specified by modified gripping matrix G', on which any external forces and moments $\vec{e} = \left(f_x, f_y, f_z, \tau_x, \tau_y, \tau_z\right)^T \in \mathbb{R}^6$ can be applied, if

$$\forall \vec{e} = \left(f_x, f_y, f_z, \tau_x, \tau_y, \tau_z\right)^T \in \mathbb{R}^6 \ \exists \vec{c} \in \mathbb{R}^6\text{:}\ \ G' \cdot \vec{c} + \vec{e} = \vec{0}$$

Form Closed Grips

Form closed grip of an object



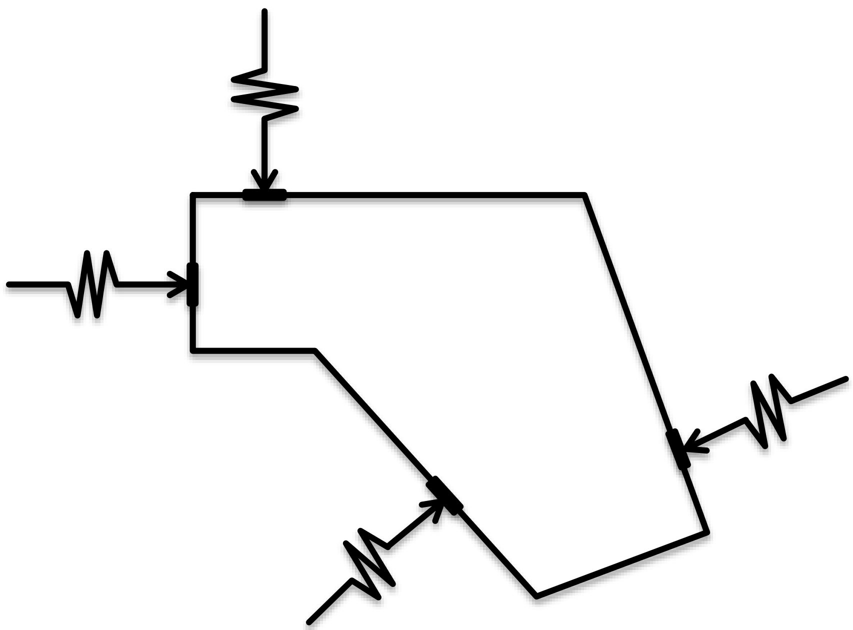
Stable Grips

- Previous condition: Rigid gripper fingers
- Improvement: Modeling of finger forces that compensate for small changes in the nominal position of the gripped object
- Description with a potential function $V: \mathbb{R}^6 \rightarrow \mathbb{R}$
- V Specifies the potential energy stored in the grip as a function of the position and orientation of the gripped object

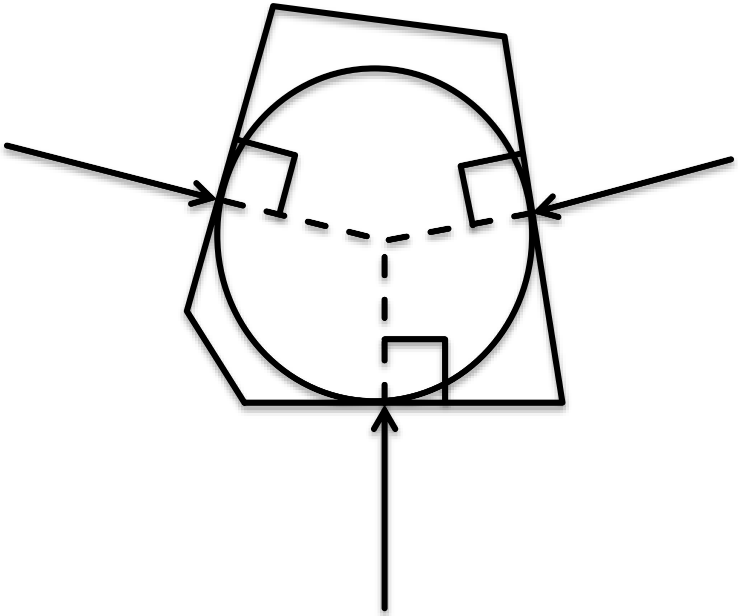
Stable Grips: Definition

- If the potential energy stored in an equilibrium grip of an object is specified via a potential function V and if
$$\delta\vec{q} = \left(\delta_x, \delta_y, \delta_z, \delta_{\varphi x}, \delta_{\varphi y}, \delta_{\varphi z}\right)^T \in \mathbb{R}^6 \neq \vec{0}$$
describes an infinitesimal change in position of the gripped object and the resulting change in the potential energy, then the grip is stable if
$$\forall \delta\vec{q} \in \mathbb{R}^6 : \delta\vec{V} > \vec{0}$$
- Thus, an equilibrium grip is unstable when a position change exists for which the resulting change in potential energy is less than zero

Stable Grips



Stable and locked grip of a polygon based on 4 non-rigid point contacts with friction



Stable triangle handle of a polygon;

Not locked

Coming up next...

Planning systems