Mobile manipulator

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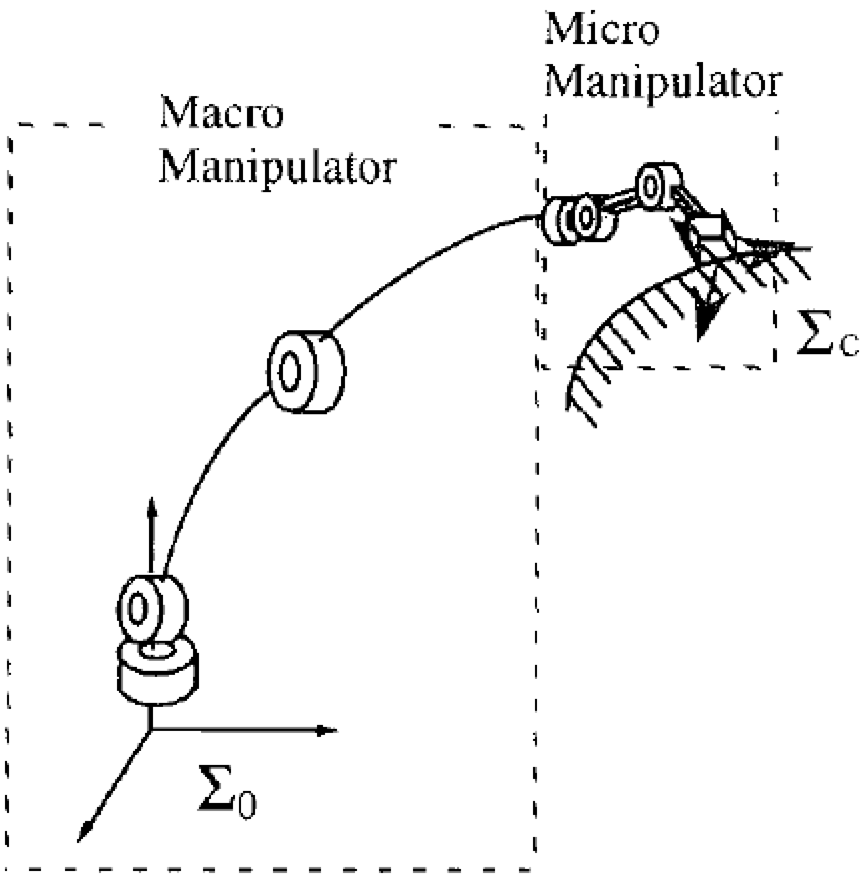
Quiz (10 pts)

- (4 pts) Explain the control strategy for a flexible-macro rigid-micro-structure robot?
- A macro-micro robot manipulator can be controlled for optimizing the manipulability of micro-structure.
  - (3 pts) Describe one control strategy that can **maintain** the manipulability above a threshold
  - (3 pts) Describe one control strategy that can **increase** the manipulability of micro-structure

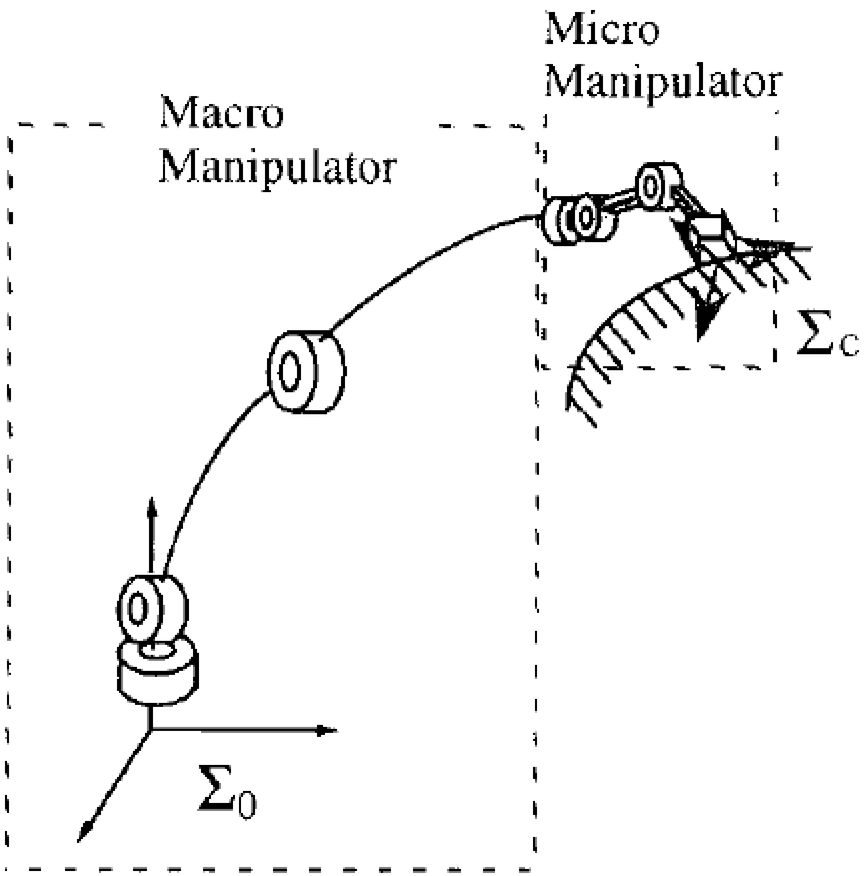
Flexible-macro rigid-micro manipulators

- Macro-structure
  - Flexible arm of wide motion range
  - Neither fast nor precise due to flexibility
- Micro-structure
  - Limited motion range
  - Fast and precise motion



Hybrid position/force control for flexible macro-micro manipulators [1]

- Macro-structure
  - Roughly realize the desired trajectory, and suppress vibration
- Micro-structure
  - Compensate for the position and force errors due to the elasticity in the macro-structure



Heuristic Method

- Choose a reference finger manipulability W_f
  - If $W_f(k) \geq W_{fr}$, the finger will keep moving and tracing the desired trajectory, while the arm maintains its previous position
  - If $W_f(k) < W_{fr}$, moving the arm becomes necessary

Heuristic Method

- When it is necessary to move the arm

$$\Delta p_d(k) = s_1 \Delta p_t(k)$$

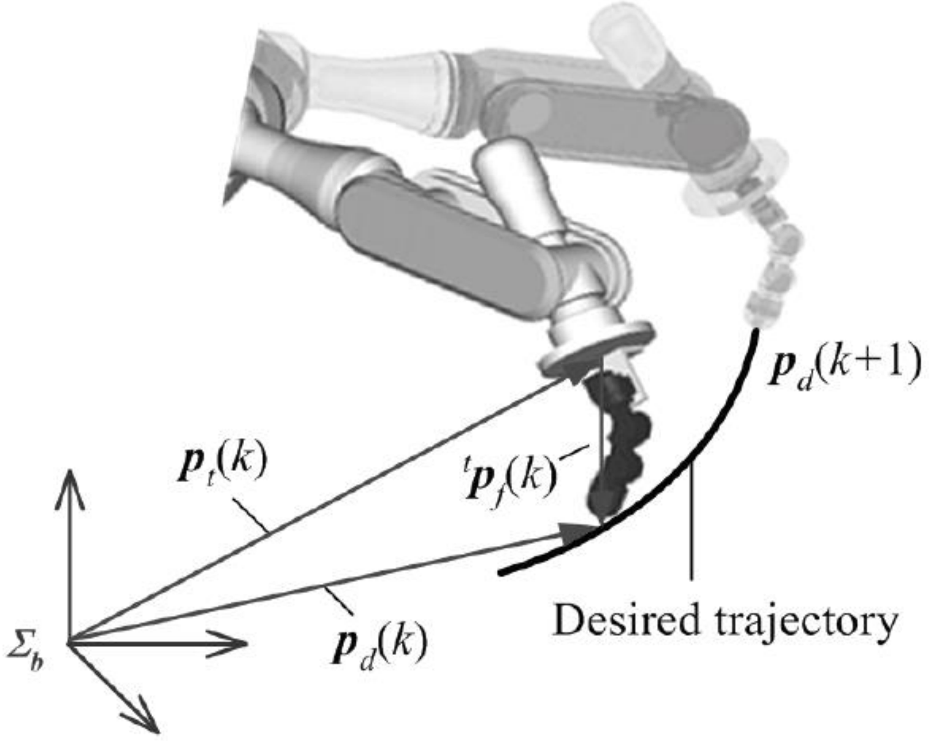
- Finger remains motion less

$$\dot{\theta}_f(k) = 0$$

- Finger manipulability unchanged

$$\Delta W_f = 0$$

- **Moving the arm instead of moving the finger can theoretically prevent any further decrease**
- **However, switching control between the arm results in a sudden change in velocity**



Steepest Ascent Method

- When the finger manipulability is under the defined threshold,
  - Computer the finger joint angles needed for increase manipulability

$$\boldsymbol{\theta}_{fd}(k) = \boldsymbol{\theta}_{fd}(k-1) + \lambda \frac{\partial W_f}{\partial \boldsymbol{\theta}_f}$$

  - Computer desired frame transform of finger w.r.t. to the EE of arm

$${}^{t}\boldsymbol{p}_f(k) = \Lambda_f(\boldsymbol{\theta})$$

  - Given the desired finger EE position, compute the desired the EE of arm

$$\boldsymbol{p}_{td}(k) = \mathbf{s}_1^T(\boldsymbol{p}_d(k) - \boldsymbol{R}_t \cdot {}^{t}\boldsymbol{p}_f(k))$$

Mobile manipulator

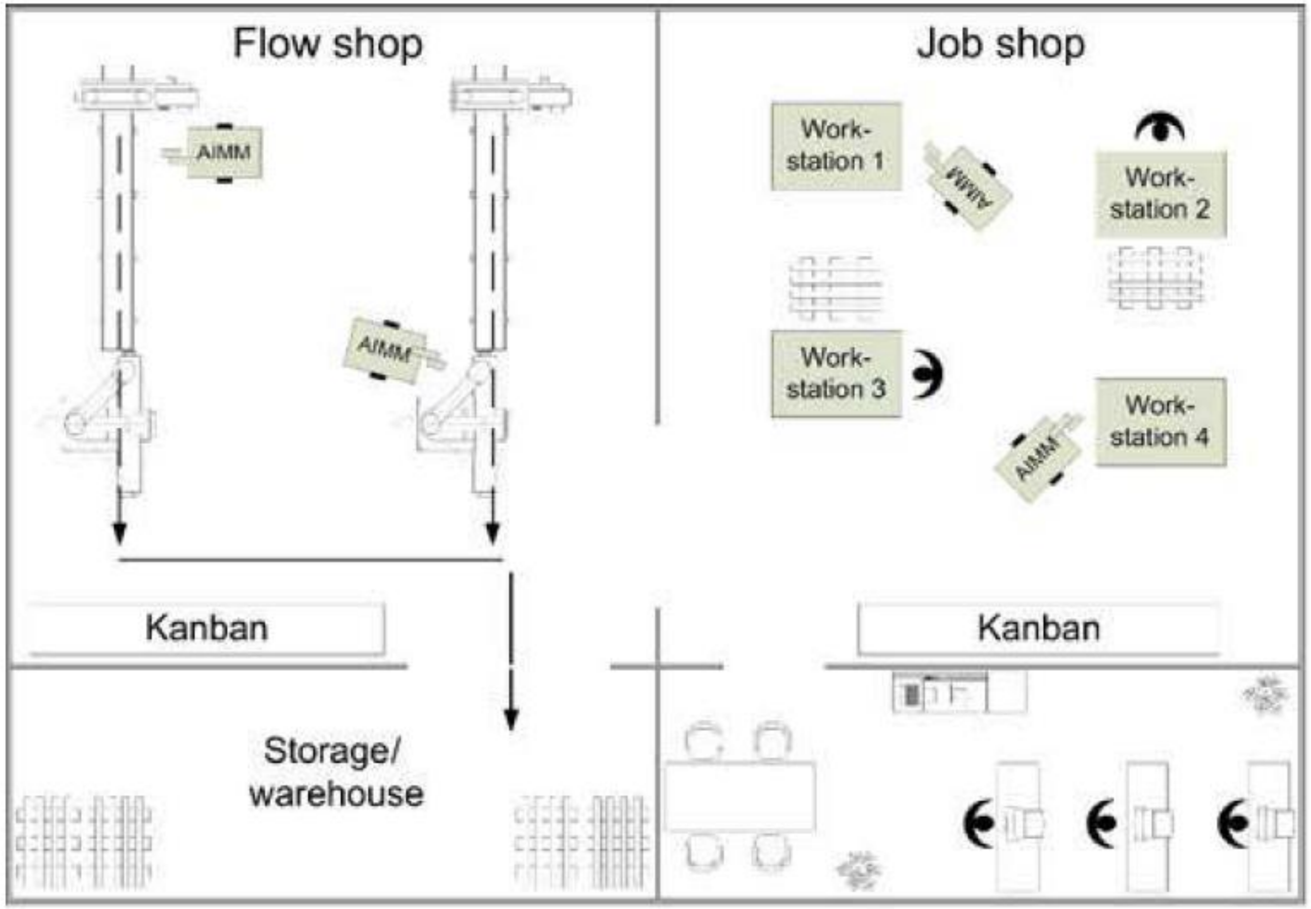
State-of-the-art mobile manipulators [2]

Amazon picking challenge 2015

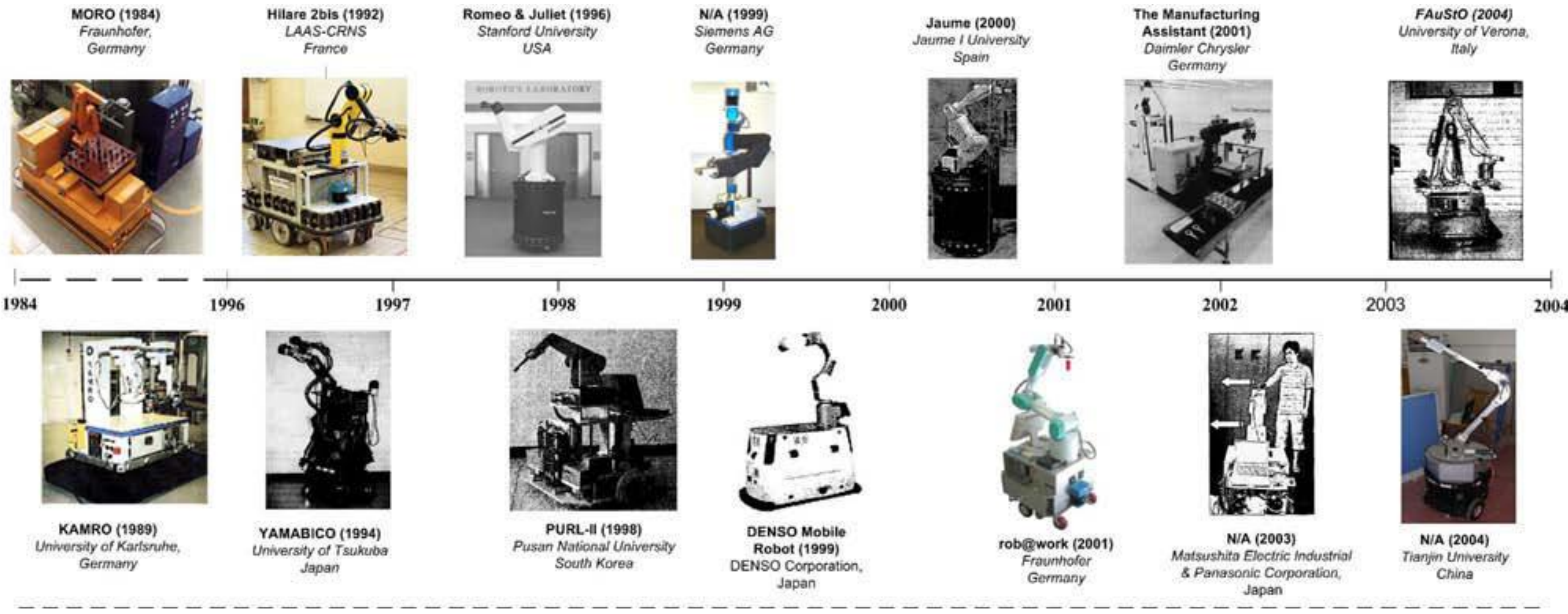
Commercialized

Autonomous industrial mobile manipulator (AIMM) [1]

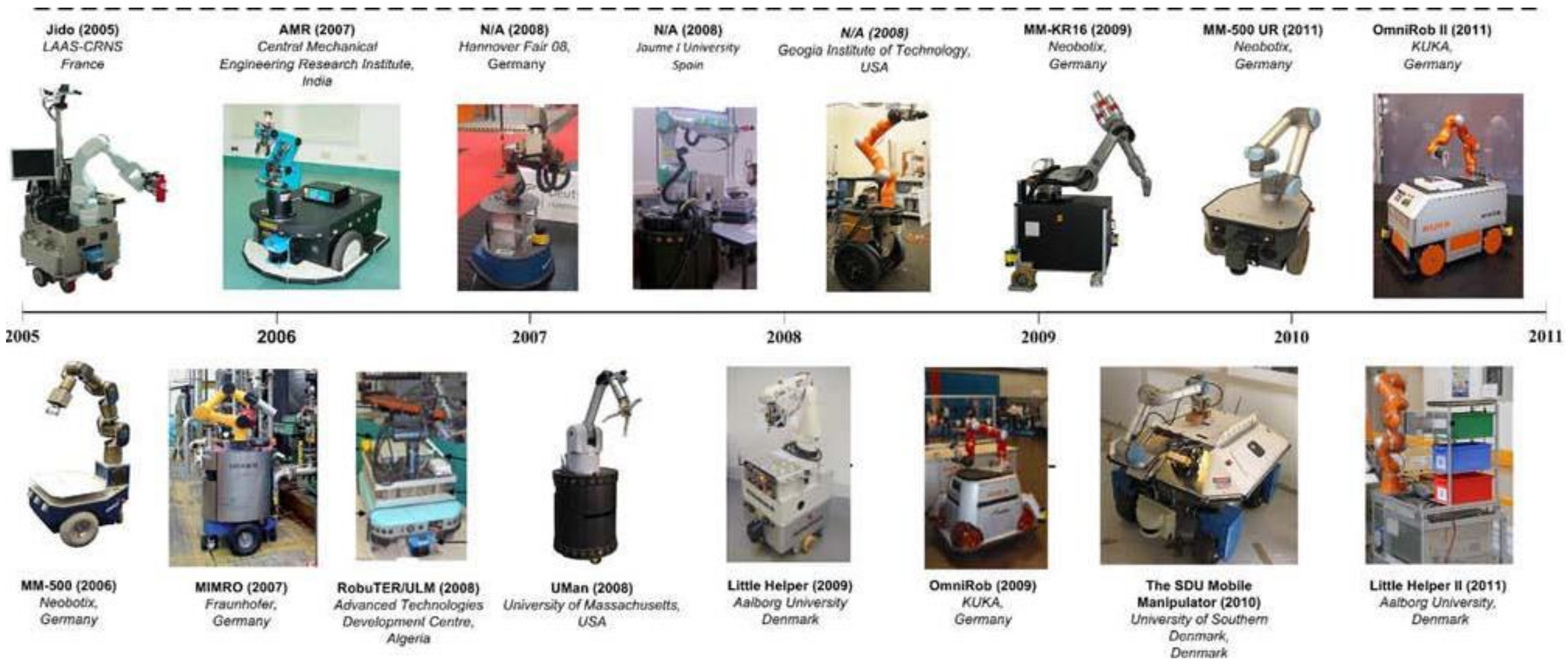
- Mass production
  - Efficiency
- Manual production
  - Flexibility



Early technologies [1]



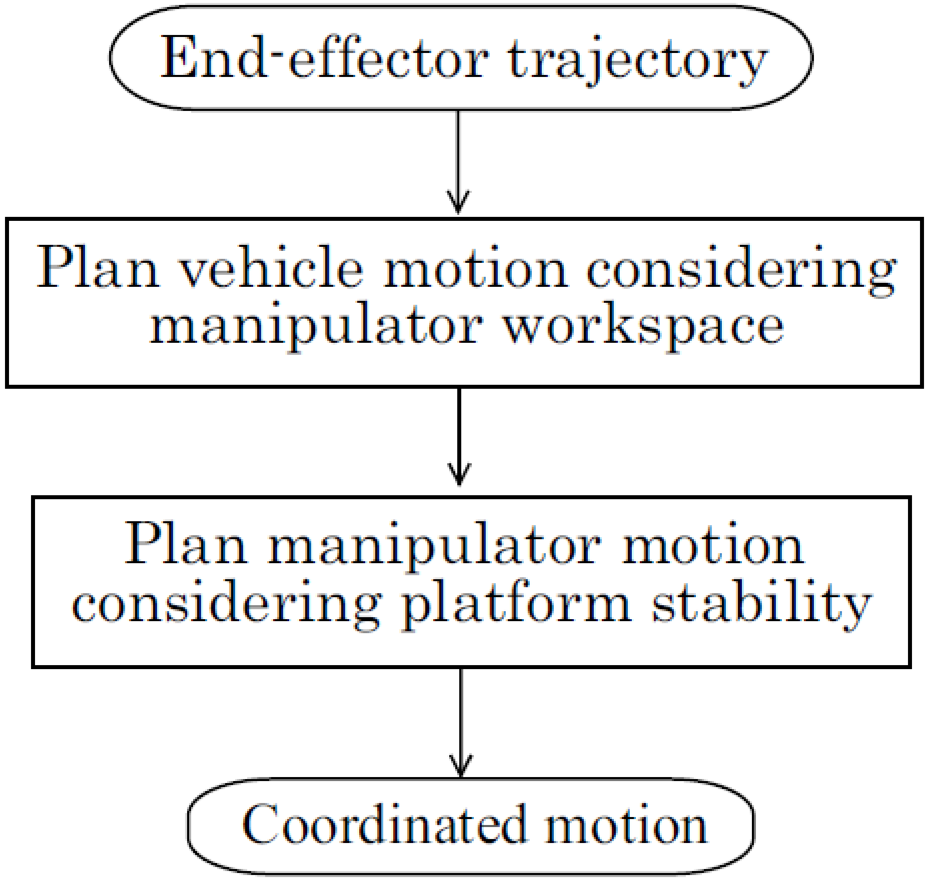
Recent technologies [1]

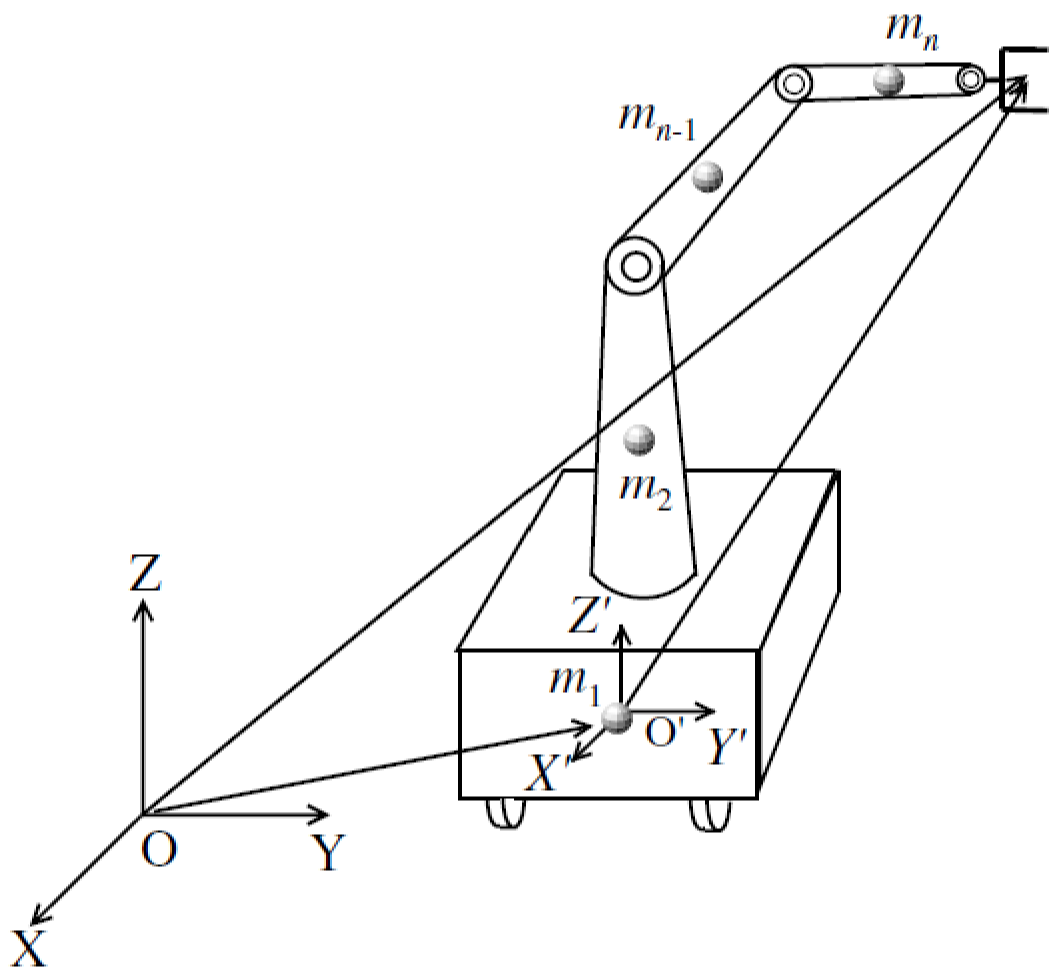


Research focuses [2]

- Planning and control of redundant DOFs to achieve
  - Coordination of locomotion and manipulation
  - Configuration Optimization
  - Control stability
  - Obstacle avoidance
  - Robot-robot / human-robot cooperation
  - Outdoor applications

Coordination of manipulation and locomotion [3]





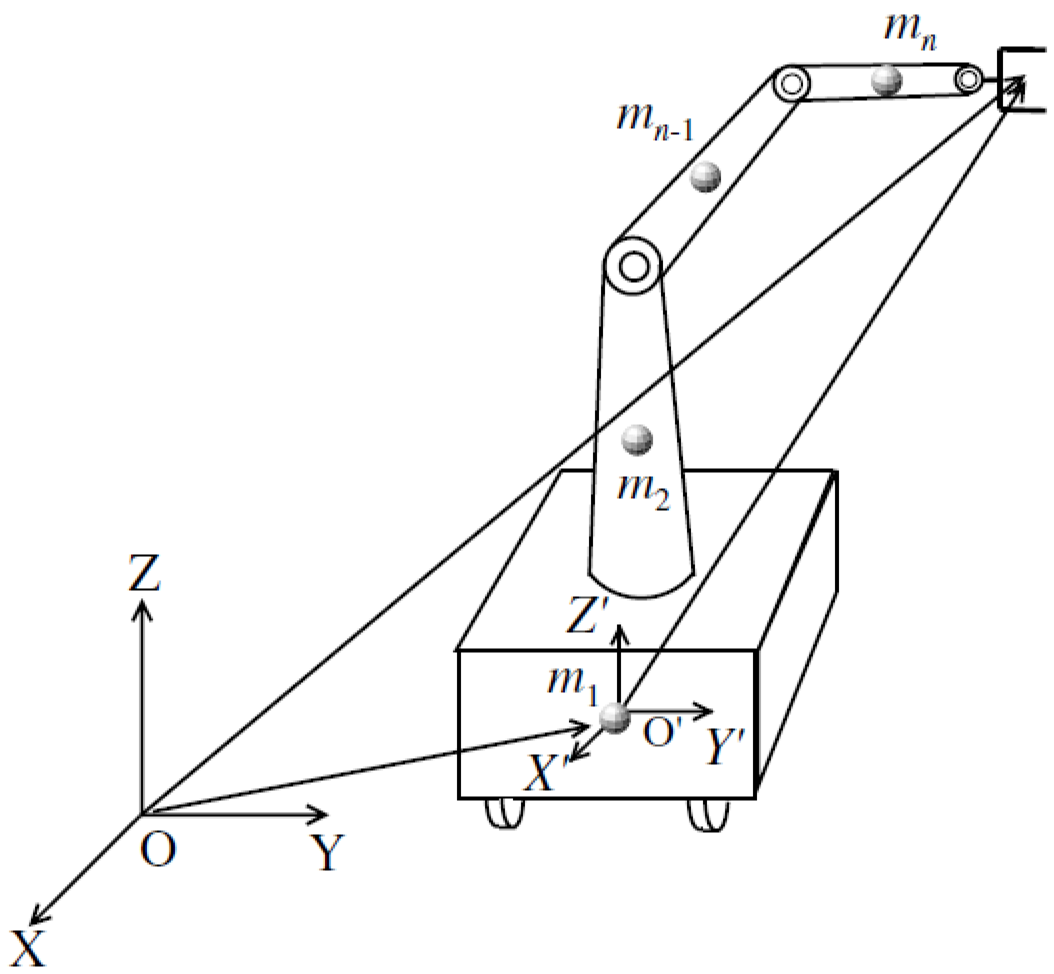
Stability criterion

- ZMP = zero moment point

$$x_{zmp} = \frac{\sum_{i=1}^{n} m_i(\ddot{z}_i + g)x_i - \sum_{i=1}^{n} m_i \ddot{x}_i z_i}{\sum_{i=1}^{n} m_i(\ddot{z}_i + g)}$$

$$y_{zmp} = \frac{\sum_{i=1}^{n} m_i(\ddot{z}_i + g)y_i - \sum_{i=1}^{n} m_i \ddot{y}_i z_i}{\sum_{i=1}^{n} m_i(\ddot{z}_i + g)}$$

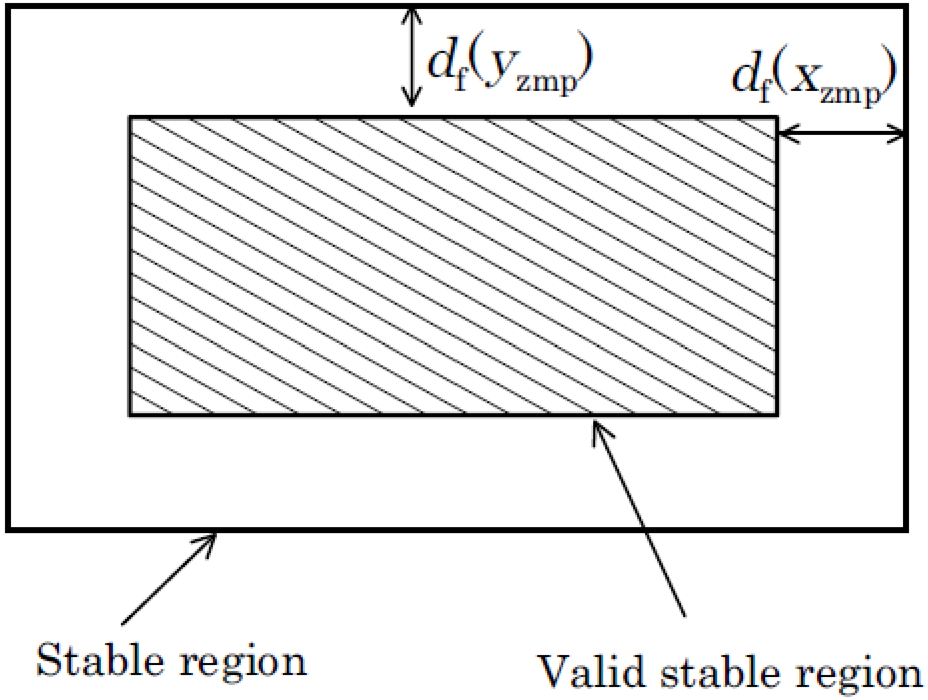
$$\Omega = \left\{ (x_{zmp}, y_{zmp}) \mid d_s(x_{zmp}) \geq d_f(x_{zmp}), \; d_s(y_{zmp}) \geq d_f(y_{zmp}) \right\},$$



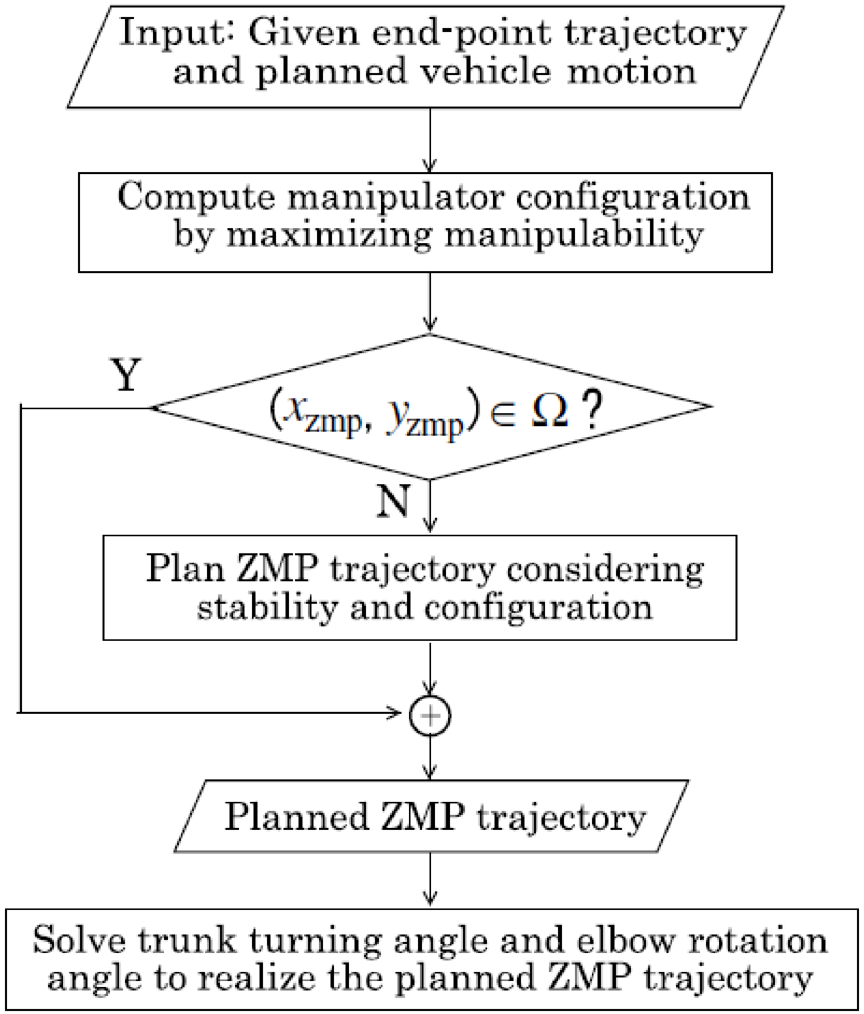
Viable stability region

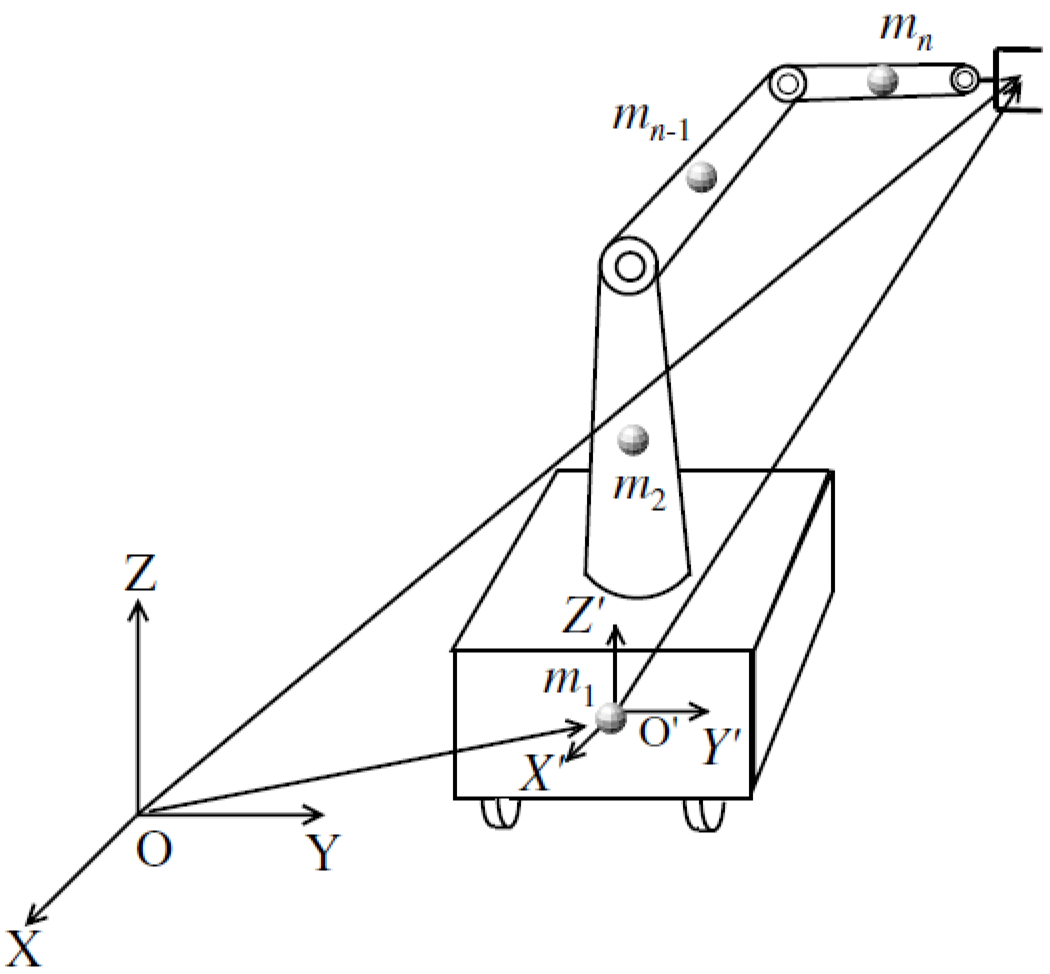
$$d_f(x_{zmp}) = \frac{\sum_{i=1}^{n} (S_{zj} F_{xj} - S_{xj} F_{zj})}{\sum_{i=1}^{n} m_i(\ddot{z}_i + g) - \sum_{i=1}^{n} F_{zj}}$$

$$d_f(y_{zmp}) = \frac{\sum_{i=1}^{n} (S_{zj} F_{yj} - S_{yj} F_{zj})}{\sum_{i=1}^{n} m_i(\ddot{z}_i + g) - \sum_{i=1}^{n} F_{zj}}$$



Motion coordination

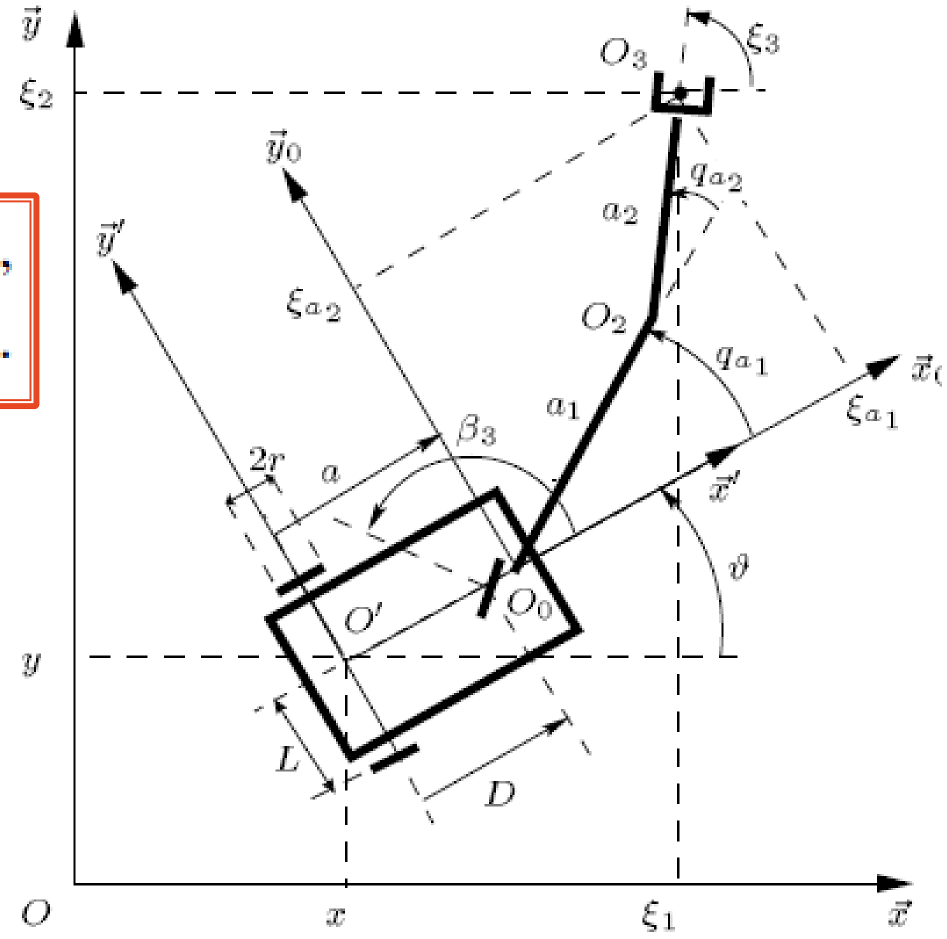




Manipulability affected by mobile base [4]

$$\xi_1 = x + (a + a_1 C_1 + a_2 C_{12}) C_\vartheta - (a_1 S_1 + a_2 S_{12}) S_\vartheta ,$$
$$\xi_2 = y + (a + a_1 C_1 + a_2 C_{12}) S_\vartheta + (a_1 S_1 + a_2 S_{12}) C_\vartheta .$$

$$\dot{\boldsymbol{\xi}} = \begin{bmatrix} \dot{\xi}_1 \\ \dot{\xi}_2 \end{bmatrix} = \bar{J}(q_{a_1},\ q_{a_2},\ \vartheta,\ \beta_3) \begin{bmatrix} \dot{q}_{a_1} \\ \dot{q}_{a_2} \\ \eta_p \end{bmatrix}$$



Manipulability metrics

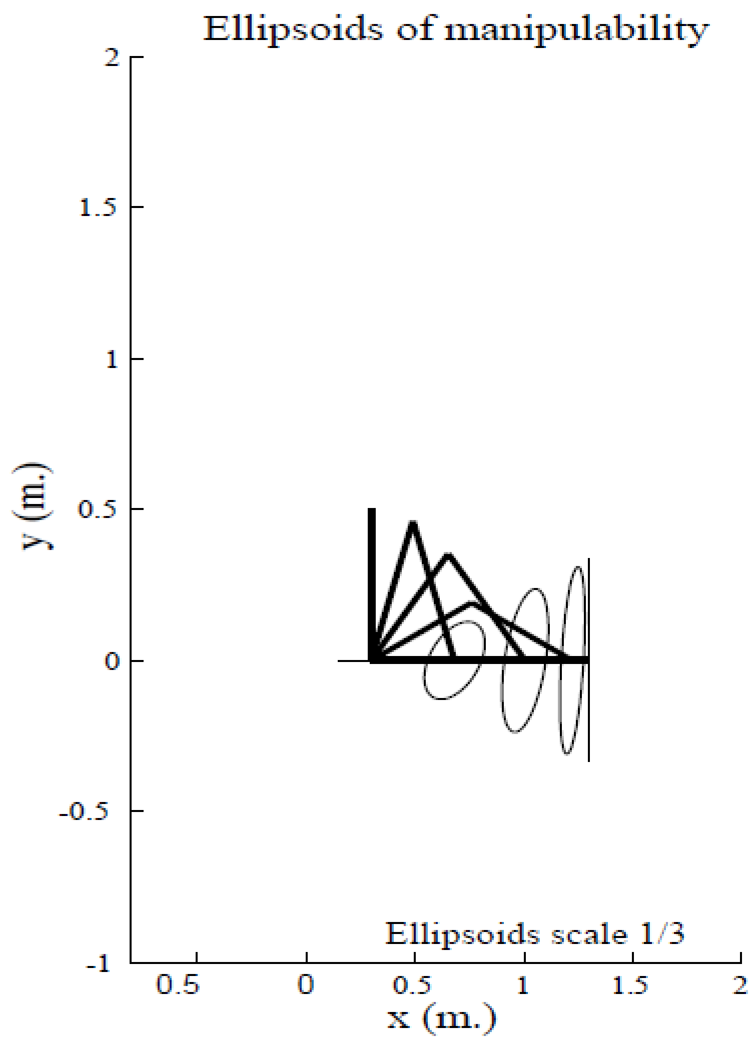
$$w_{a_5} = \sqrt{1 - \frac{\sigma_{m_a}^2}{\sigma_1^2}}$$

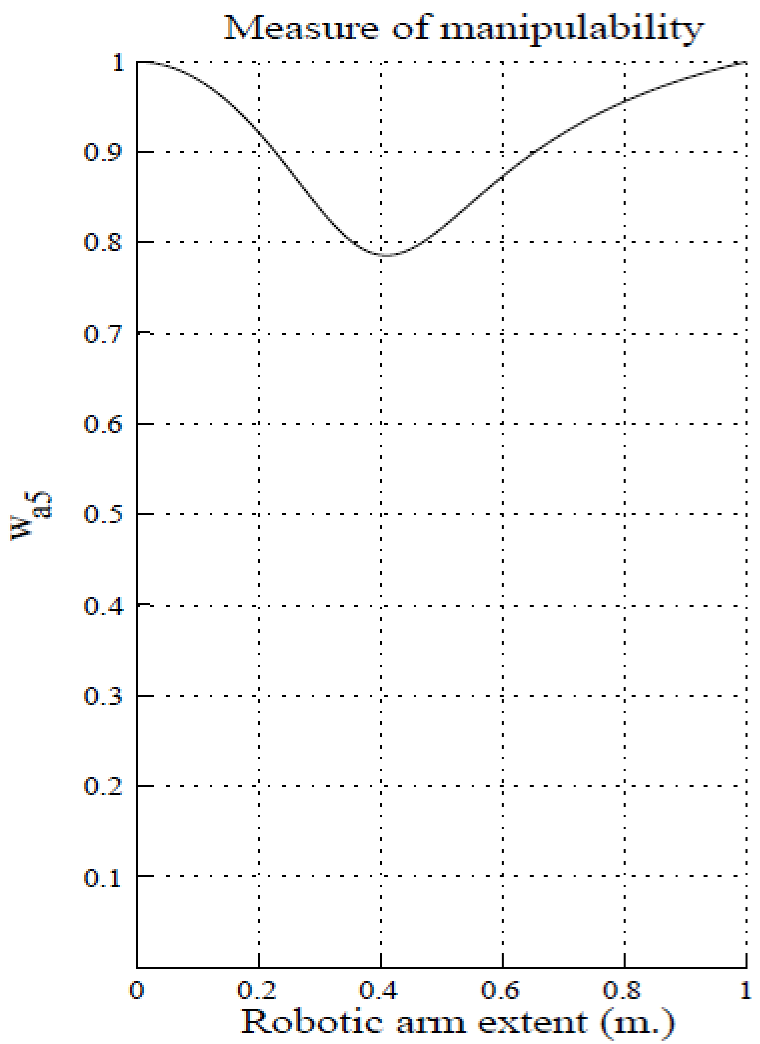
Isotropy = 1/ condition number

$$\dot{\boldsymbol{\xi}} = \begin{bmatrix} \dot{\xi}_1 \\ \dot{\xi}_2 \end{bmatrix} = \bar{J}(q_{a_1}, q_{a_2}, \vartheta, \beta_3) \begin{bmatrix} \dot{q}_{a_1} \\ \dot{q}_{a_2} \\ \eta_p \end{bmatrix}$$

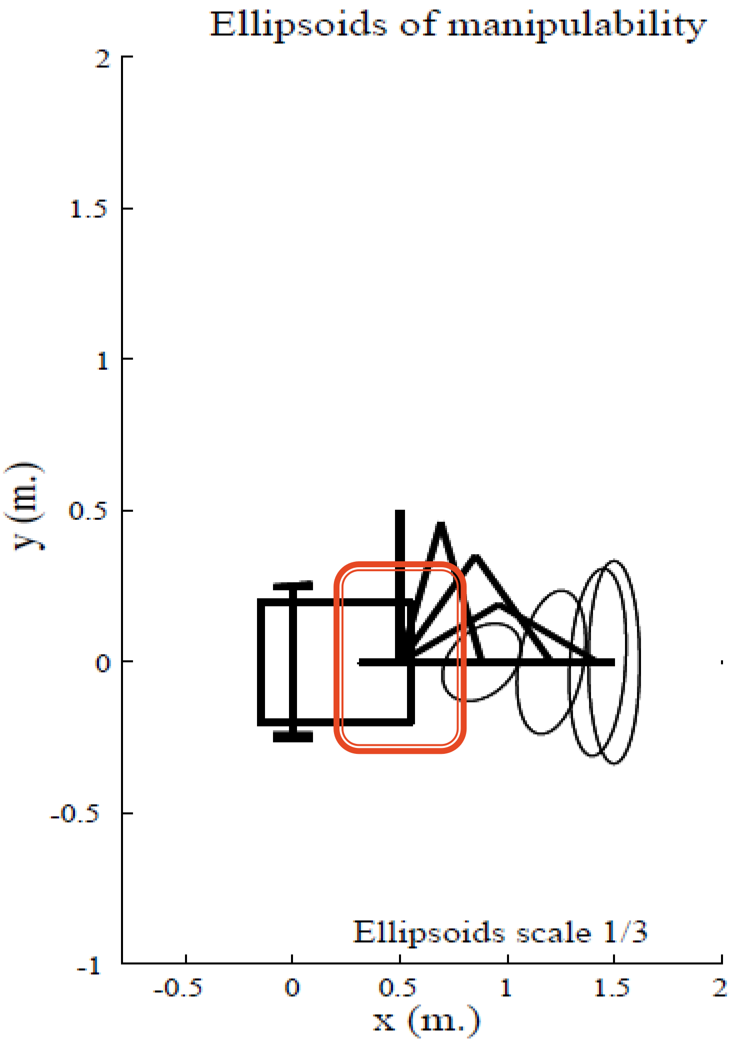
$$A' = U[\Sigma \; 0] \begin{bmatrix} V^T \\ 0 \end{bmatrix}$$

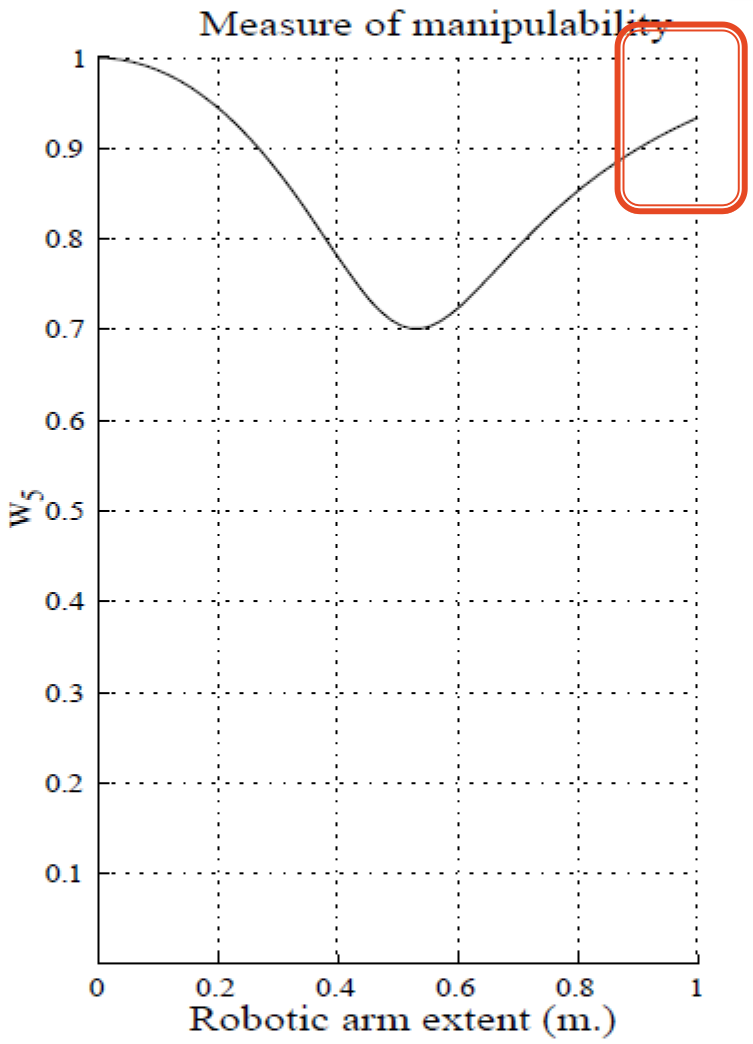
Manipulability of 2-DOF arm



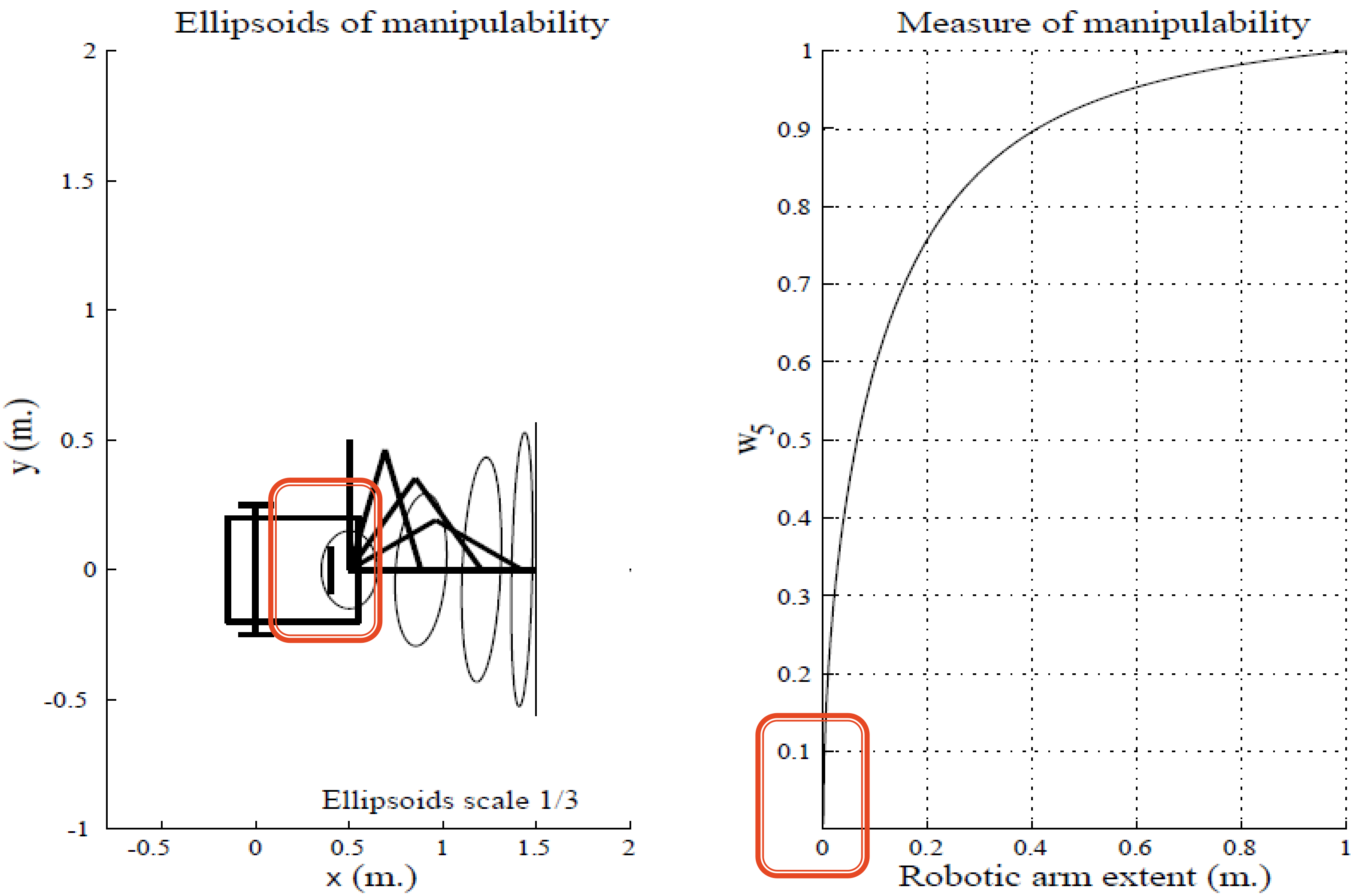


Manipulability of mobile manipulator



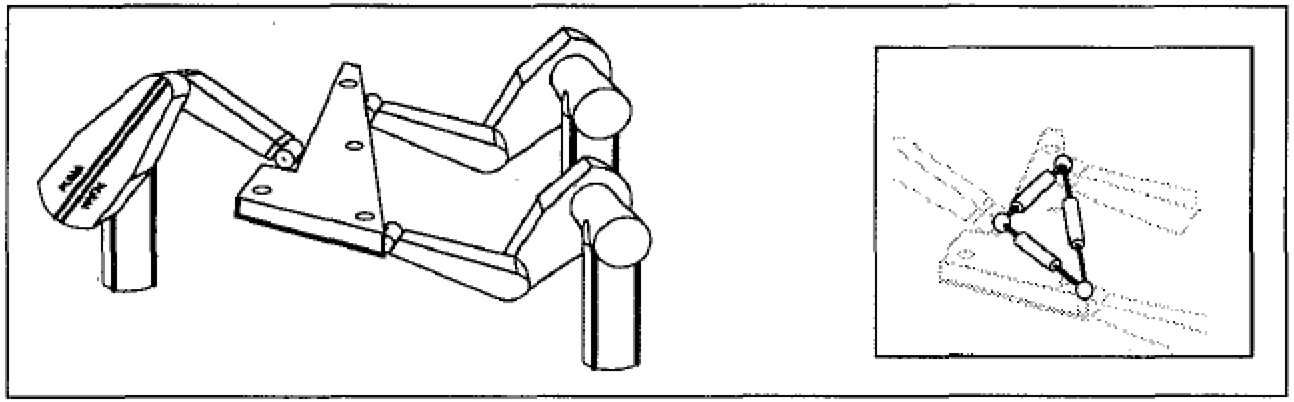


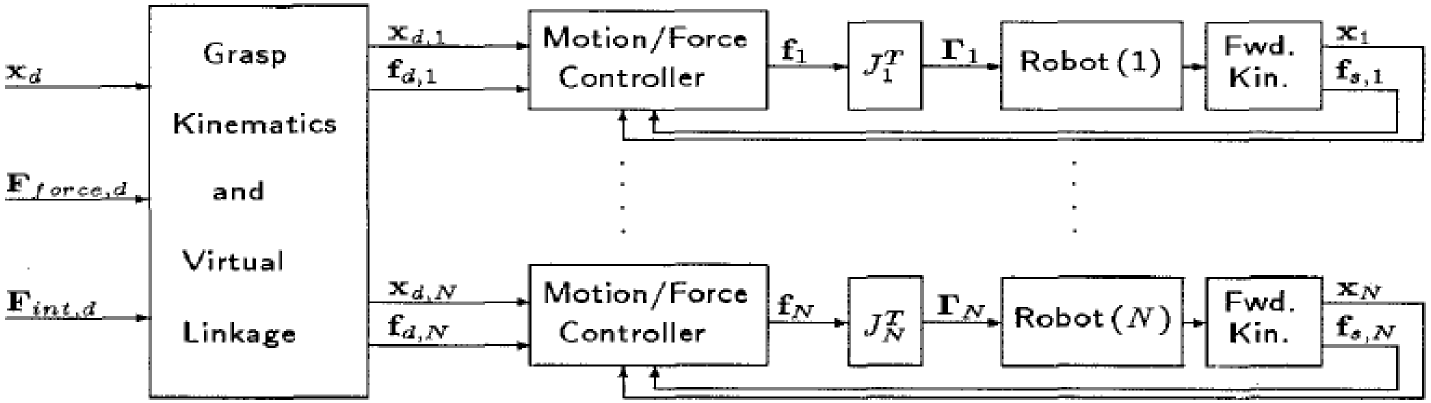
Manipulability of mobile manipulator

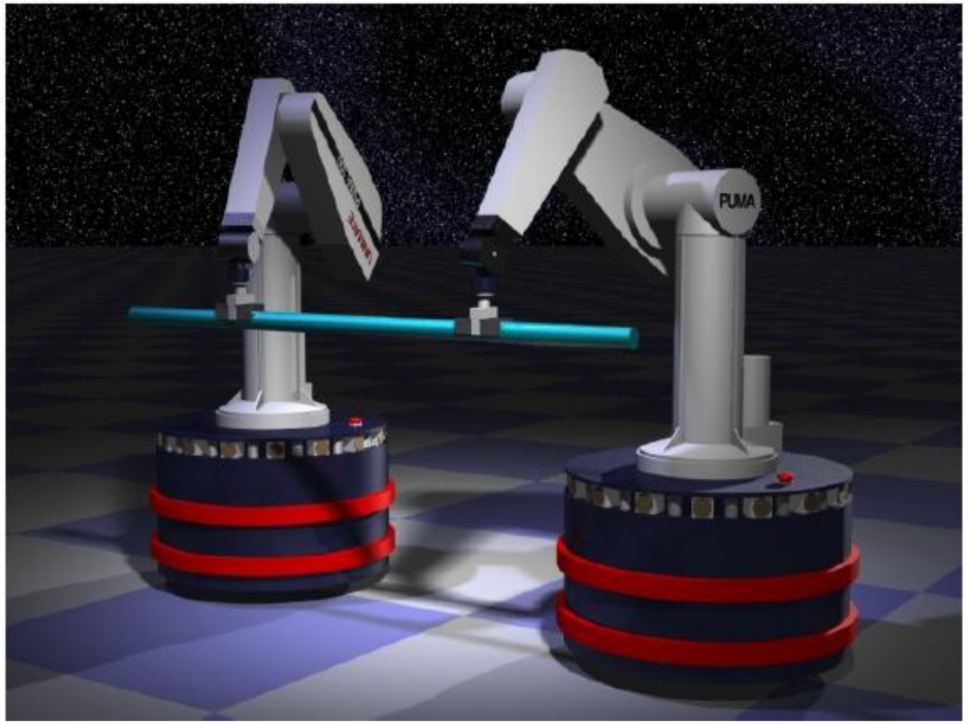


Cooperative mobile manipulator [5]

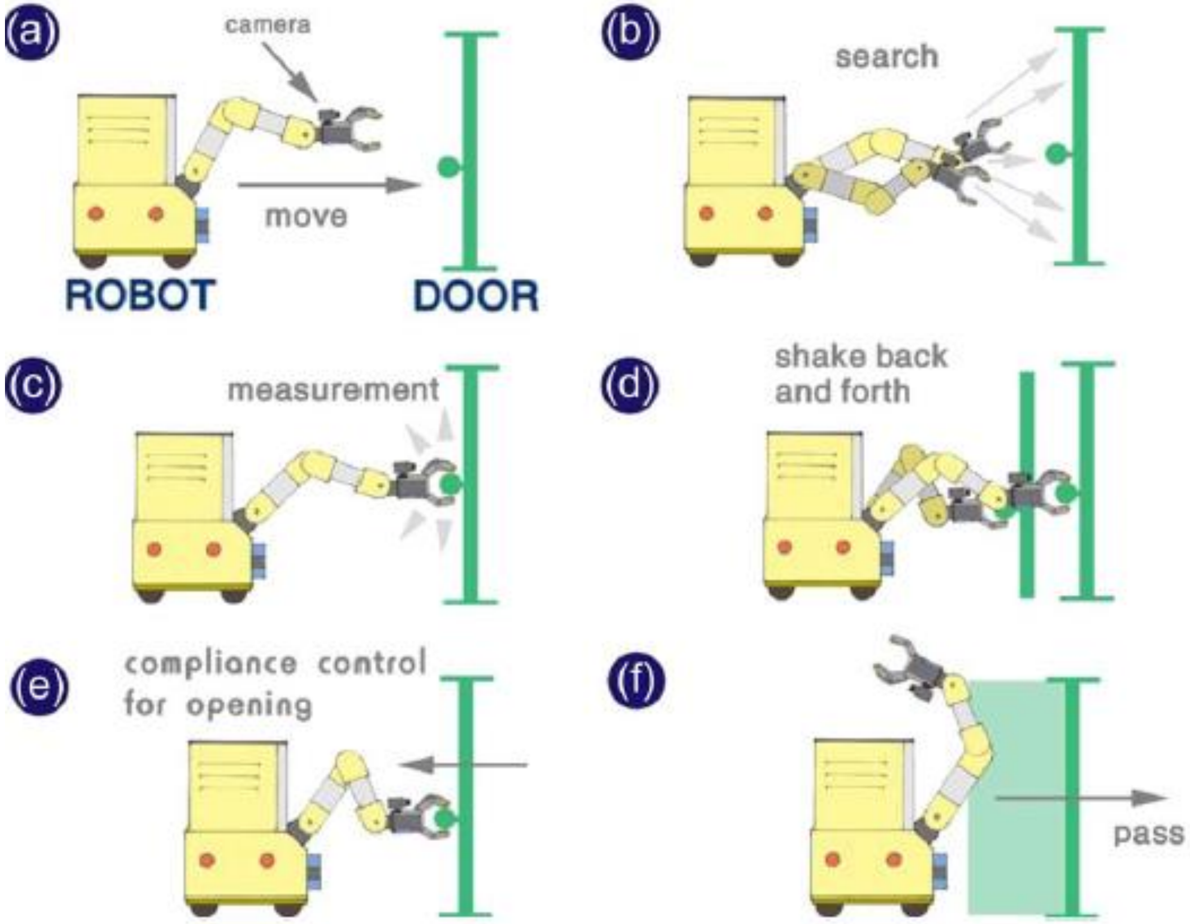
- How to minimized the internal forces?







Role assignment and coordination of heterogeneous robot components [6]



Role assignment of robot component

Phase	Action	HAND	ARM	MOBILE
A	Moving	Idle	Idle	
B	Searching	Idle	Position control	Idle
C	Measuring	Position/force control	Position control	Idle
D	Pulling	Grasp force control, Position measurement	Position control	Idle
E	Opening	Grasp force control	Position/force control	Idle
F	Passing	Position control	Position control	Position control

Reference

- [1] Hvilshøj, Mads, et al. "Autonomous industrial mobile manipulation (AIMM): past, present and future." *Industrial Robot: An International Journal* 39.2 (2012): 120-135.
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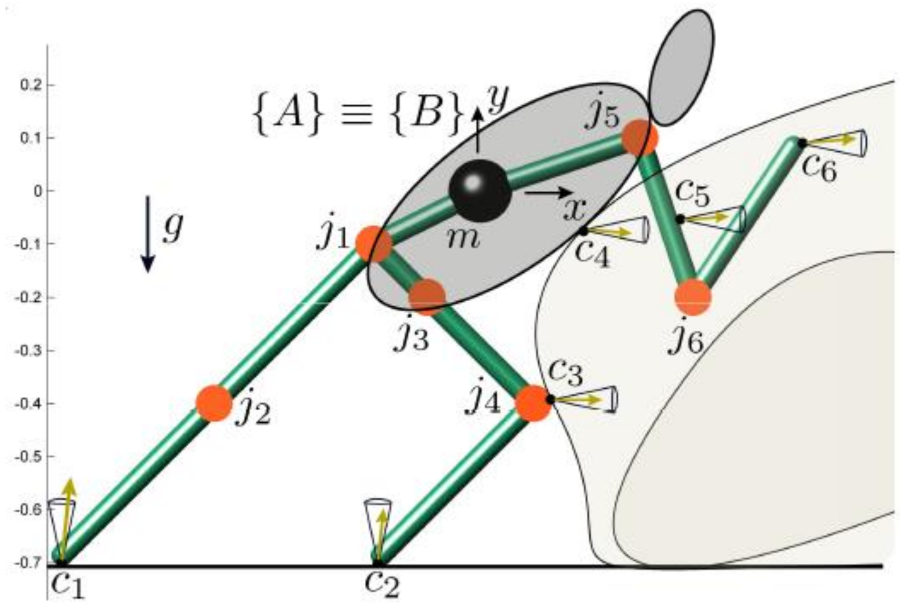
- [3] Huang, Q., Tanie, K., & Sugano, S. (2000). Coordinated motion planning for a mobile manipulator considering stability and manipulation. *The International Journal of Robotics Research*, *19*(8), 732-742.
- [4] Bayle, Bernard, J-Y. Fourquet, and Marc Renaud. "Manipulability of wheeled mobile manipulators: Application to motion generation." *The International Journal of Robotics Research* 22.7-8 (2003): 565-581.
- [5] Khatib, Oussama, et al. "Vehicle/arm coordination and multiple mobile manipulator decentralized cooperation." *Intelligent Robots and Systems' 96, IROS 96, Proceedings of the 1996 IEEE/RSJ International Conference on*. Vol. 2. IEEE, 1996.
- [6] Chung, Woojin, et al. "Door-opening control of a service robot using the multifingered robot hand." *IEEE Transactions on Industrial Electronics* 56.10 (2009): 3975-3984.

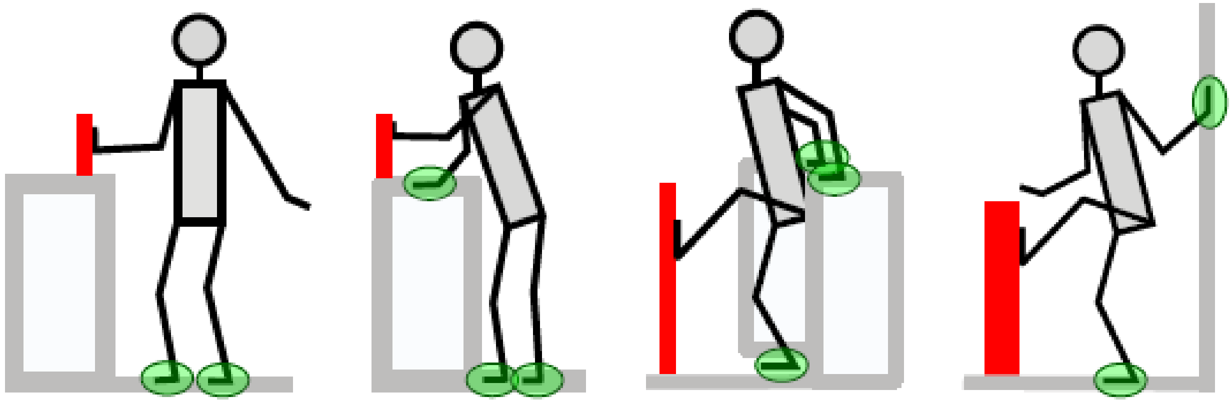
Loco-Manipulation

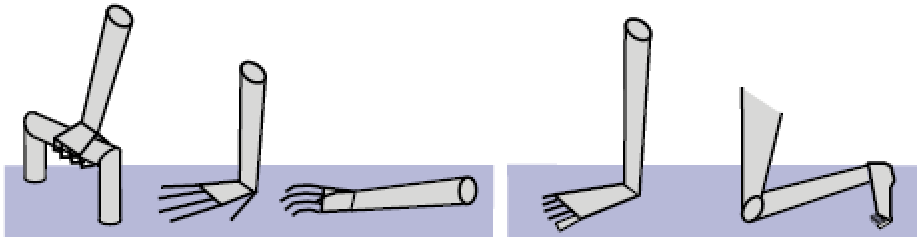
Overview

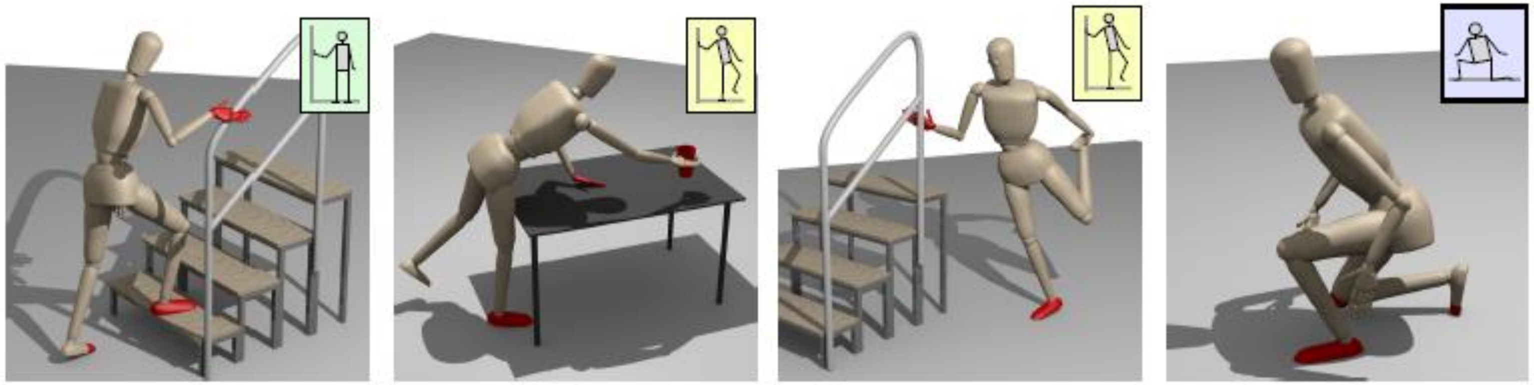
- Loco-manipulation
  - Affordance
- Loco-manipulation motion planning
  - Motion Primitives
- Motion skill transferring from humans to humanoid robots
  - Inverse optimal control

Typical loco-manipulation tasks





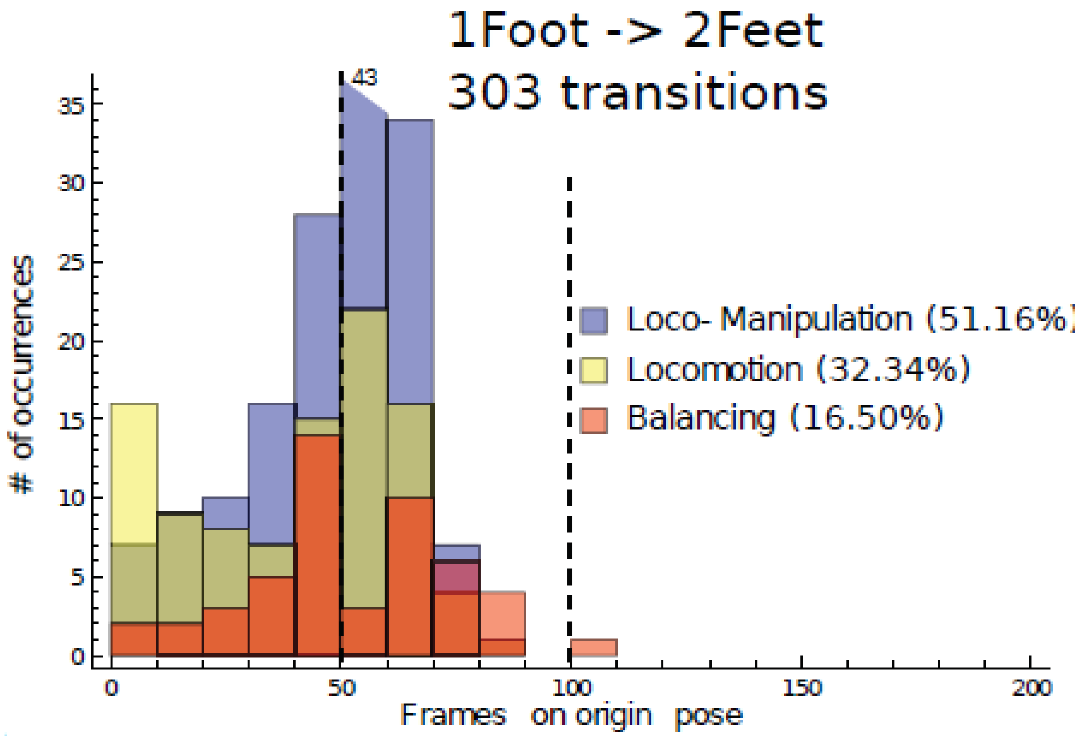




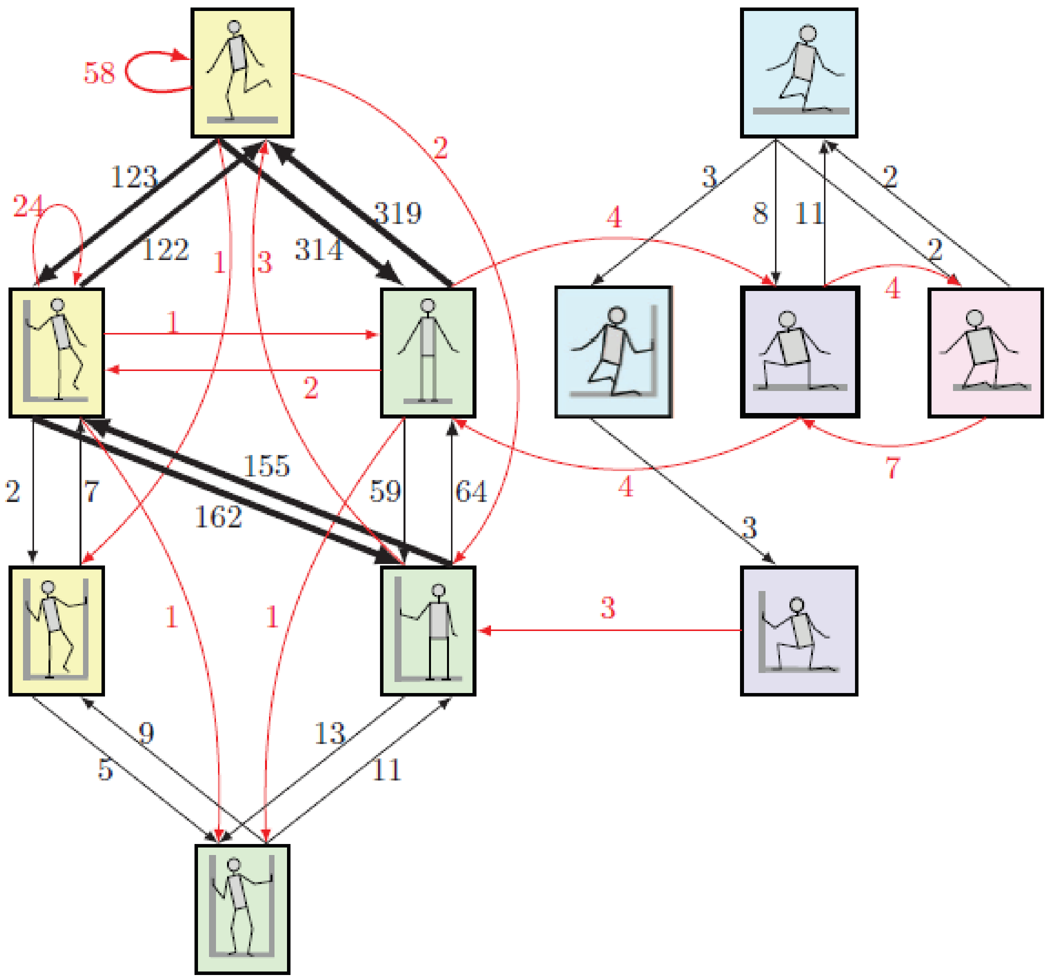
Support Pose Transitions [1]

Description
Locomotion tasks
downstairs w. handle
upstairs w. handle
upstairs, turn and downstairs
walks w. hand sup. to avoid obst.
walk over beam w. handle
Loco-Manipulation tasks
kick box with foot w. hand sup.
lean to place a cup on table
lean to pick a cup on table
lean to pick a cup in air
lean to wipe
bimanual pick and place
pick up from floor w. hand sup.
Balancing tasks
push rec. fr. behind push w. lean
push rec. fr. left push w. lean
inspect show sole w. sup.
rec. fr. lost balance on 1 leg
lean on table w. hands
Kneeling tasks
kneel down
kneel up

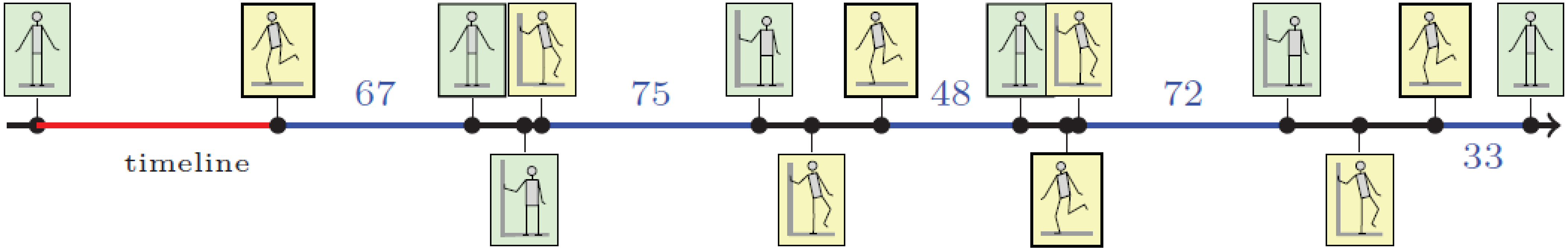
Pose transition time



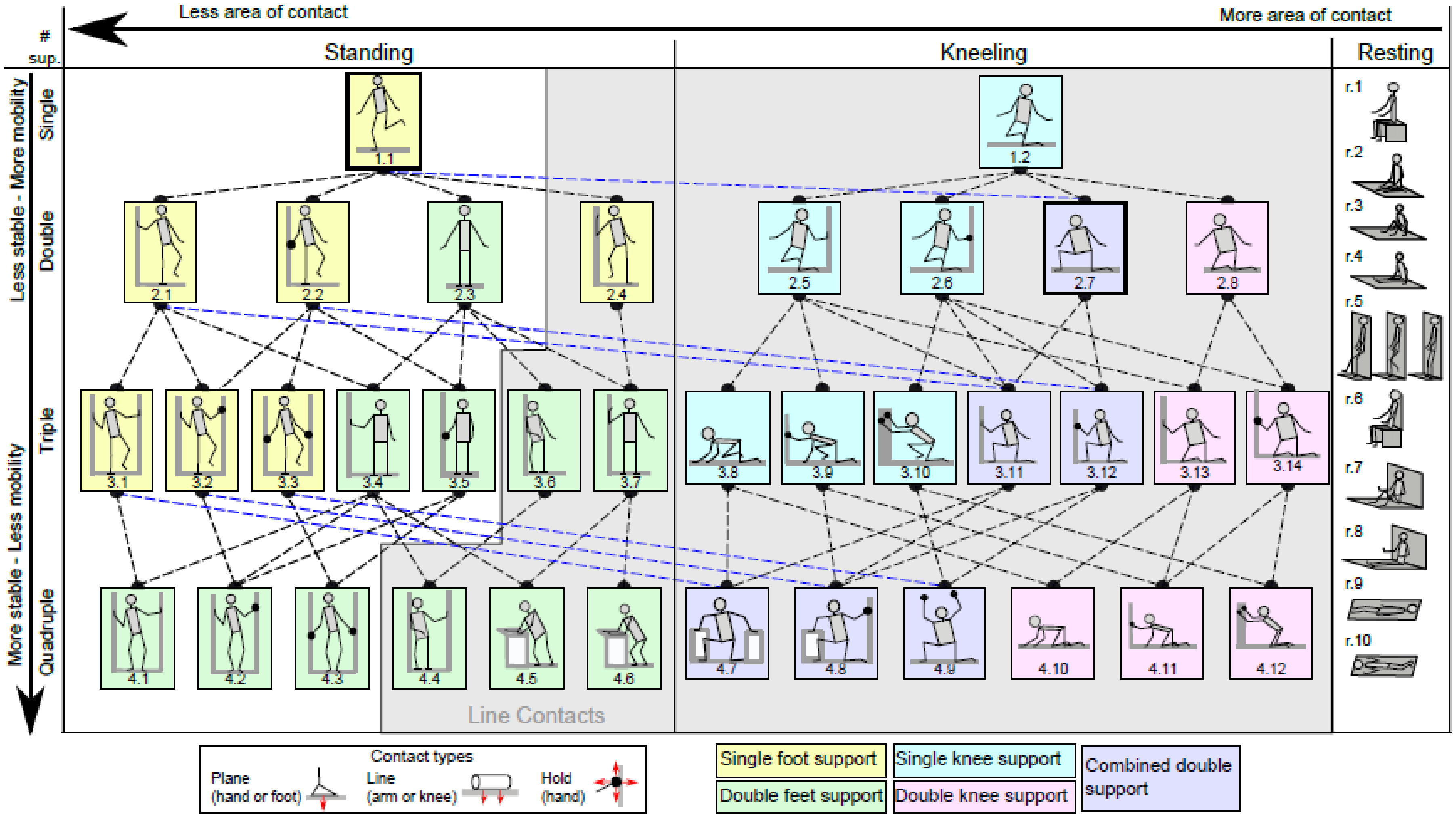
Pose transition probability



Motion segmentation



Taxonomy of support poses



Characteristics of support poses

- Number of contacts
  - Each support point creates a new closed kinematic loop
  - Motion planning complexity increases with number of supports
- Type of contact
  - 5 types = Hold, palm, arm, feet, and knee support
  - Selecting 36 out of 51 total combination → the more commonly used

Characteristics of support poses

- Stability
- Power grasps vs. resting poses
  - In addition to the standing and kneeling poses, there are 10 extra classes where there is contact with the torso (i.e., resting poses)
  - Transitions to and from resting poses are more complex (future work)

Hand grasping v.s. whole-body poses

- Similarity
  - Contact affordance matters
- Difference
  - Hand grasping can start with no contact with environment
  - Whole-body poses always start with at least one contact with environment (due to gravity)

Affordance of loco-manipulation [2]

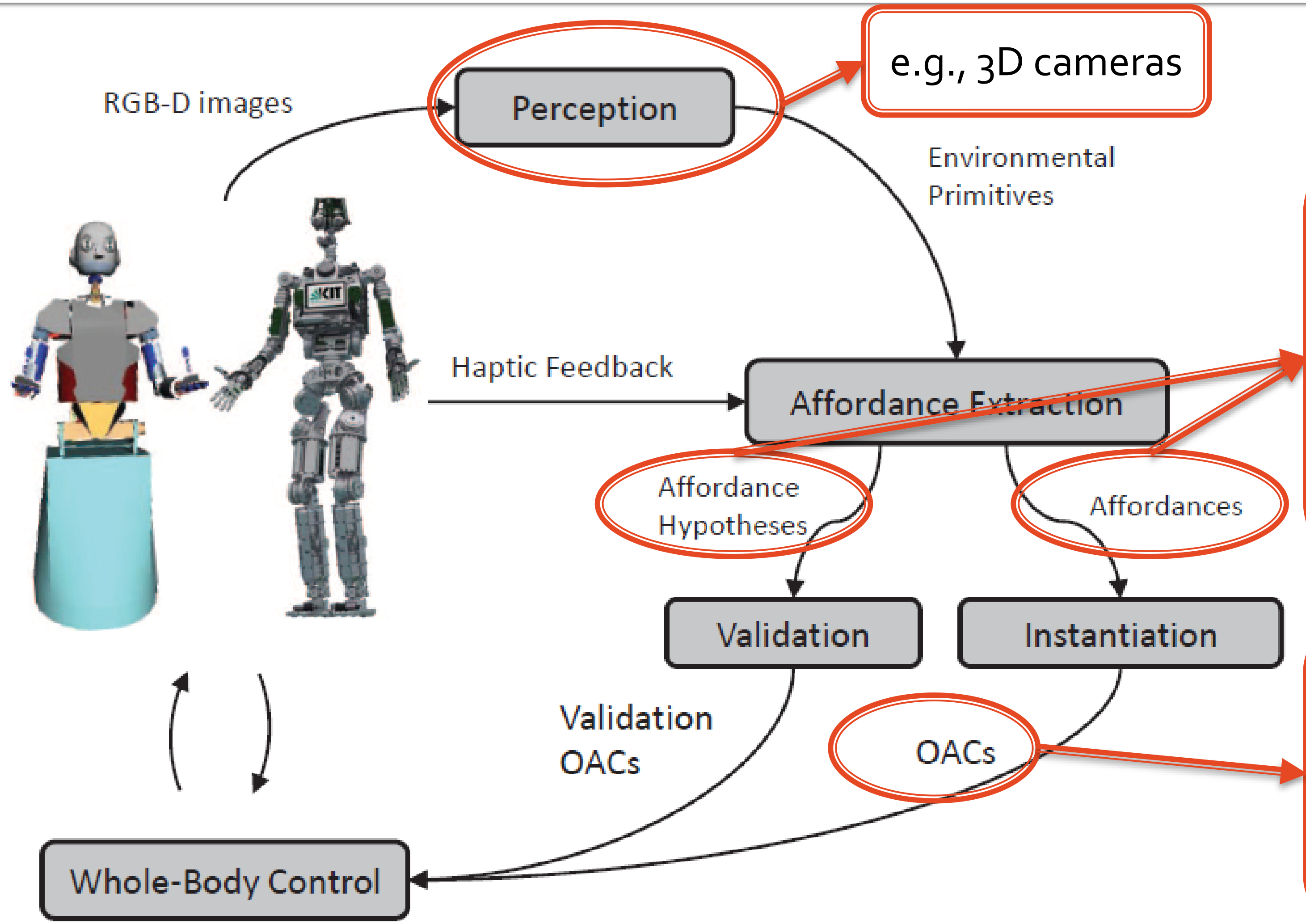
- Efficiently identify actions in unknown environment
  - Detect environment elements that allow interaction (e.g., doors, handles, handrails, stairs, etc.)
  - Utilize fixed environment structure for stable loco-manipulation



Affordance of loco-manipulation

- Loco-manipulation affordance
  - Actions that involve the whole body for stabilization, locomotion or manipulation
- Affordance validation
  - Assign whole-body affordance to environmental primitives, based on their shape, orientation and extent
  - Use perception feedback to validate the affordance hypotheses
  - Execute the task

Affordance of loco-manipulation



Affordance Validation

Depending on the measured **haptic feedback** and the resulting **level of confidence**, the affordance hypotheses become actual affordances and can be instantiated as Object Action Complexes (OACs)

Object Action Complexes

A framework that represents the sensorimotor experience and behaviors based on the coupling of objects and actions

Affordance extraction

Registered point cloud

↓

Segmentation

↓

Geometric primitives

↓

Affordance hypothesis

Geometric primitive extraction

Match segment s against geometric models, e.g., plane, cylinder, sphere

Before adding to the set of discovered primitives, the underlying point cloud is further partitioned in a clustering process based on Euclidean distances between points → Why?

Algorithm 1 primitiveExtraction($\mathcal{S}$, $\tau_{\min}$, $\tau_{\max}$)
Input Segmentation $\mathcal{S}$
Input Minimum and maximum point cloud sizes $\tau_{\min}$, $\tau_{\max}$
Output A set of environmental primitives Ψ

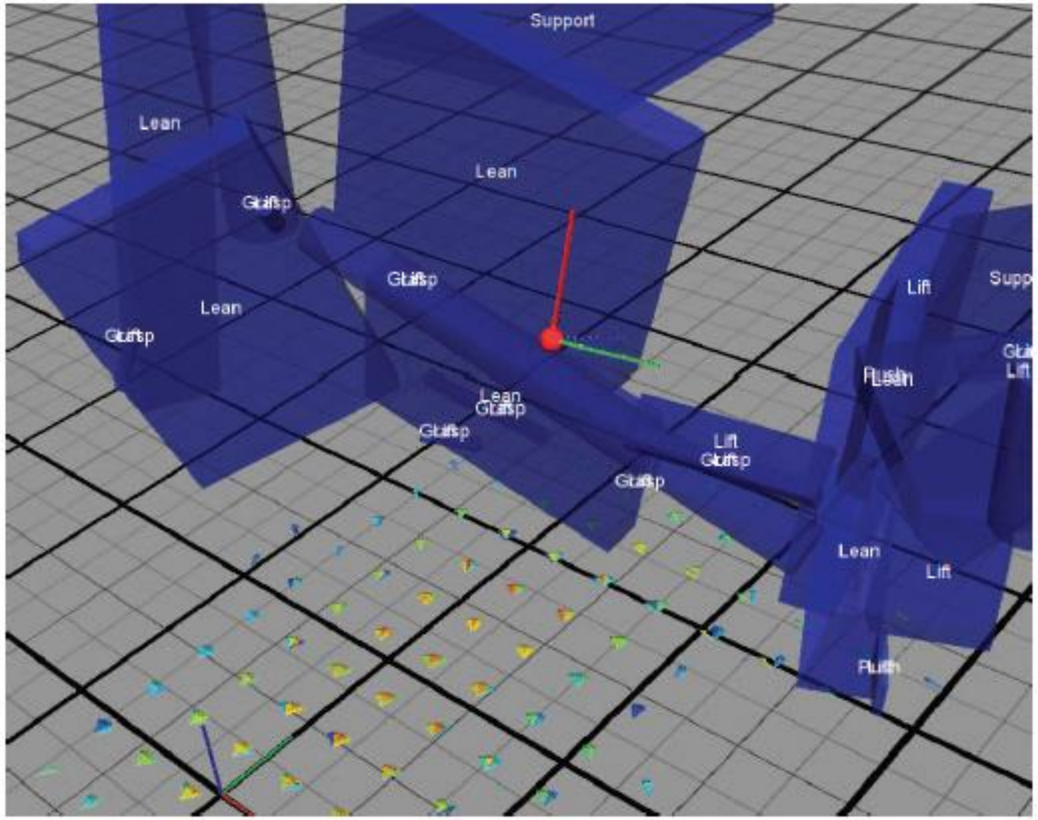
$\Psi \leftarrow \emptyset$
for each $s \in \mathcal{S}$ **do**
  $\mathcal{O} \leftarrow s$
  while $|\mathcal{O}| \in (\tau_{\min}, \tau_{\max})$ **do**
    $\psi_{\text{plane}} \leftarrow \text{RANSAC}_{\text{plane}}(\mathcal{O})$
    $\psi_{\text{cylinder}} \leftarrow \text{RANSAC}_{\text{cylinder}}(\mathcal{O})$
    $\psi_{\text{sphere}} \leftarrow \text{RANSAC}_{\text{sphere}}(\mathcal{O})$
    $\psi_{\text{best}} \leftarrow \arg\max_{\psi \in \{\psi_{\text{plane}}, \psi_{\text{cylinder}}, \psi_{\text{sphere}}\}} |\mathcal{P}_{\psi}|$
    if $\psi_{\text{best}} = \emptyset$ **then**
      break
    $\Psi_{\text{new}} \leftarrow \text{euclideanClustering}(\mathcal{P}_{\psi_{\text{best}}})$
    $\Psi \leftarrow \Psi \cup \Psi_{\text{new}}$
    $\mathcal{O} \leftarrow \mathcal{O} \setminus \mathcal{P}_{\psi_{\text{best}}}$
return Ψ

Assign Affordance hypothesis

Affordance	Shape	Parameters	Conditions[1,2]	Valid.
Support (S)	Planar	Normal n Area a	$n \uparrow z_{world}$ $a \geq \lambda_1$	(1a)
Lean (Ln)	Planar	Normal n Area a	$n \perp z_{world}$ $a \geq \lambda_2$	(1a)
Grasp (G)	Planar	Normal n Area a	$a \in [\lambda_3, \lambda_4]$	(3)
	Cylindrical	Radius r Direction d	$r \in [\lambda_5, \lambda_6]$ $\|d\| \leq \lambda_7$	
	Spherical	Radius r	$r \in [\lambda_8, \lambda_9]$	
Hold (H)	Cylindrical	Radius r Direction d	$r \in [\lambda_{10}, \lambda_{11}]$ $\|d\| \geq \lambda_{12}$	(2a)
Push (P)	Planar	Normal n Area a	$n \perp z_{world}$ $a \leq \lambda_{13}$	(1b)
Lift (Lf)	Planar	Normal n Area a	$a \leq \lambda_{15}$	(2b)
	Cylindrical	Radius r Direction d	$r \leq \lambda_{15}$ $\|d\| \leq \lambda_{16}$	
	Spherical	Radius r	$r \leq \lambda_{17}$	

Grasp point and robot location

- Compute possible grasp points
- Computer robot location through inverted reachability
- Additional information that helps with affordance validation

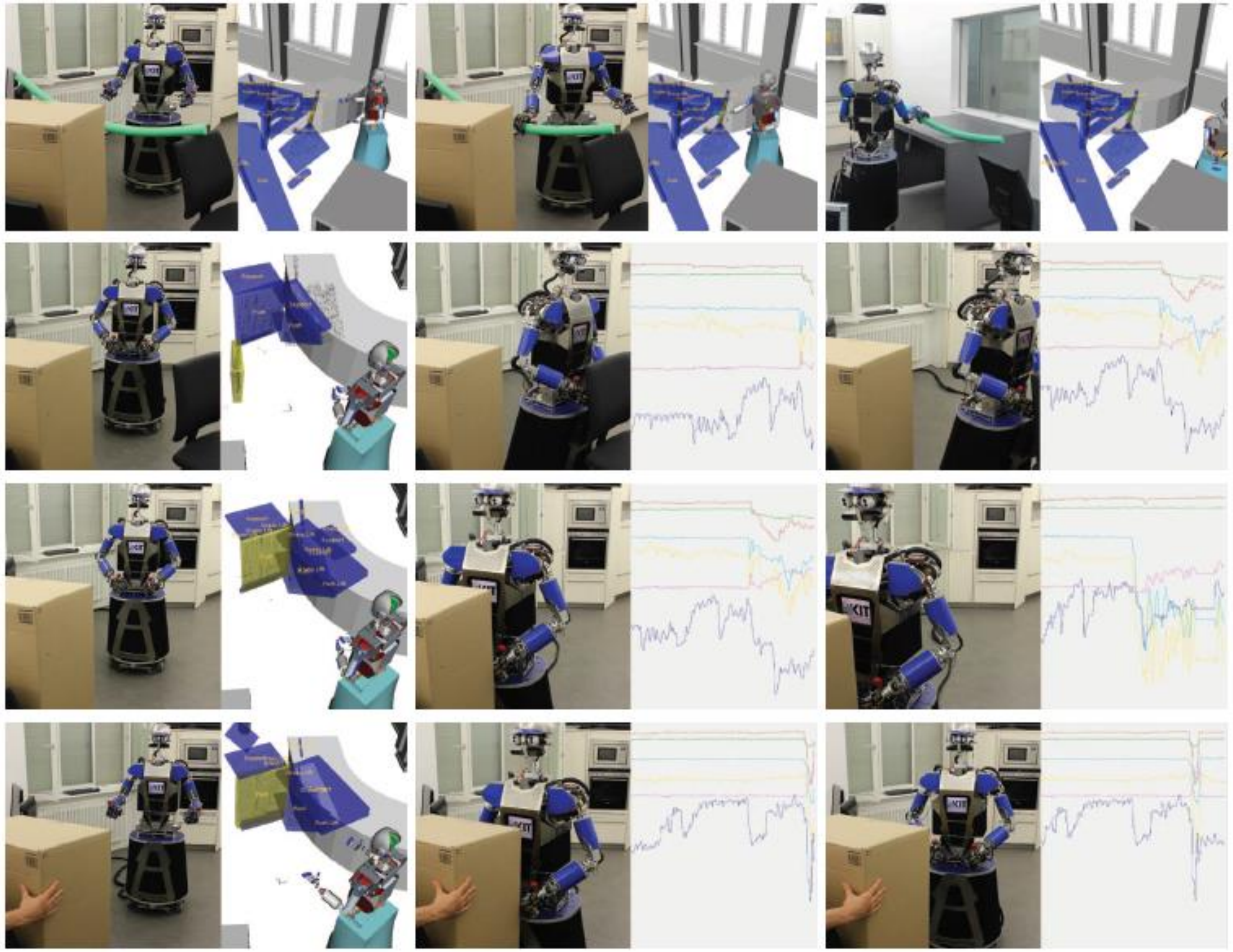


Experimental affordance validation

- Touch
  - Touch the primitive and exert forces along the primitive's normal direction. Compare the resistance force against threshold
- Grasp
  - Grasp the primitive and exert forces along the expected direction of utilization. Compare the resistance force against threshold
- Push
  - Push the primitive and perceive the caused effect

Experimental affordance validation

- Pipe
  - Grasp + lift
- Chair
  - Push
- Box 1
  - Can be pushed
- Box 2
  - Cannot be pushed



Reference

- [1] Asfour, Tamim, et al. "On the Dualities Between Grasping and Whole-Body Loco-Manipulation Tasks." *Robotics Research*. Springer, Cham, 2018. 305-322.
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