Humanoid robots - Social HRI II Motion planning for HRI and humanoids

Doc. Mgr. Matěj Hoffmann, Ph.D.

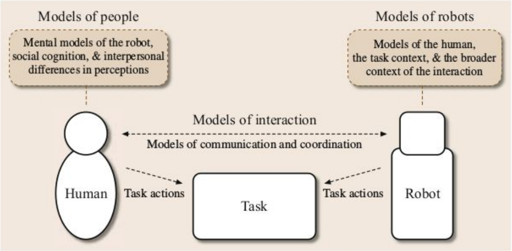
Outline

1. Spatial interaction in HRI - proxemics
2. Motion planning for human-populated environments
3. Motion planning for humanoids

Action and perception for social HRI

Perceive / display.

- verbal interaction - speech
- nonverbal interaction
    - gaze
    - facial expressions
    - gesture
    - touch
    - posture
    - …
- **location - proxemics…**
- emotion



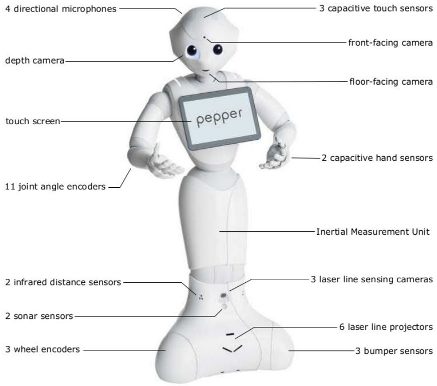


Fig 3.3 in Bartneck, C., Belpaeme, T., Eyssel, F., Kanda, T., Keijsers, M., & Šabanović, S. (2020). *Human-Robot Interaction: An Introduction*. Cambridge University Press.

Proxemics

- How people take up space in relation to others and how spatial positioning influences attitudes, behaviors, and interpersonal interaction. (Bartneck et al. 2020, Ch. 5)
- Culture-dependent.

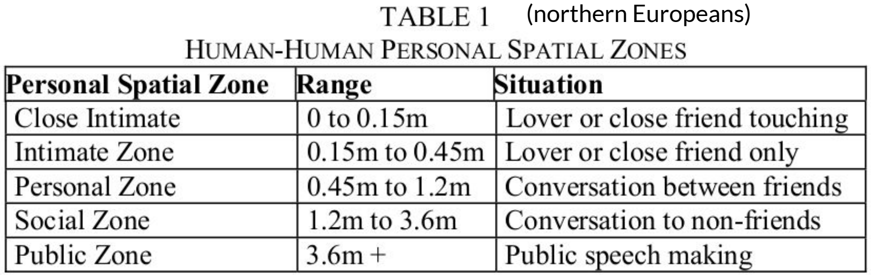


TABLE 1 (northern Europeans)

HUMAN-HUMAN PERSONAL SPATIAL ZONES

Personal Spatial Zone	Range	Situation
Close Intimate	0 to 0.15m	Lover or close friend touching
Intimate Zone	0.15m to 0.45m	Lover or close friend only
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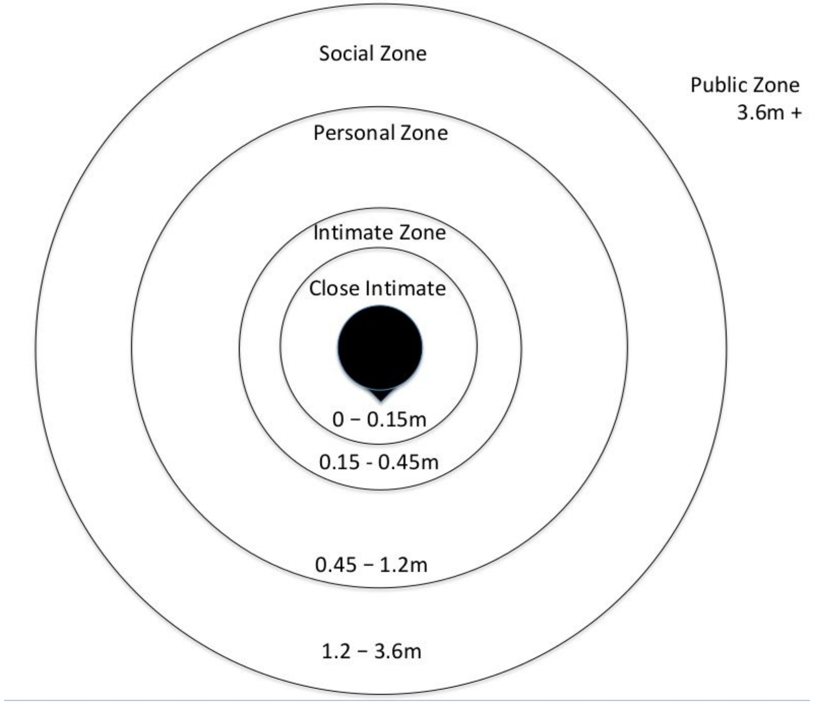
Social Zone	1.2m to 3.6m	Conversation to non-friends
Public Zone	3.6m +	Public speech making



Human-Human Personal Space Zones
(Hall 1966; Lamberts 2004)

Spatial interactions in HRI

- Mobile robots and obstacle avoidance.
  - Corridor scenario (Bartneck et al. 2020, 5.2.2).
    - Robot and human walking against each other in a corridor. If robot treats human as an obstacle, it may avoid it in the last moment. Very unnatural!
  - Most mapping techniques for robots only provide geometrical maps, where people are considered obstacles. They do not contain information on which direction people are facing, if they are having a conversation or just standing close to each other, or how people are moving.

Ch. 5 in Bartneck, C., Belpaeme, T., Eyssel, F., Kanda, T., Keijsers, M., & Šabanović, S. (2020). *Human-Robot Interaction: An Introduction*. Cambridge University Press.

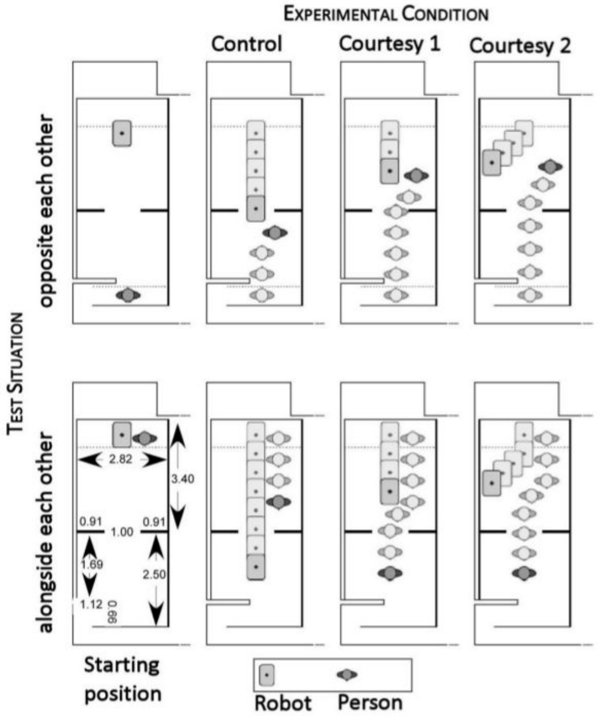


Fig. 1. Test situations: (a) Control condition (i.e., no courtesy cues), (b) Courtesy 1 condition (i.e., appearing to grant the right of way by stopping), and (c) Courtesy 2 condition (i.e., appearing to grant the right of way by stopping and moving out of the way). Numbers reflect the spatial distances in meters.

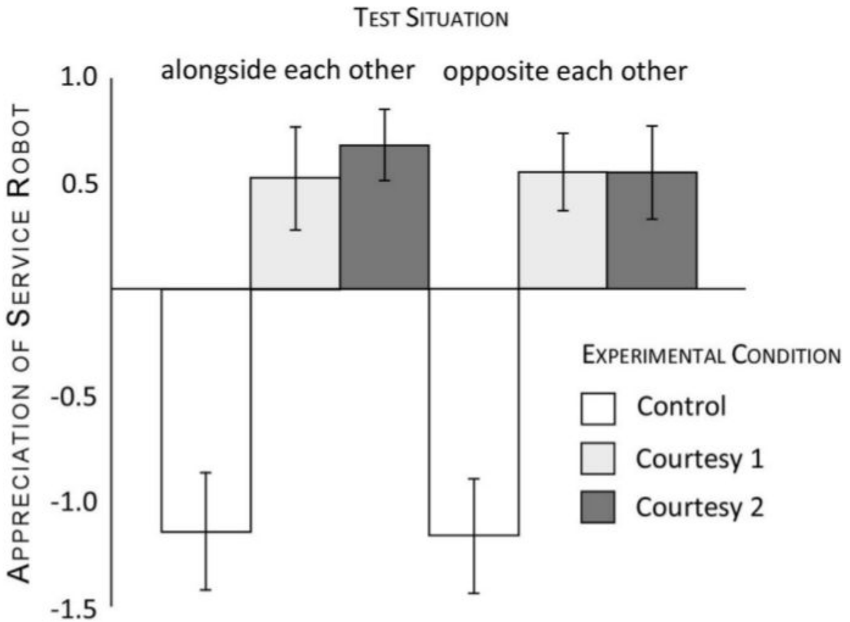


Fig. 2. Appreciation of a service robot (in mean z-values and 95% confidence intervals) that exhibits no courtesy cues (i.e., Control condition), that appears to grant the right of way by stopping (i.e., Courtesy 1 condition), or that appears to grant the right of way by stopping and moving out of the way (i.e., Courtesy 2 condition).

Kaiser, F. G., Glatte, K., & Lauckner, M. (2019). How to make nonhumanoid mobile robots more likable: Employing kinesic courtesy cues to promote appreciation. *Applied ergonomics*, *78*, 70-75.

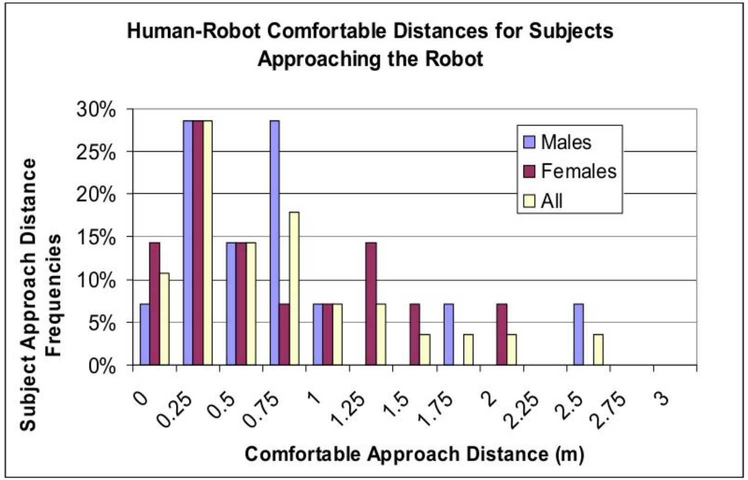
Factors that may affect “comfortable” distance

- who is approaching whom
- robot look… / level of anthropomorphism
- robot size
- personality traits (human)
- context
  - task - e.g. handover
  - communication / perception

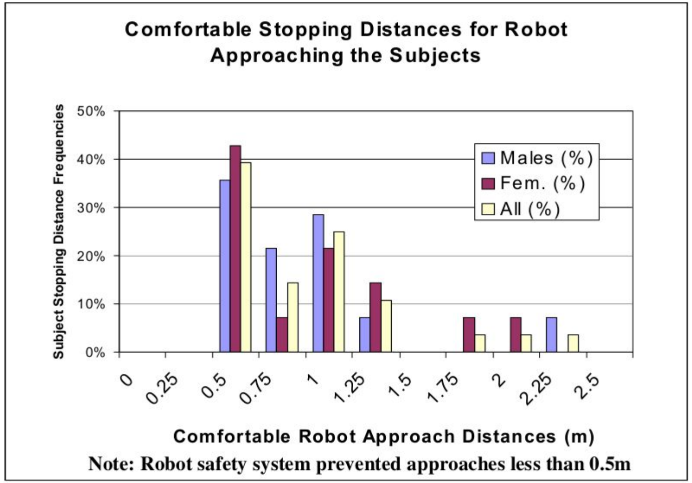
See also

- Table 2.2 in Rojík, A. (2021), 'Personal Spatial Zones in Human-Robot Interaction Scenarios', Bachelor thesis, Faculty of Electrical Engineering, Czech Technical University in Prague. [link to thesis page][pdf]

Robot with mechanistic appearance



Human-Robot Comfortable Distances for Subjects Approaching the Robot



Comfortable Stopping Distances for Robot Approaching the Subjects

Note: Robot safety system prevented approaches less than 0.5m

- 40% of people came very close to the robot; why?
- Did not treat the robot as a social entity.

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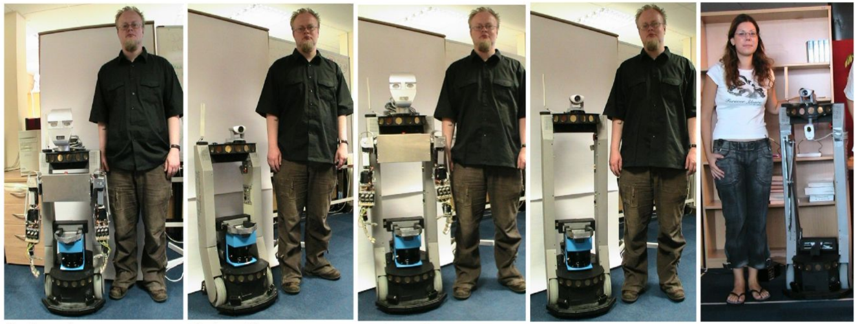
Public Zone	3.6m +	Public speech making

Walters, M. L., Dautenhahn, K., Te Boekhorst, R., Koay, K. L., Kaouri, C., Woods, S., ... & Werry, I. (2005, August). The influence of subjects' personality traits on personal spatial zones in a human-robot interaction experiment. In *ROMAN 2005. IEEE International Workshop on Robot and Human Interactive Communication, 2005.* (pp. 347-352). IEEE.

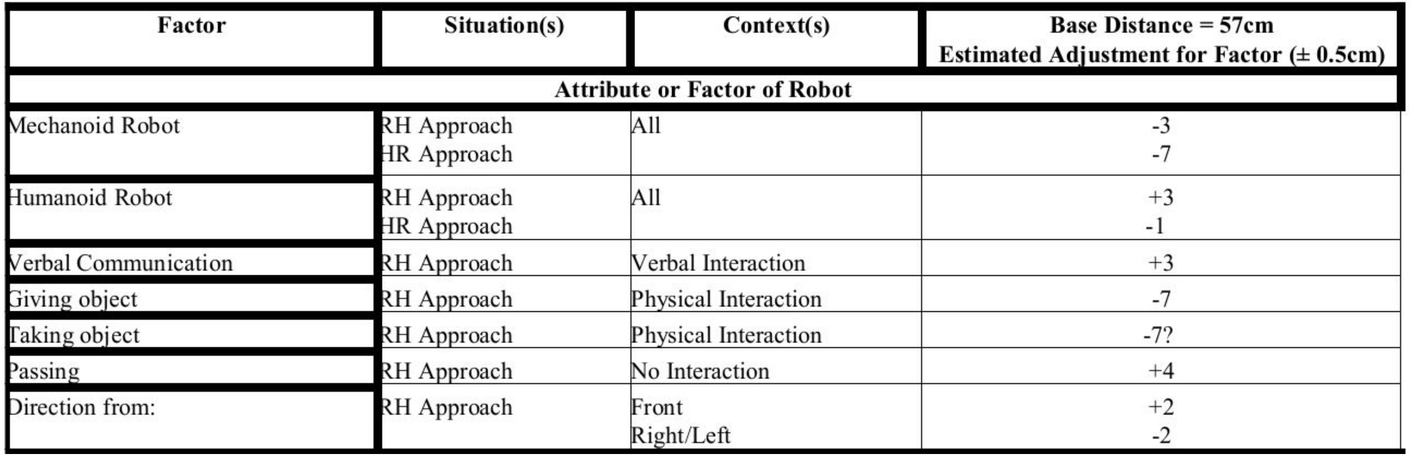
Modulators of interpersonal distance in HRI



Robot A *Robot B* *Robot C* *Robot D* *Robot E*

Figure 1 The PeopleBot™ Robots used for the large HRI Studies: A) Short Mechanoid, B) Short Humanoid, C) Tall Mechanoid, D) Tall Humanoid. and E) the Mechanoid robot used for the robot voice style trial.

Walters, M. L., Dautenhahn, K., Te Boekhorst, R., Koay, K. L., Syrdal, D. S., & Nehaniv, C. L. (2009). An empirical framework for human-robot proxemics. *Procs of new frontiers in human-robot interaction*.



Factor	**Situation(s)**	**Context(s)**	**Base Distance = 57cm Estimated Adjustment for Factor (± 0.5cm)**
Attribute or Factor of Robot			
Mechanoid Robot	RH Approach HR Approach	All	-3 -7
Humanoid Robot	RH Approach HR Approach	All	+3 -1
Verbal Communication	RH Approach	Verbal Interaction	+3
Giving object	RH Approach	Physical Interaction	-7
Taking object	RH Approach	Physical Interaction	-7?
Passing	RH Approach	No Interaction	+4
Direction from:	RH Approach	Front Right/Left	+2 -2

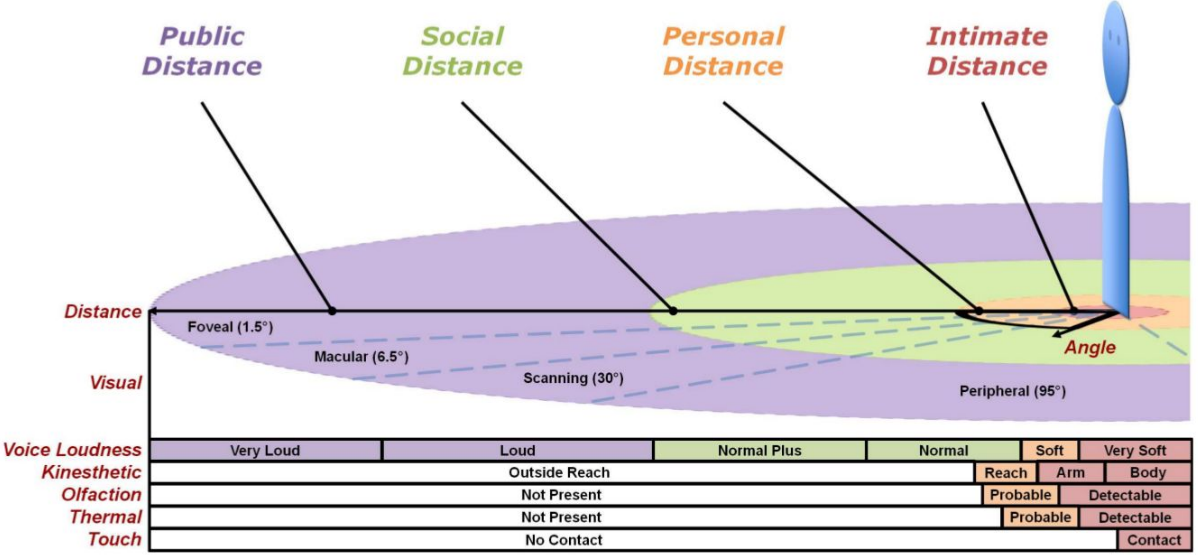


Fig. 1. Relationships between interpersonal pose and sensory experiences [3, 2, 11].

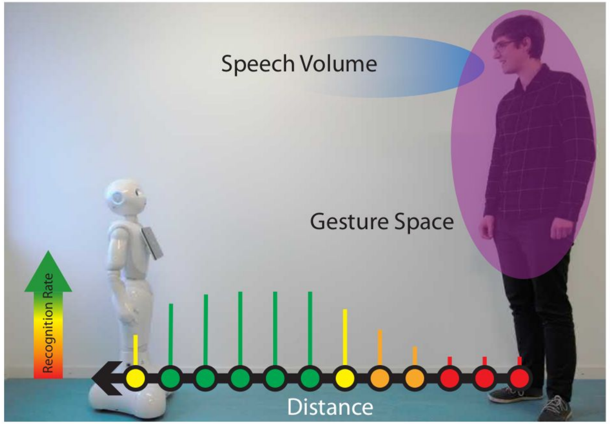
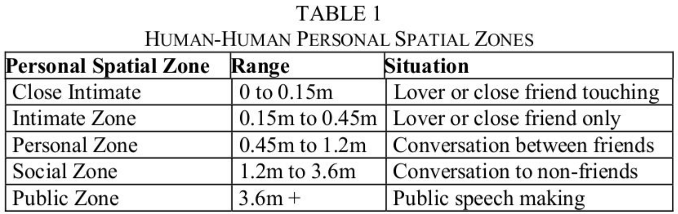


Fig. 5.6 in Bartneck, C., Belpaeme, T., Eyssel, F., Kanda, T., Keijsers, M., & Šabanović, S. (2020). *Human-Robot Interaction: An Introduction*. Cambridge University Press.

Mead, R., & Matarić, M. J. (2016). Perceptual models of human-robot proxemics. In *Experimental robotics* (pp. 261-276). Springer, Cham.



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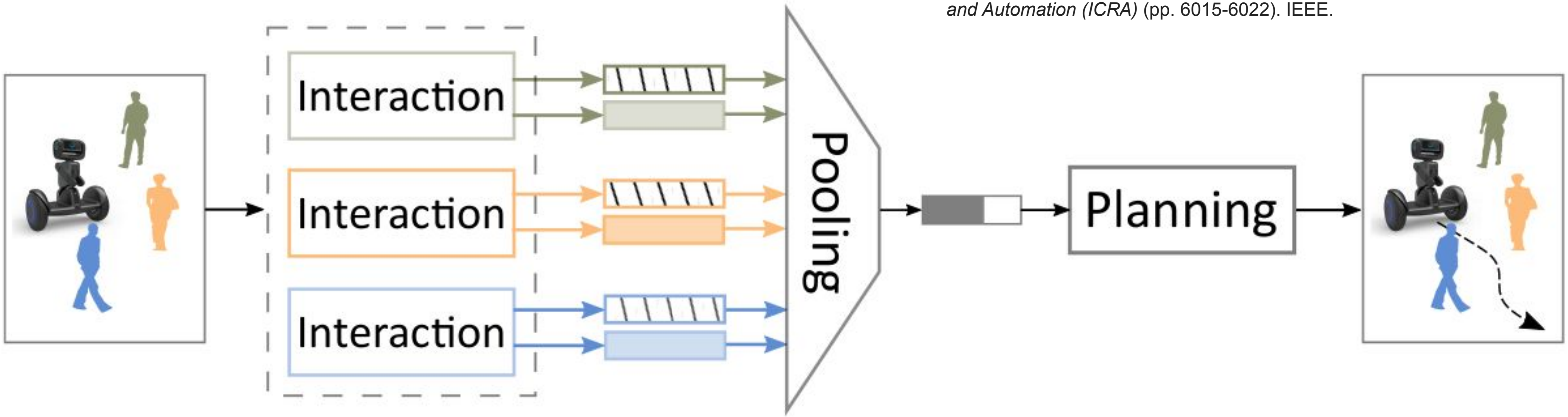
Robot in a crowd

Chen, C., Liu, Y., Kreiss, S., & Alahi, A. (2019, May). Crowd-robot interaction: Crowd-aware robot navigation with attention-based deep reinforcement learning. In *2019 International Conference on Robotics and Automation (ICRA)* (pp. 6015-6022). IEEE.



Crowdbot.eu

http://u4y.fed.myftpupload.com/data-sets-softwares/

Human or robot spatial zones?

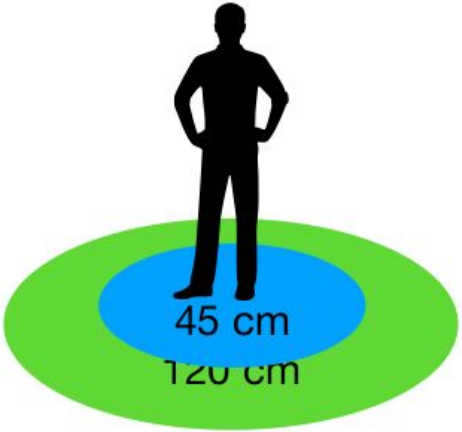
- Most literature is concerned with the *comfort of the human*, i.e. robots not inappropriately invading human spatial zones.
- Do people also care about the robot’s personal space?
  - Do they expect it to scale with the robot size?
  - Do they expect the robot to protect it / signal that it is not comfortable with his space being invaded?

Robot personal space

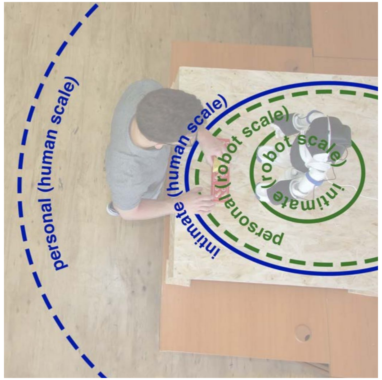
https://youtu.be/gvICAkfK2CA

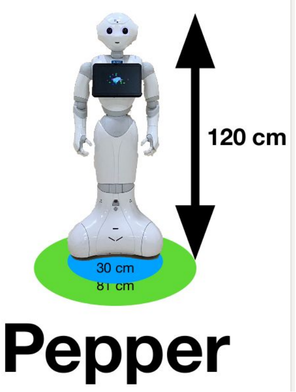
Lehmann, H.; Rojík, A. & Hoffmann, M. (2020), Should a small robot have a small personal space? Investigating personal spatial zones and proxemic behavior in human-robot interaction, *in* 'CognitIve RobotiCs for intEraction (CIRCE) Workshop at IEEE International Conference On Robot and Human Interactive Communication (RO-MAN)'.

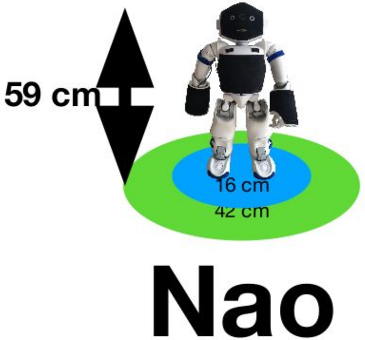
Scaling of personal space to robot size?



intimate space
personal space

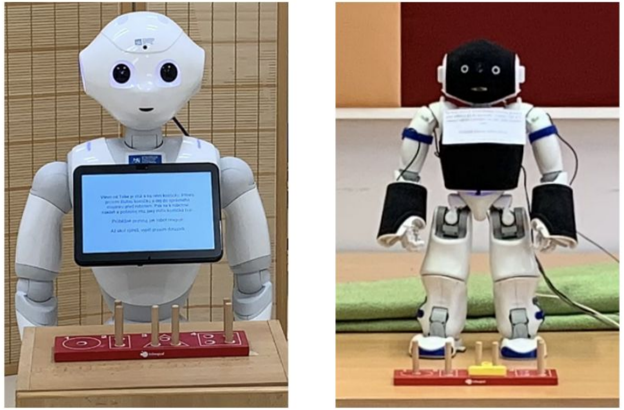






Rojík, A. (2021), 'Personal Spatial Zones in Human-Robot Interaction Scenarios', Bachelor thesis, Faculty of Electrical Engineering, Czech Technical University in Prague. [link to thesis page][pdf]

Experimental setup



Experiment	Robot	Condition	Gaze distance	Lean-back distance	Differential lean-back distance
NAO-1	Nao	Robot Human	0.42 m 1.2 m	0.16 m 0.45 m	-
Pepper	Pepper	Robot Human	0.81 m 1.2 m	-	0.3 m—0.1 m 0.45 m—0.1 m
NAO-2	Nao	Robot Human	0.42 m 1.2 m	-	0.16 m—0.1 m 0.45 m—0.1 m

Table 4.2: Triggering distances for different conditions and robots. Control condition is omitted as it is random.

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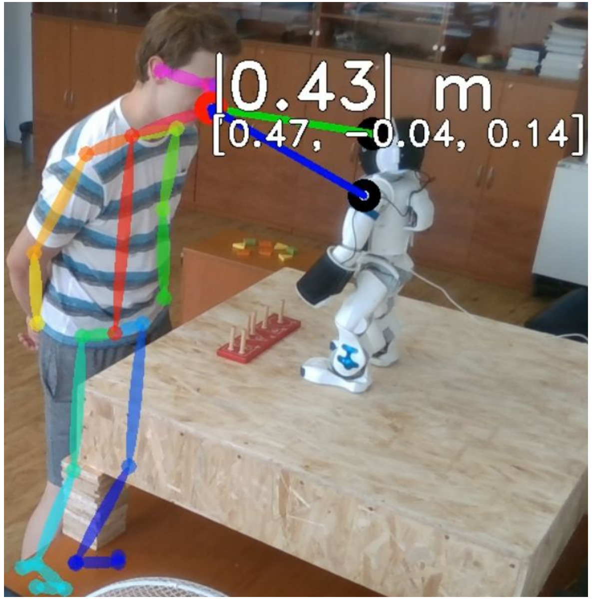
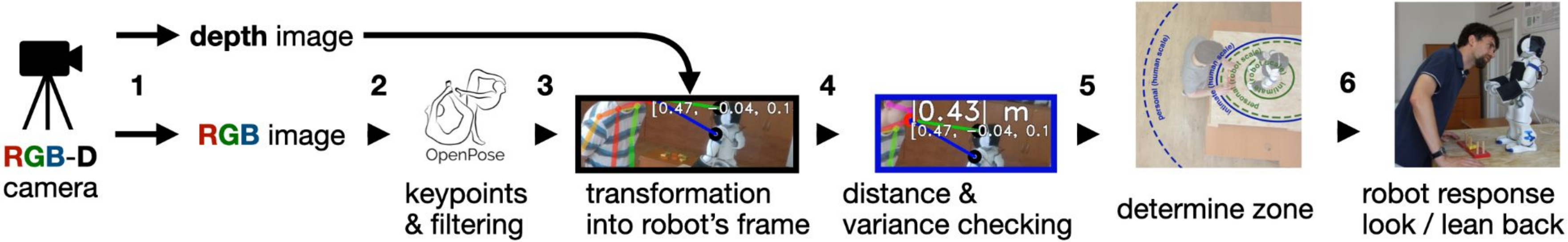
Perceiving the distance





depth image

1

RGB-D camera

RGB image

2

OpenPose

keypoints & filtering

3

transformation into robot's frame

4

distance & variance checking

5

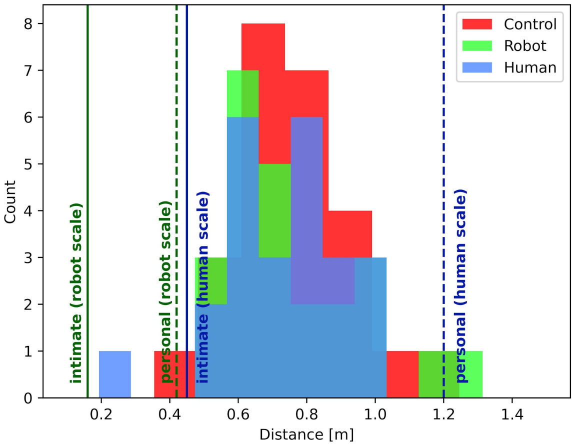
determine zone

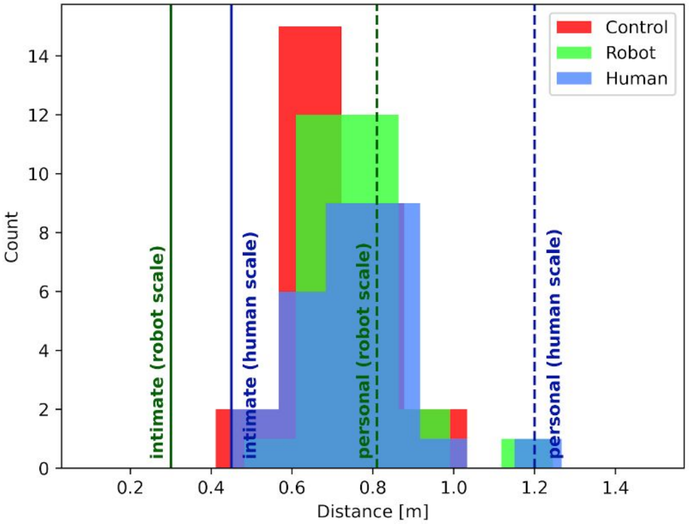
6

robot response look / lean back

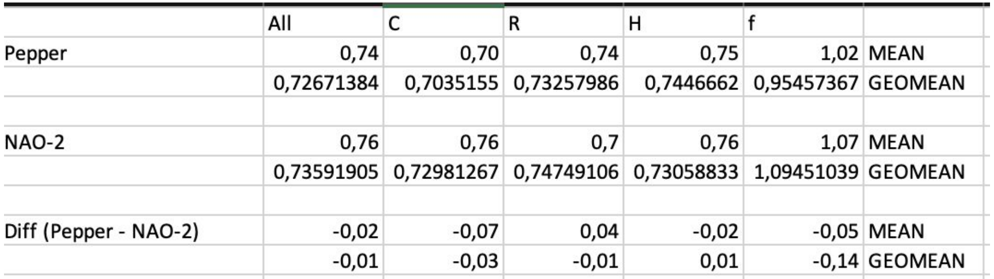
Lehmann, H.; Rojík, A. & Hoffmann, M. (2020), Should a small robot have a small personal space? Investigating personal spatial zones and proxemic behavior in human-robot interaction, *in* 'CognitIve RobotiCs for intEraction (CIRCE) Workshop at IEEE International Conference On Robot and Human Interactive Communication (RO-MAN)'.

Results - distance from the robot where people stopped


Nao


Pepper

- people do not scale robot personal space with its size



	All	C	R	H	f	
Pepper	0,74	0,70	0,74	0,75	1,02	MEAN
	0,72671384	0,7035155	0,73257986	0,7446662	0,95457367	GEOMEAN
NAO-2	0,76	0,76	0,7	0,76	1,07	MEAN
	0,73591905	0,72981267	0,74749106	0,73058833	1,09451039	GEOMEAN
Diff (Pepper - NAO-2)	-0,02	-0,07	0,04	-0,02	-0,05	MEAN
	-0,01	-0,03	-0,01	0,01	-0,14	GEOMEAN

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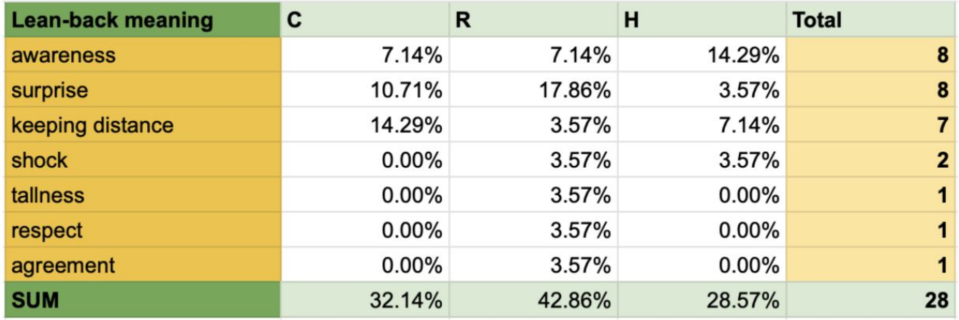
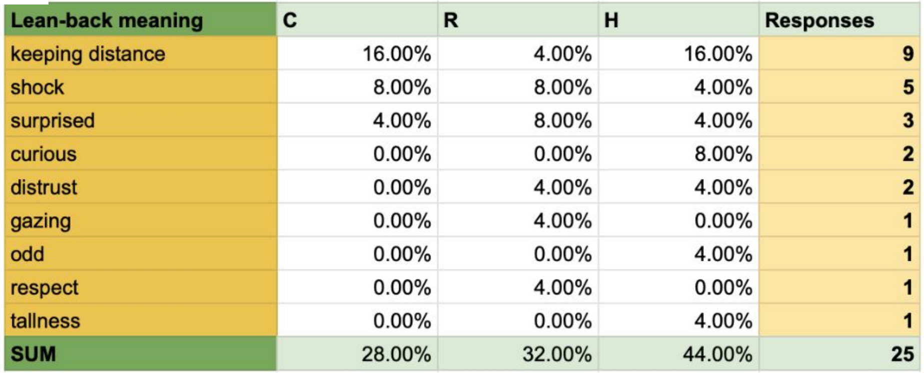
Leaning back to signal intrusion of personal space



Lean-back meaning	C	R	H	Total
awareness	7.14%	7.14%	14.29%	**8**
surprise	10.71%	17.86%	3.57%	**8**
keeping distance	14.29%	3.57%	7.14%	**7**
shock	0.00%	3.57%	3.57%	**2**
tallness	0.00%	3.57%	0.00%	**1**
respect	0.00%	3.57%	0.00%	**1**
agreement	0.00%	3.57%	0.00%	**1**
SUM	32.14%	42.86%	28.57%	**28**

Table 7.9: Participants interpretation of the Nao's lean-back behavior.

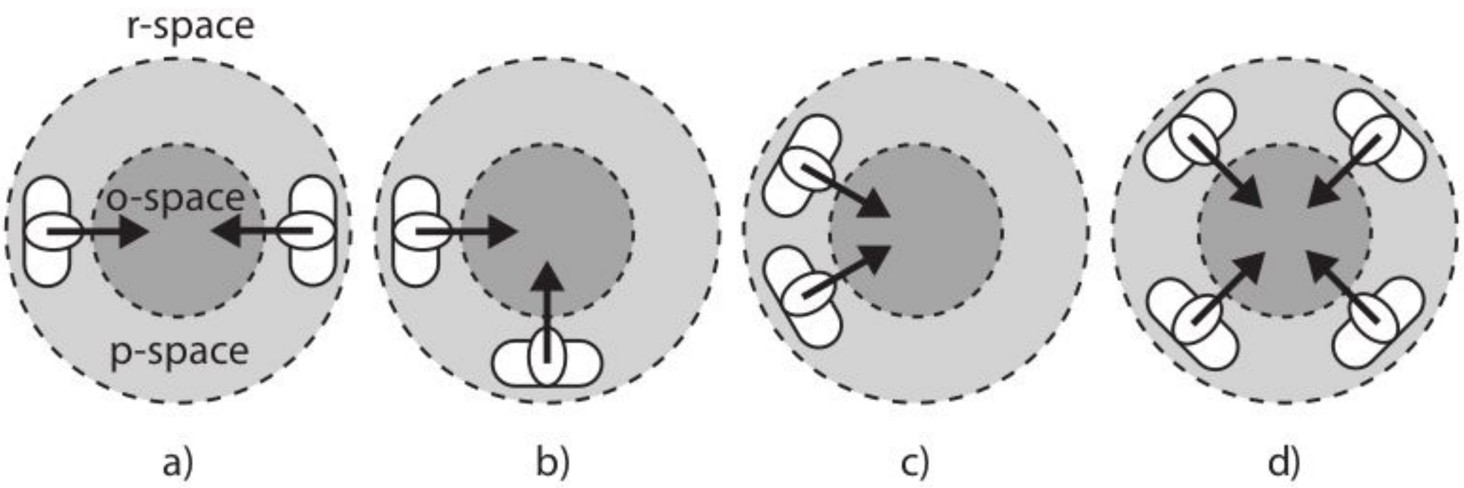


Lean-back meaning	C	R	H	Responses
keeping distance	16.00%	4.00%	16.00%	**9**
shock	8.00%	8.00%	4.00%	**5**
surprised	4.00%	8.00%	4.00%	**3**
curious	0.00%	0.00%	8.00%	**2**
distrust	0.00%	4.00%	4.00%	**2**
gazing	0.00%	4.00%	0.00%	**1**
odd	0.00%	0.00%	4.00%	**1**
respect	0.00%	4.00%	0.00%	**1**
tallness	0.00%	0.00%	4.00%	**1**
SUM	28.00%	32.00%	44.00%	**25**

Table 7.4: Participants interpretation of the Pepper's lean-back behavior.

Group spatial interaction dynamics

Figure 5.4 Kendon's F-formations come in several variants, all of which include the components of o-, p-, and r-space, namely (a) the face-to-face, (b) the L, (c) the side-by-side, and (d) the circular formation.



Bartneck, C., Belpaeme, T., Eyssel, F., Kanda, T., Keijsers, M., & Šabanović, S. (2020). *Human-Robot Interaction: An Introduction*. Cambridge University Press.

Distance in sHRI and pHRI

Expectable motion unit

Kirschner, R. J., Mayer, H., Burr, L., Mansfeld, N., Abdolshah, S., & Haddadin, S. (2022). Expectable Motion Unit: Avoiding Hazards From Human Involuntary Motions in Human-Robot Interaction. *IEEE Robotics and Automation Letters*.

https://ieeexplore.ieee.org/abstract/document/9690007/media#media

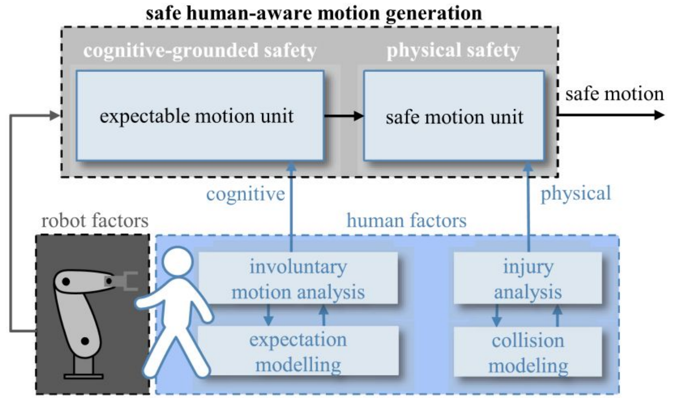
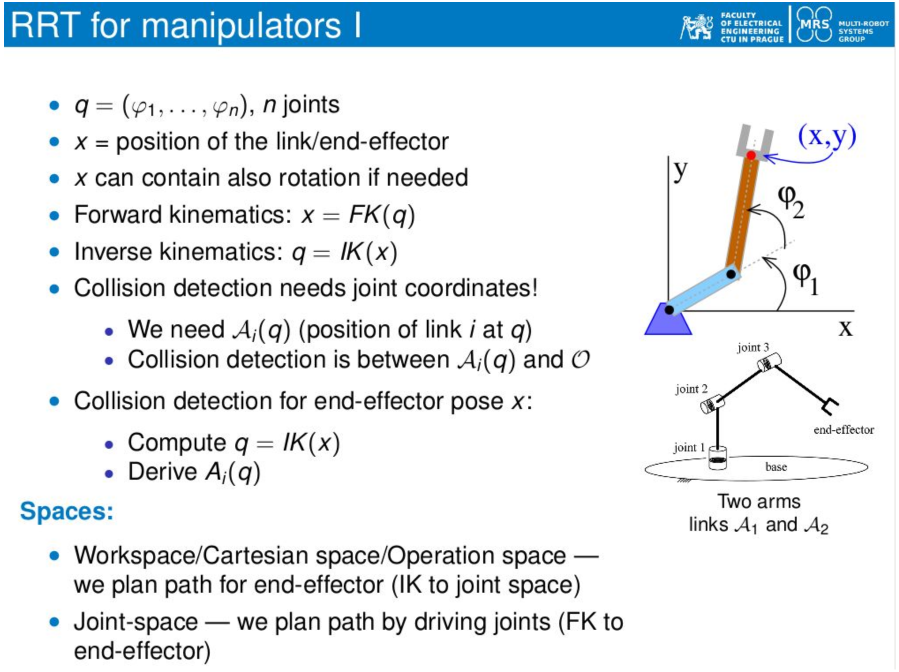


Fig. 1. Proposed framework for safe human-aware motion generation that combines cognitive-grounded safety aspects and well-established physical safety considerations and paradigms. The main contribution of this work is an experimental model of human involuntary motion (IM) occurrence in HRI and the derivation of the Expectable Motion Unit (EMU), which avoids potentially dangerous human IM in HRI.

Motion planning - what you already know

Robotika (B3B33ROB1) - Motion planning (Vladimír Petrík) /
Autonomous Robotics (B3M33ARO) - Vojtěch Vonásek

- configuration space (vs. task space)
- path vs. trajectory
- sampling-based motion planning (RRT, RRT*, PRM)



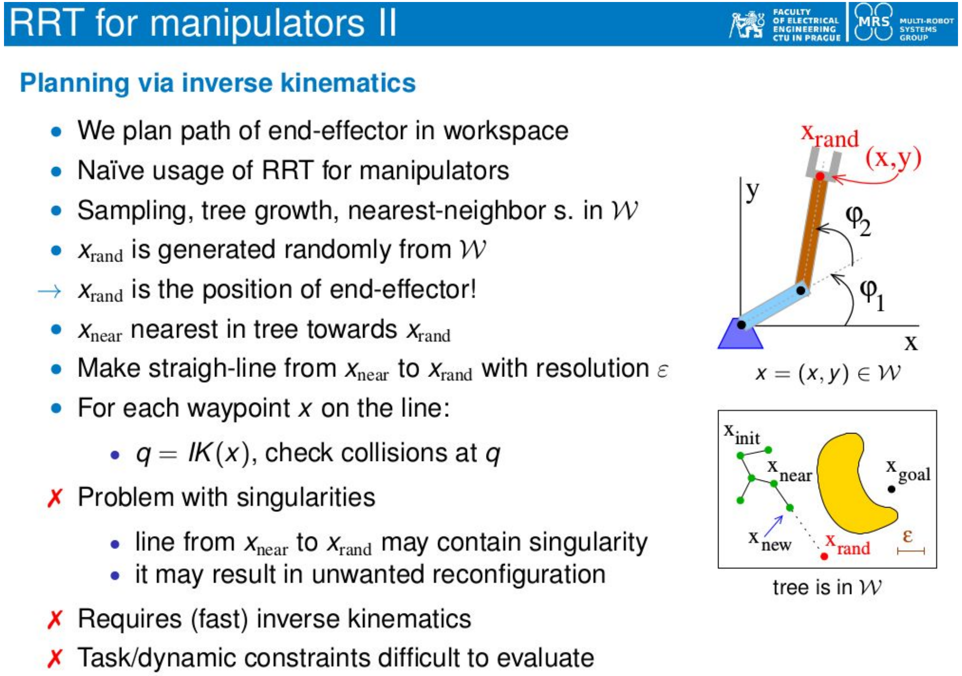
RRT for manipulators I

- $q = (\varphi_1, \ldots, \varphi_n)$, n joints
- x = position of the link/end-effector
- x can contain also rotation if needed
- Forward kinematics: $x = FK(q)$
- Inverse kinematics: $q = IK(x)$
- Collision detection needs joint coordinates!
  - We need $\mathcal{A}_i(q)$ (position of link i at q)
  - Collision detection is between $\mathcal{A}_i(q)$ and $\mathcal{O}$
- Collision detection for end-effector pose x:
  - Compute $q = IK(x)$
  - Derive $A_i(q)$

Two arms
links $\mathcal{A}_1$ and $\mathcal{A}_2$

Spaces:

- Workspace/Cartesian space/Operation space — we plan path for end-effector (IK to joint space)
- Joint-space — we plan path by driving joints (FK to end-effector)



RRT for manipulators II

Planning via inverse kinematics

- We plan path of end-effector in workspace
- Naïve usage of RRT for manipulators
- Sampling, tree growth, nearest-neighbor s. in $\mathcal{W}$
- x_{rand} is generated randomly from $\mathcal{W}$

→ x_{rand} is the position of end-effector!

- x_{near} nearest in tree towards x_{rand}
- Make straigh-line from x_{near} to x_{rand} with resolution ε
- For each waypoint x on the line:
  - $q = IK(x)$, check collisions at q

✗ Problem with singularities
  - line from x_{near} to x_{rand} may contain singularity
  - it may result in unwanted reconfiguration

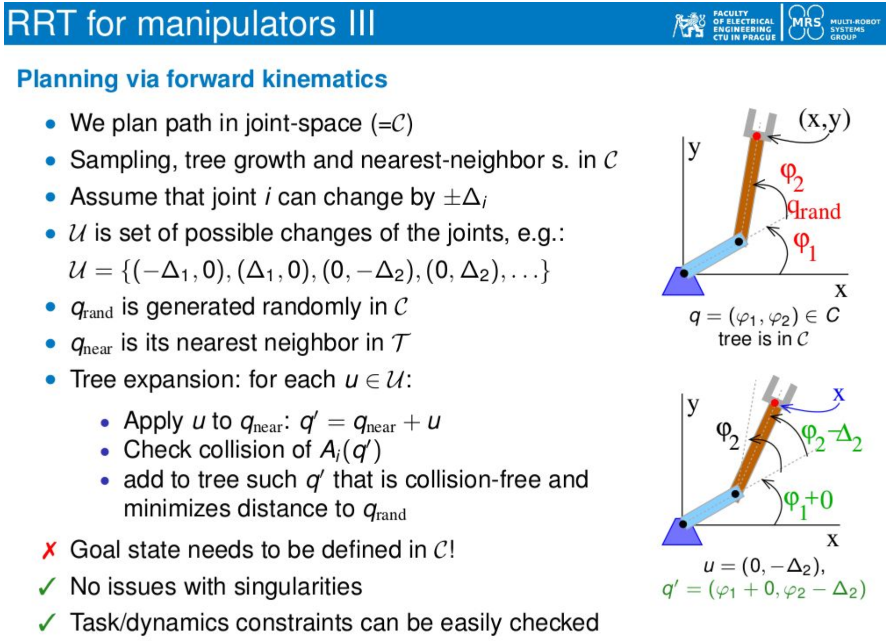
✗ Requires (fast) inverse kinematics

✗ Task/dynamic constraints difficult to evaluate

$x = (x, y) \in \mathcal{W}$

tree is in $\mathcal{W}$

V. Vonásek: ARO, Motion Planning III - sampling-based motion planners, slides 12-13
https://cw.fel.cvut.cz/b212/_media/courses/b3m33aro/lectures/planning-sampling2.pdf



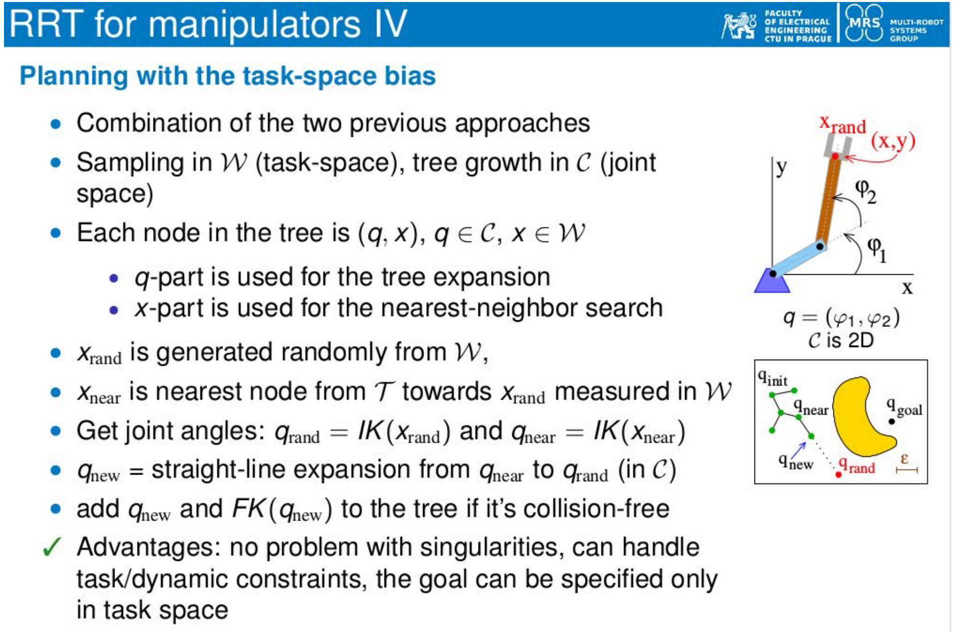
RRT for manipulators III

Planning via forward kinematics

- We plan path in joint-space (=$\mathcal{C}$)
- Sampling, tree growth and nearest-neighbor s. in $\mathcal{C}$
- Assume that joint i can change by $\pm\Delta_i$
- $\mathcal{U}$ is set of possible changes of the joints, e.g.:
  $\mathcal{U} = \{(-\Delta_1, 0), (\Delta_1, 0), (0, -\Delta_2), (0, \Delta_2), \ldots\}$
- q_{rand} is generated randomly in $\mathcal{C}$
- q_{near} is its nearest neighbor in $\mathcal{T}$
- Tree expansion: for each $u \in \mathcal{U}$:
  - Apply u to q_{near}: $q' = q_{\text{near}} + u$
  - Check collision of $A_i(q')$
  - add to tree such q' that is collision-free and minimizes distance to q_{rand}
- ✗ Goal state needs to be defined in $\mathcal{C}$!
- ✓ No issues with singularities
- ✓ Task/dynamics constraints can be easily checked

$q = (\varphi_1, \varphi_2) \in C$
tree is in $\mathcal{C}$

$u = (0, -\Delta_2)$,
$q' = (\varphi_1 + 0, \varphi_2 - \Delta_2)$



RRT for manipulators IV

Planning with the task-space bias

- Combination of the two previous approaches
- Sampling in $\mathcal{W}$ (task-space), tree growth in $\mathcal{C}$ (joint space)
- Each node in the tree is (q, x), $q \in \mathcal{C}$, $x \in \mathcal{W}$
  - q-part is used for the tree expansion
  - x-part is used for the nearest-neighbor search
- x_{rand} is generated randomly from $\mathcal{W}$,
- x_{near} is nearest node from $\mathcal{T}$ towards x_{rand} measured in $\mathcal{W}$
- Get joint angles: $q_{\text{rand}} = IK(x_{\text{rand}})$ and $q_{\text{near}} = IK(x_{\text{near}})$
- q_{new} = straight-line expansion from q_{near} to q_{rand} (in $\mathcal{C}$)
- add q_{new} and $FK(q_{\text{new}})$ to the tree if it's collision-free
- ✓ Advantages: no problem with singularities, can handle task/dynamic constraints, the goal can be specified only in task space

$q = (\varphi_1, \varphi_2)$
$\mathcal{C}$ is 2D

V. Vonásek: ARO, Motion Planning III - sampling-based motion planners, slides 14-15
https://cw.fel.cvut.cz/b212/_media/courses/b3m33aro/lectures/planning-sampling2.pdf

Next: path/trajectory not to scare people!

Shortest path vs. fastest path vs. path for good spraying

V. Vonásek: ARO, Motion Planning I - basic concepts, slide 48

https://cw.fel.cvut.cz/b212/_media/courses/b3m33aro/lectures/planning-basics.pdf

Object hand-over

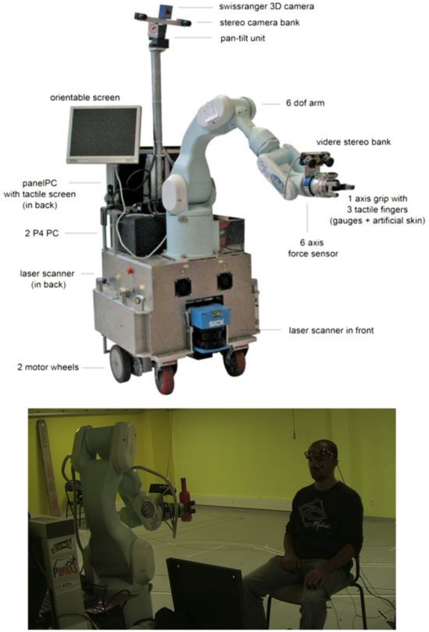
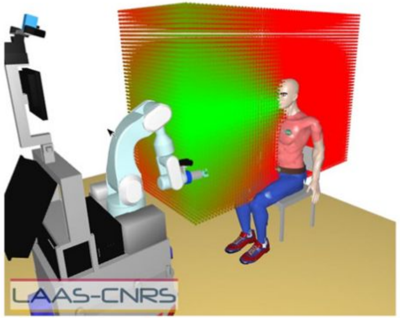


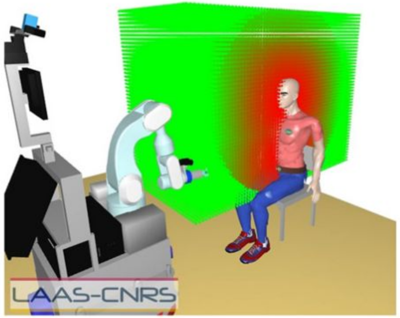
Fig. 1. Jido and a view from the experimental setup. The human is placed in front of the robot on a chair.

What is being optimized?

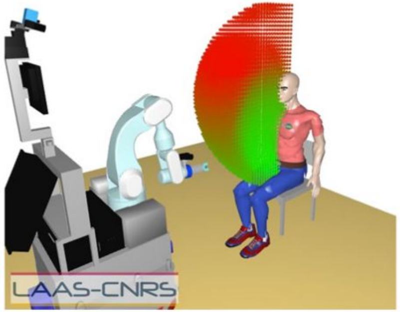
legibility (here ~ visibility)



safety



physical comfort



Dehais, F., Sisbot, E. A., Alami, R., & Causse, M. (2011). Physiological and subjective evaluation of a human–robot object hand-over task. *Applied ergonomics*, *42*(6), 785-791.

Planning around humans

- Navigation - humans are not obstacles.
    - Need to consider:
        - interpersonal social zones
        - gaze
        - context
- Motion should be:
    - **safe**, i.e. that does not harm the human,
    - **reliable and effective**, i.e. that achieves the task adequately considering the motion capacities of the robot,
    - **socially acceptable**, i.e. that takes into account the comfort of the human as well as his/her preferences and needs; and that expresses the intention of the robot clearly (~ legible, which also adds to safety)...
    - Sisbot, E. A., Marin-Urias, L. F., Broquere, X., Sidobre, D., & Alami, R. (2010). Synthesizing robot motions adapted to human presence. *International Journal of Social Robotics*, *2*(3), 329-343.

Shomin, M., Vaidya, B., Hollis, R., & Forlizzi, J. (2014, September). Human-approaching trajectories for a person-sized balancing robot. In *2014 IEEE International Workshop on Advanced Robotics and its Social Impacts* (pp. 20-25). IEEE.

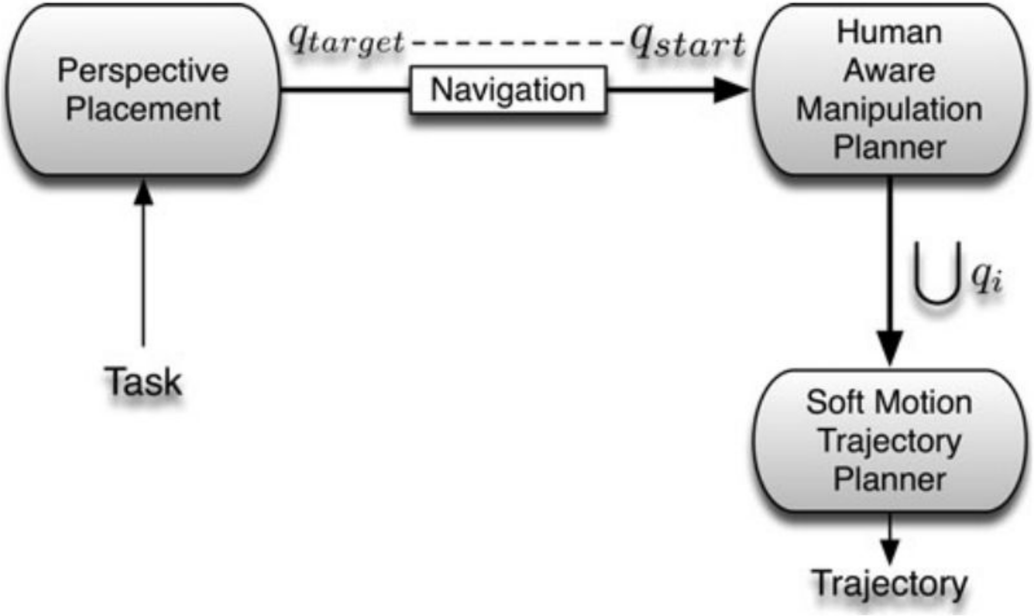


Fig. 2 The data flow between the three motion synthesis system components

Sisbot, E. A., Marin-Urias, L. F., Broquere, X., Sidobre, D., & Alami, R. (2010). Synthesizing robot motions adapted to human presence. *International Journal of Social Robotics*, *2*(3), 329-343.

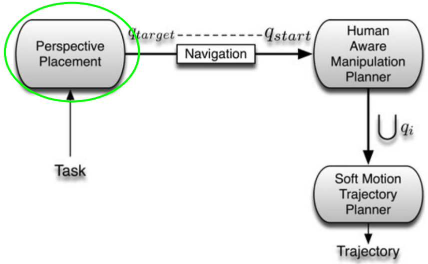
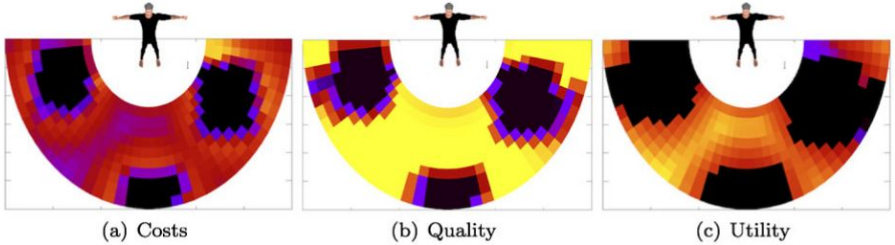
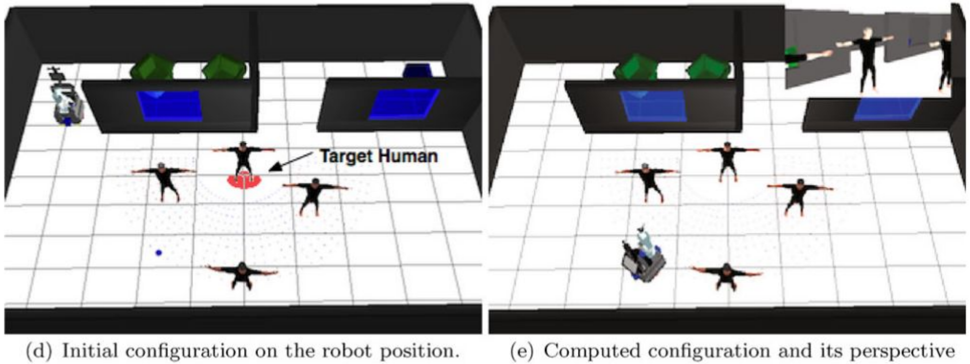


Fig. 2 The data flow between the three motion synthesis system components



(a) Costs (b) Quality (c) Utility



(d) Initial configuration on the robot position. (e) Computed configuration and its perspective

Fig. 5 The robot has to compute a placement where it can talk with the human in the middle of the scene (indicated with an arrow). The presence of the other persons in the environment influences the costs and the quality of the position. (**a**), (**b**), and (**c**) illustrate the resulting costs, quality and utility functions for the target human on the grid. (**d**) The initial position of the robot. (**e**) The placement that has been computed by PSP. Note that, on the top right, the system shows the estimated camera view of the robot. Safety and comfort distances toward the other persons present in the environment are also respected

Sisbot, E. A., Marin-Urias, L. F., Broquere, X., Sidobre, D., & Alami, R. (2010). Synthesizing robot motions adapted to human presence. *International Journal of Social Robotics*, *2*(3), 329-343.

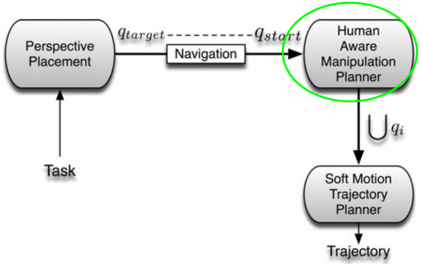


Fig. 2 The data flow between the three motion synthesis system components

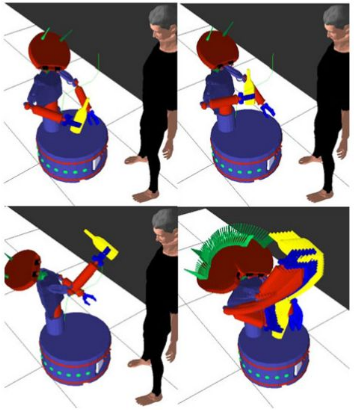


Fig. 7 Calculated path for a "handing over an object" scenario. The robot looks at the object during this motion, ensuring the clarity of its intention to the human. As seen in the final figure, a "simple" hand over task results in a quite complete robot motion involving almost all its upper body in order to increase the legibility

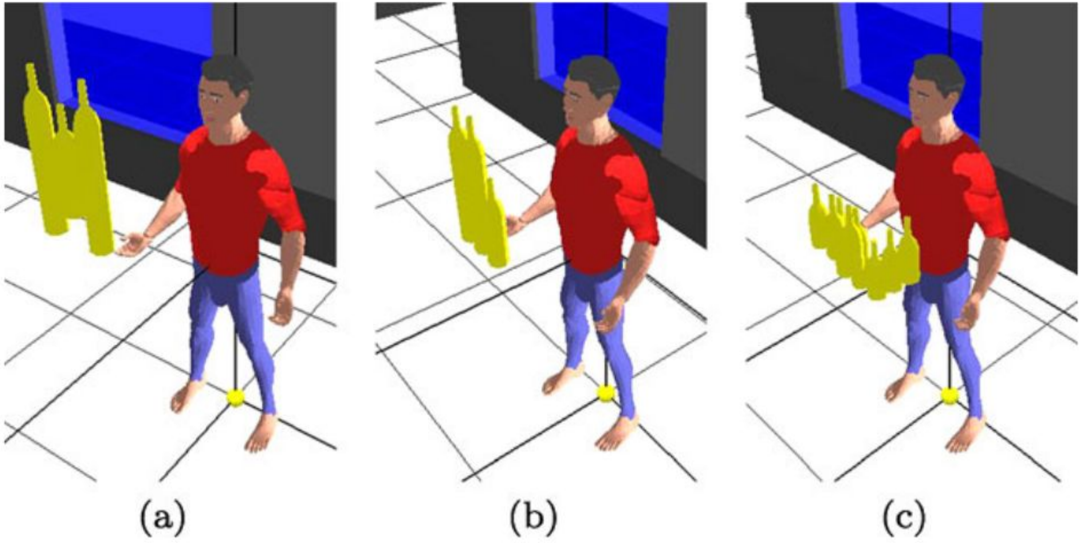


Fig. 6 10 points around the human having lowest costs to place the object. The order of weights change drastically the result of the process. The figure illustrates the case where (**a**) the safety is the most important. In case of figure (**b**) the visibility is dominant, in figure (**c**) the comfort of the arm is more important

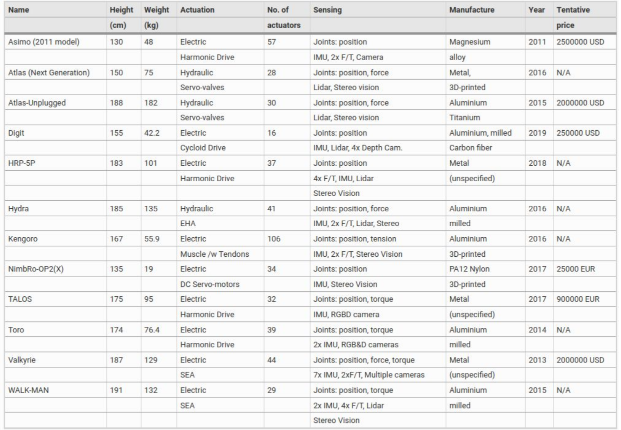
Sisbot, E. A., Marin-Urias, L. F., Broquere, X., Sidobre, D., & Alami, R. (2010). Synthesizing robot motions adapted to human presence. *International Journal of Social Robotics*, *2*(3), 329-343.

Planning for humanoids

“C-space of 4 dimensions is already considered high-dimensional.”

V. Vonasek: ARO - Motion Planning I - basic concepts. https://cw.fel.cvut.cz/b212/_media/courses/b3m33aro/lectures/planning-basics.pdf

Most recently developed bipedal humanoid robots with a full humanoid body plan, from left to right, top to bottom: Asimo, Atlas, Atlas-Unplugged, Digit, HRP-5P, Hydra, Kengoro, NimbRo-OP2X, TALOS, Toro, Valkyrie, WALK-MAN



Name	Height (cm)	Weight (kg)	Actuation	No. of actuators	Sensing	Manufacture	Year	Tentative price
Asimo (2011 model)	130	48	Electric	57	Joints: position	Magnesium	2011	2500000 USD
			Harmonic Drive		IMU, 2x F/T, Camera	alloy		
Atlas (Next Generation)	150	75	Hydraulic	28	Joints: position, force	Metal,	2016	N/A
			Servo-valves		Lidar, Stereo vision	3D-printed		
Atlas-Unplugged	188	182	Hydraulic	30	Joints: position, force	Aluminium	2015	2000000 USD
			Servo-valves		Lidar, Stereo vision	Titanium		
Digit	155	42.2	Electric	16	Joints: position	Aluminium, milled	2019	250000 USD
			Cycloid Drive		IMU, Lidar, 4x Depth Cam.	Carbon fiber		
HRP-5P	183	101	Electric	37	Joints: position	Metal	2018	N/A
			Harmonic Drive		4x F/T, IMU, Lidar	(unspecified)		
					Stereo Vision			
Hydra	185	135	Hydraulic	41	Joints: position, force	Aluminium	2016	N/A
			EHA		IMU, 2x F/T, Lidar, Stereo	milled		
Kengoro	167	55.9	Electric	106	Joints: position, tension	Aluminium	2016	N/A
			Muscle /w Tendons		IMU, 2x F/T, Stereo Vision	3D-printed		
NimbRo-OP2(X)	135	19	Electric	34	Joints: position	PA12 Nylon	2017	25000 EUR
			DC Servo-motors		IMU, Stereo Vision	3D-printed		
TALOS	175	95	Electric	32	Joints: position, torque	Metal	2017	900000 EUR
			Harmonic Drive		IMU, RGBD camera	(unspecified)		
Toro	174	76.4	Electric	39	Joints: position, torque	Aluminium	2014	N/A
			Harmonic Drive		2x IMU, RGB&D cameras	milled		
Valkyrie	187	129	Electric	44	Joints: position, force, torque	Metal	2013	2000000 USD
			SEA		7x IMU, 2xF/T, Multiple cameras	(unspecified)		
WALK-MAN	191	132	Electric	29	Joints: position, torque	Aluminium	2015	N/A
			SEA		2x IMU, 4x F/T, Lidar	milled		
					Stereo Vision			

Ficht, G., & Behnke, S. (2021). Bipedal humanoid hardware design: A technology review. *Current Robotics Reports*, *2*(2), 201-210.

Decomposition: upper body: manipulation; lower body: walking

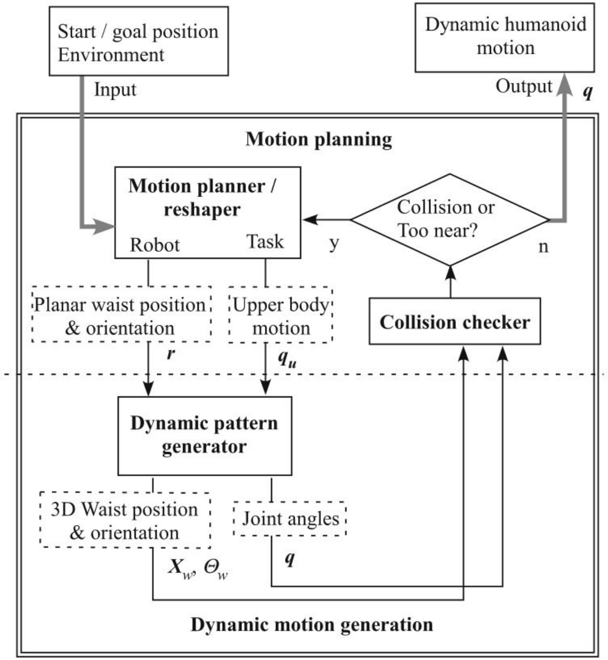


Fig. 1 Two-stage motion planning framework. Based on kinematic and geometric motion planning, the first stage generates a collision-free path that is later converted into dynamic motion in the second stage. If collisions are detected the path is sent back to the first stage. This process is repeated until a collision-free dynamic trajectory is obtained

Fig. 2 Humanoid modeled by *rectangle box* with a bar. In the first stage, the geometric and kinematic path planner generates collision-free path for the 9-DOF system including robot waist ($\boldsymbol{r}$, 3-DOF) and object ($\boldsymbol{R}_o$, 6-DOF)

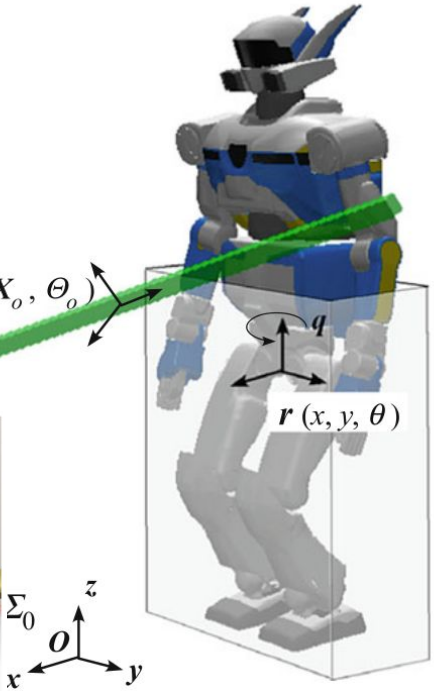
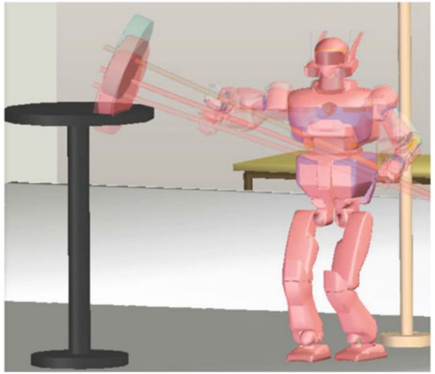


Fig. 3 Transition of robot configurations during the reshaping. The colliding part of the carried object goes away from the obstacle by increasing tolerance



Yoshida, E., Kanehiro, F., & Laumond, J. P. (2017). Whole-body motion planning. *Humanoid Robotics: A Reference*, 1575-1599.

Task-driven local whole-body motion generation

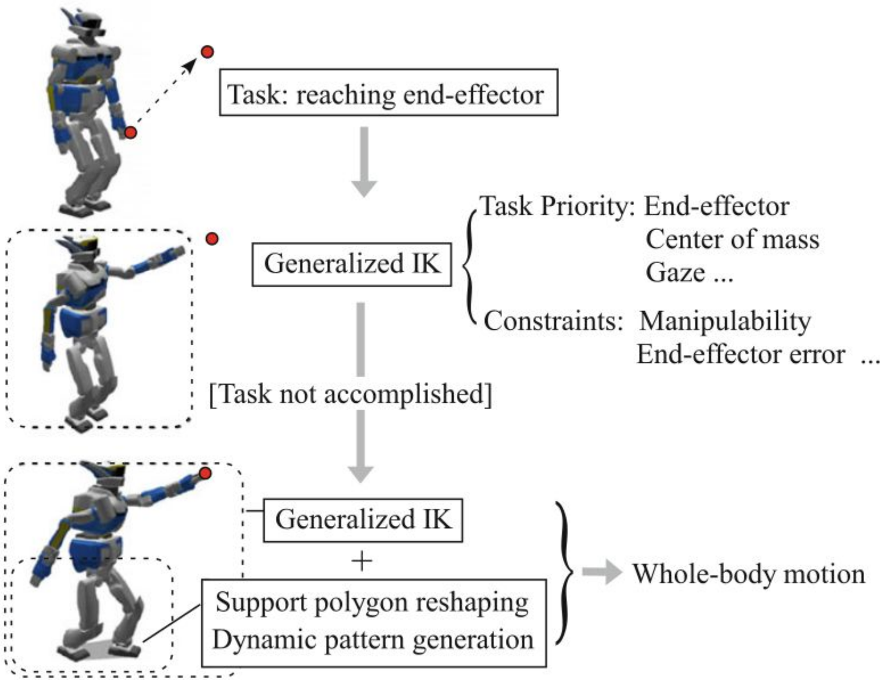


Fig. 5 A general framework for task-driven whole-body motion including simultaneous reaching and stepping [53]. If the desired tasks cannot be achieved, stepping motion is generated to increase the workspace

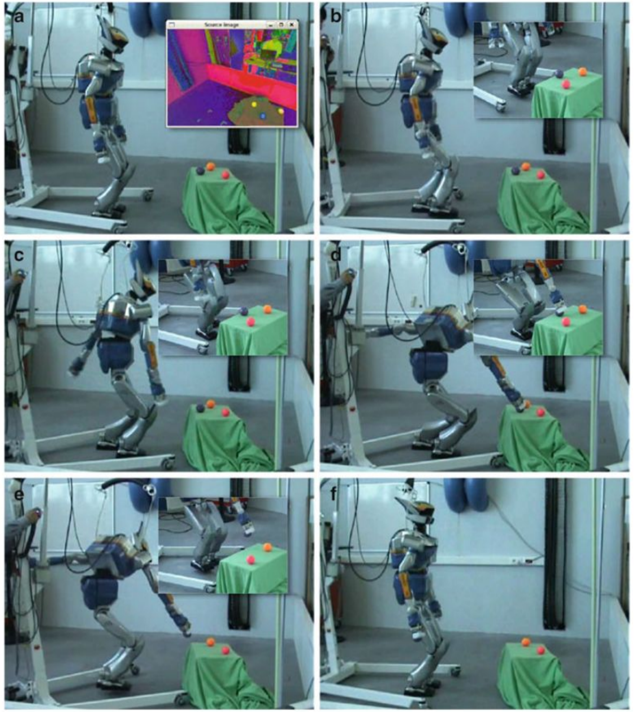


Fig. 6 A whole-body grasping motion generated through task-priority generalized inverse kinematics [53]. Upper and lower bodies coordinate to achieve the desired grasping task while making a step and maintaining the balance

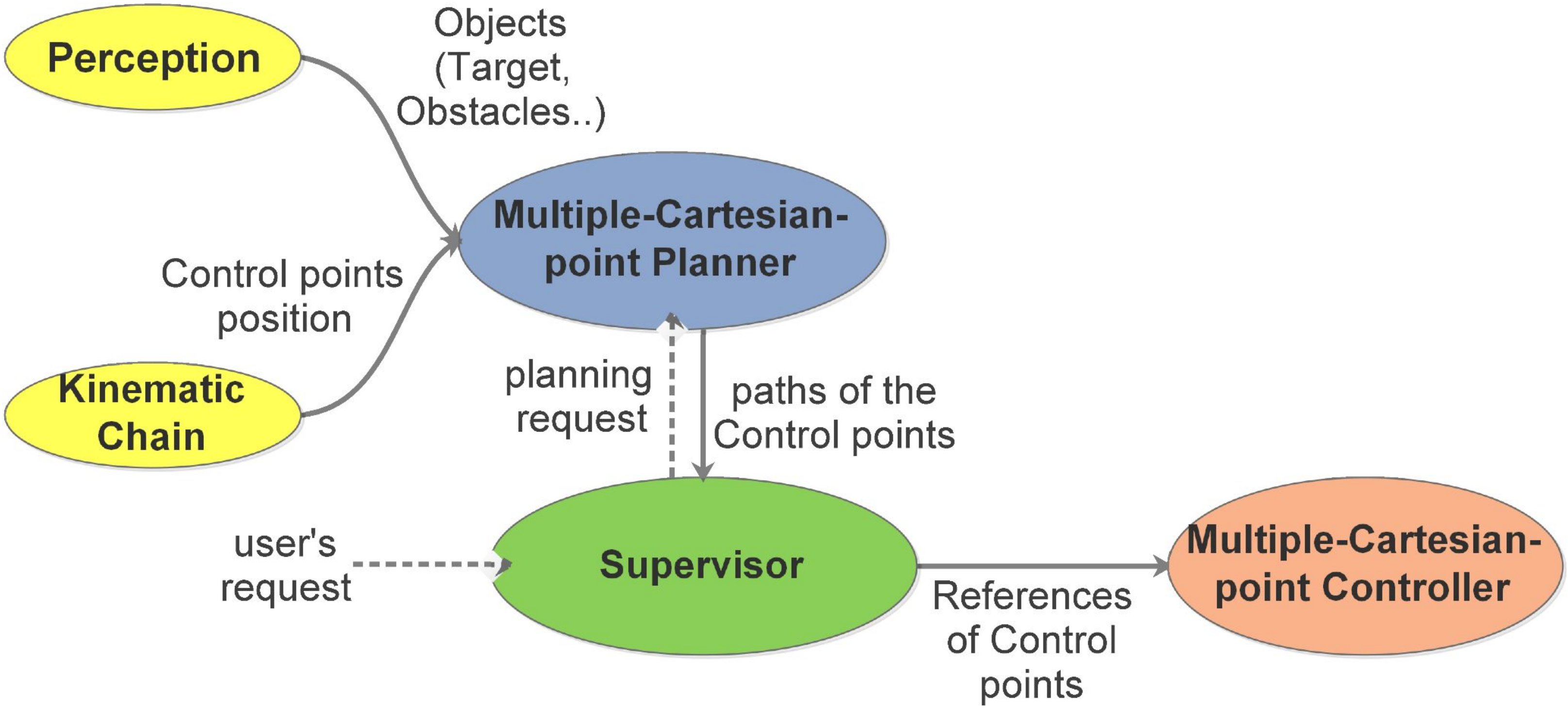
Yoshida, E., Kanehiro, F., & Laumond, J. P. (2017). Whole-body motion planning. *Humanoid Robotics: A Reference*, 1575-1599.

Motion planning for dynamic environments

https://youtu.be/A9Por3anPJ8

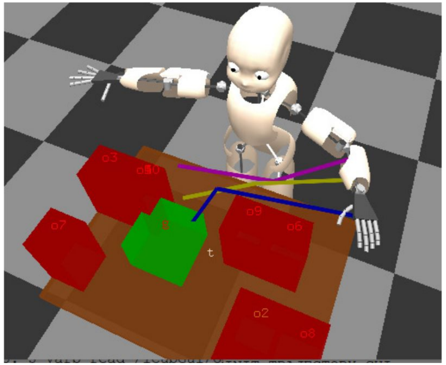
Nguyen, P. D.; Hoffmann, M.; Roncone, A.; Pattacini, U. & Metta, G. (2018), Compact real-time avoidance on a humanoid robot for human-robot interaction, *in* 'HRI '18: 2018 ACM/IEEE International Conference on Human-Robot Interaction', ACM, New York, NY, USA, pp. 416-424.

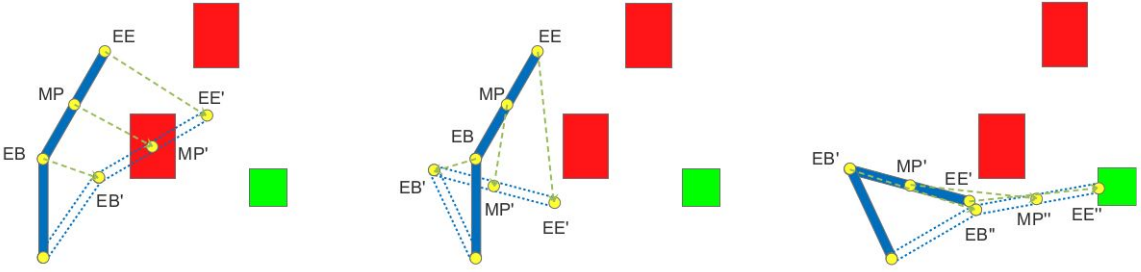
Fast heuristic Cartesian space motion planning



Nguyen, P. D.; Hoffmann, M.; Pattacini, U. & Metta, G. (2016), A fast heuristic Cartesian space motion planning algorithm for many-DoF robotic manipulators in dynamic environments, *in* 'Humanoid Robots (Humanoids), 2016 IEEE-RAS 16th International Conference on', IEEE, pp. 884-891.

Fast heuristic Cartesian space motion planning algorithm

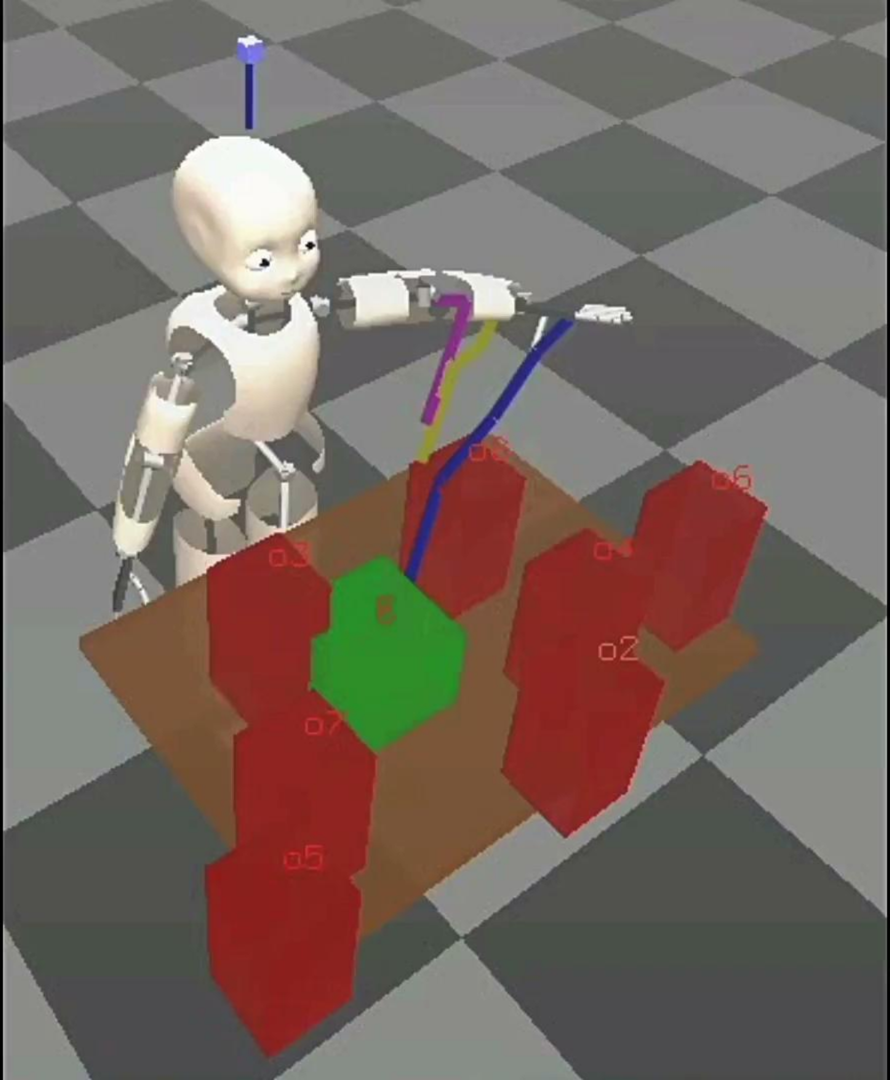




(a) (b) (c)

Fig. 3: Schematics of a 2 DoF planar manipulator with obstacles (red) and target (green). (a) Part of a plan for End-Effector and elbow (EB) illustraing that a collision-free path for the two control points does not guarantee that no collisions will occur for the whole manipulator occupancy (b) Introduction of another control point in the forearm link helps to avoid collisions, eventually leading to collision-free path from start to goal as shown in c).

Nguyen, P. D.; Hoffmann, M.; Pattacini, U. & Metta, G. (2016), A fast heuristic Cartesian space motion planning algorithm for many-DoF robotic manipulators in dynamic environments, *in* 'Humanoid Robots (Humanoids), 2016 IEEE-RAS 16th International Conference on', IEEE, pp. 884-891.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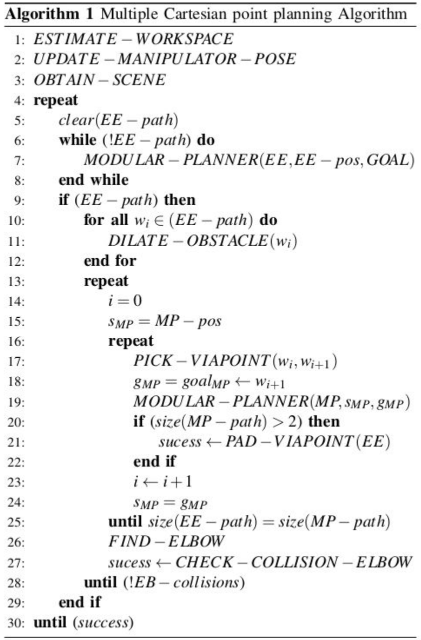
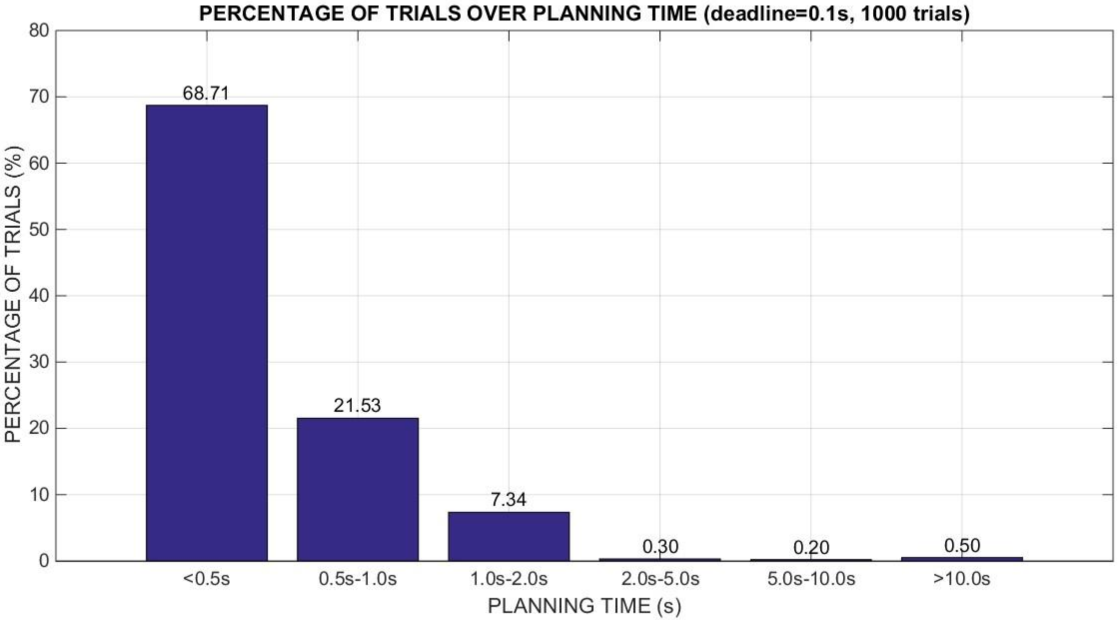
Fast heuristic Cartesian space motion planning



Algorithm 1 Multiple Cartesian point planning Algorithm

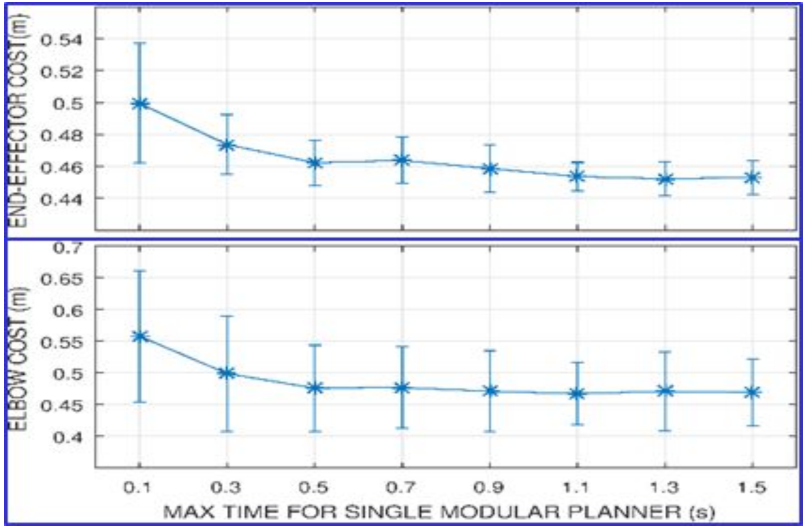
```
$ESTIMATE-WORKSPACE$
$UPDATE-MANIPULATOR-POSE$
$OBTAIN-SCENE$
repeat
    $clear(EE-path)$
    while $(!EE-path)$ do
        $MODULAR-PLANNER(EE, EE-pos, GOAL)$
    end while
    if $(EE-path)$ then
        for all $w_i \in (EE-path)$ do
            $DILATE-OBSTACLE(w_i)$
        end for
        repeat
            $i = 0$
            $s_{MP} = MP-pos$
            repeat
                $PICK-VIAPOINT(w_i, w_{i+1})$
                $g_{MP} = goal_{MP} \leftarrow w_{i+1}$
                $MODULAR-PLANNER(MP, s_{MP}, g_{MP})$
                if $(size(MP-path) > 2)$ then
                    $sucess \leftarrow PAD-VIAPOINT(EE)$
                end if
                $i \leftarrow i+1$
                $s_{MP} = g_{MP}$
            until $size(EE-path) = size(MP-path)$
            $FIND-ELBOW$
            $sucess \leftarrow CHECK-COLLISION-ELBOW$
        until $(!EB-collisions)$
    end if
until $(success)$
```



Nguyen, P. D.; Hoffmann, M.; Pattacini, U. & Metta, G. (2016), A fast heuristic Cartesian space motion planning algorithm for many-DoF robotic manipulators in dynamic environments, *in* 'Humanoid Robots (Humanoids), 2016 IEEE-RAS 16th International Conference on', IEEE, pp. 884-891.

Fast heuristic Cartesian space motion planning

Asymptotically optimal planner



Method	Success rate (%)	Mean Cal. Time (s)
RRT*	11.93	10.012
Our	100	0.454
PRM*	9.17	10.059
Our	100	0.440
RRTConnect	8.26	3.989
Our	100	0.411

Nguyen, P. D.; Hoffmann, M.; Pattacini, U. & Metta, G. (2016), A fast heuristic Cartesian space motion planning algorithm for many-DoF robotic manipulators in dynamic environments, *in* 'Humanoid Robots (Humanoids), 2016 IEEE-RAS 16th International Conference on', IEEE, pp. 884-891.

Some take-home messages

1. Spatial interaction in HRI - proxemics
   a. Humans are not obstacles.
2. Motion planning for human-populated environments
   a. Not optimal, but safe, socially acceptable, and legible behaviors.
3. Motion planning for humanoids
   a. There are many DoFs.
   b. And many constraints (e.g. balance).

Further reading and resources

- Books / book sections
  - Bartneck, C., Belpaeme, T., Eyssel, F., Kanda, T., Keijsers, M., & Šabanović, S. (2020). *Human-Robot Interaction: An Introduction*. Cambridge University Press.
  - Yoshida, E., Kanehiro, F., & Laumond, J. P. (2017). Whole-body motion planning. *Humanoid Robotics: A Reference*, 1575-1599.
- Articles
  - Sisbot, E. A., Marin-Urias, L. F., Broquere, X., Sidobre, D., & Alami, R. (2010). Synthesizing robot motions adapted to human presence. *International Journal of Social Robotics*, *2*(3), 329-343.