

# Humanoid robots - Motion planning for HRI and humanoids

**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

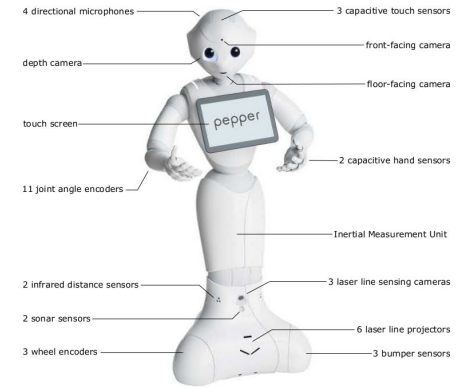
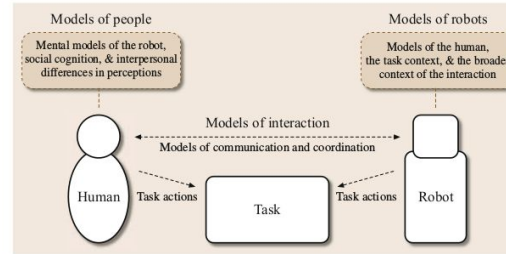


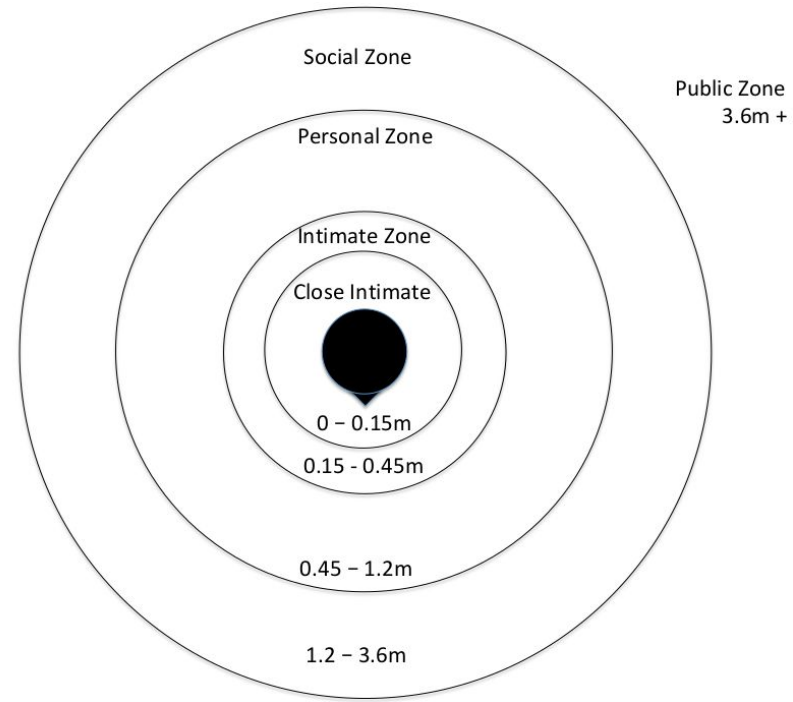
Fig 3.3 in Bartneck, C., Belpaeme, T., Eyssel, F., Kanda, T., Keijsers, M., & Šabanović, S. (2020). *Human-Robot Interaction: An Introduction*. Cambridge University Press.

# 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
Personal Zone	0.45m to 1.2m	Conversation between friends
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., Eyssele, F., Kanda, T., Keijsers, M., & Šabanović, S. (2020). *Human-Robot Interaction: An Introduction*. Cambridge University Press.

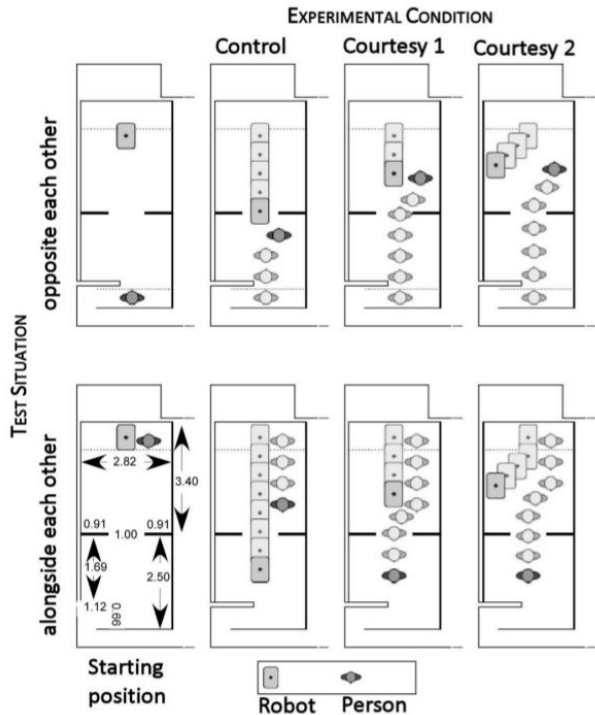


Fig. 1. Test situations: (a) Control condition (i.e., no courtesy cues), (b) Courtesy 1 condition (i.e., appearing to grant the right of way by stopping), and (c) Courtesy 2 condition (i.e., appearing to grant the right of way by stopping and moving out of the way). Numbers reflect the spatial distances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

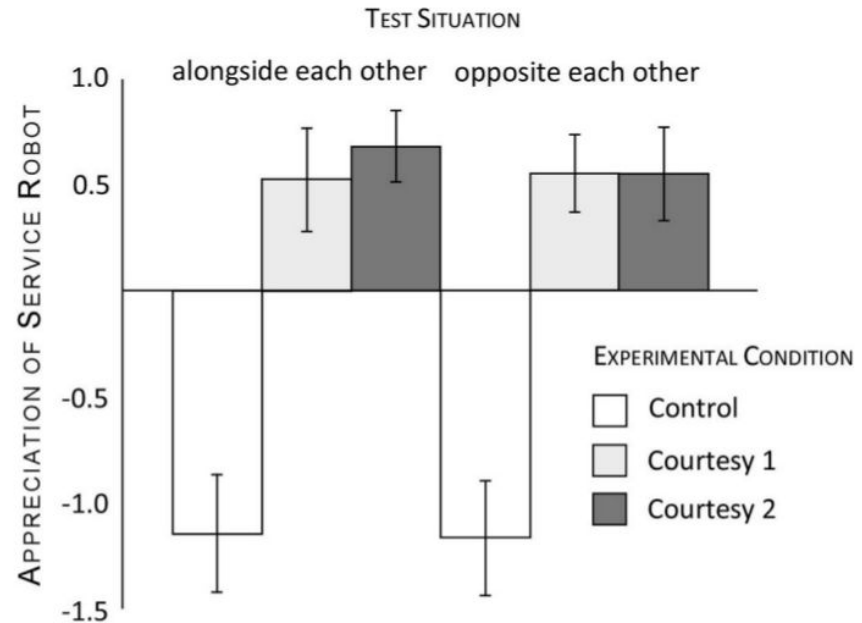


Fig. 2. Appreciation of a service robot (in mean z-values and 95% confidence intervals) that exhibits no courtesy cues (i.e., Control condition), that appears to grant the right of way by stopping (i.e., Courtesy 1 condition), or that appears to grant the right of way by stopping and moving out of the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

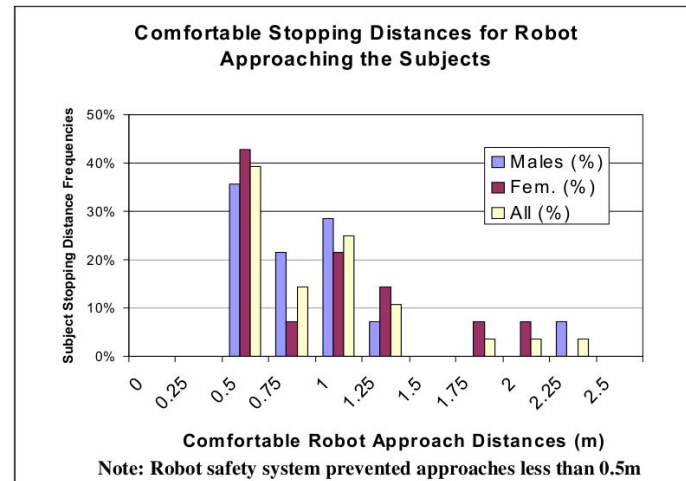
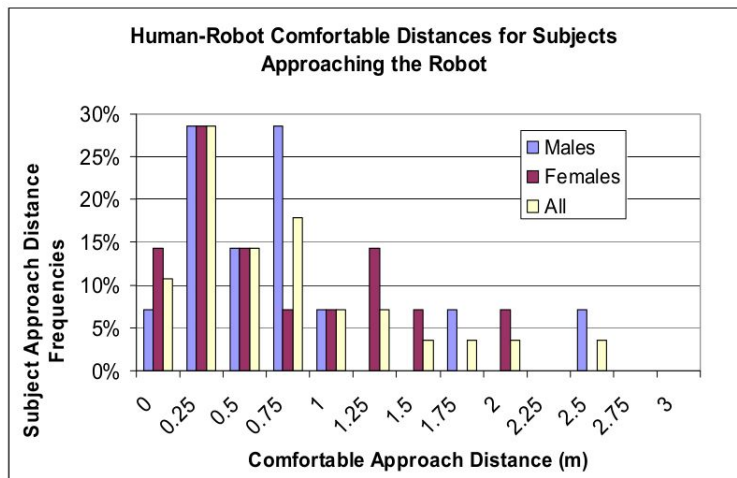
# Factors that may affect “comfortable” distance

- 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



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

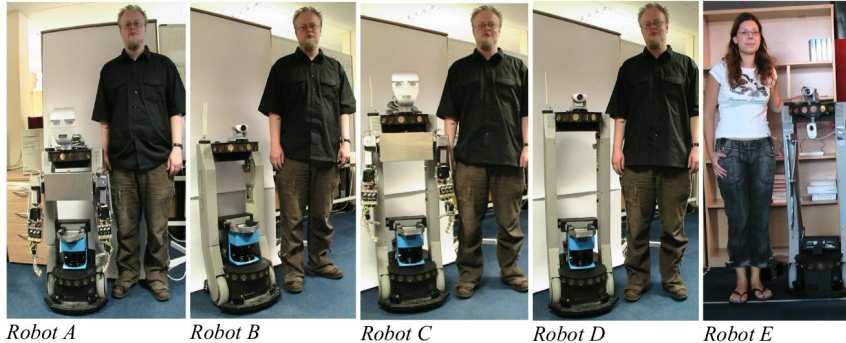
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Walters, M. L., Dautenhahn, K., Te Boekhorst, R., Koay, K. L., Kaouri, C., Woods, S., ... & Werry, I. (2005, August). The influence of subjects' personality traits on personal spatial zones in a human-robot interaction experiment. In *ROMAN 2005. IEEE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



# Modulators of interpersonal distance in HRI



**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 ( $\pm 0.5\text{cm}$ )
<b>Attribute or Factor of Robot</b>			
Mechanoid Robot	RH Approach	All	-3
	HR Approach		-7
Humanoid Robot	RH Approach	All	+3
	HR Approach		-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	+2
		Right/Left	-2

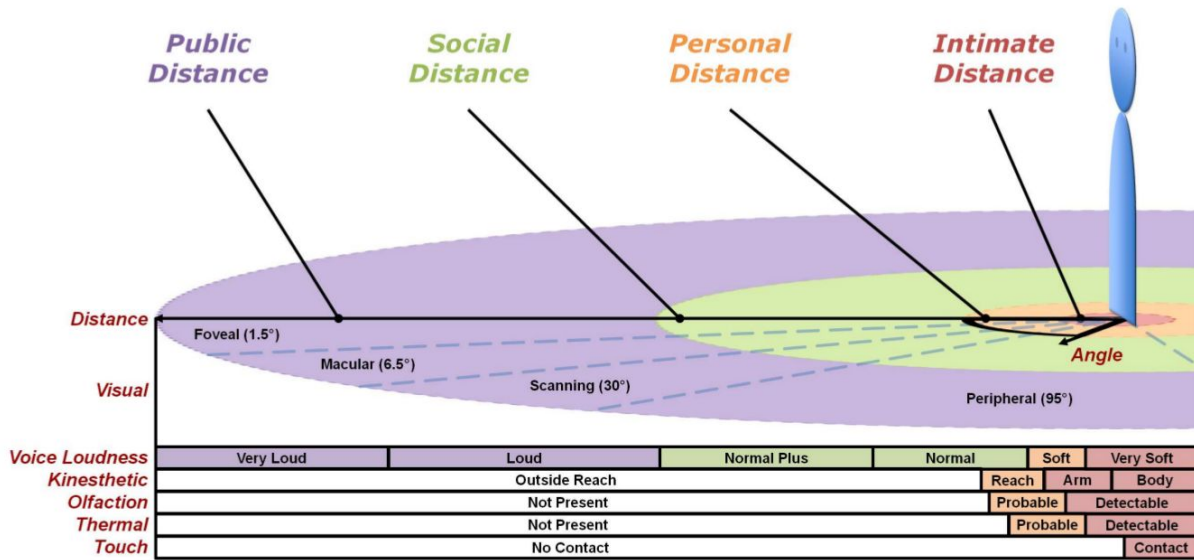


Fig. 1. Relationships between interpersonal pose and sensory experiences [3, 2, 11].

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

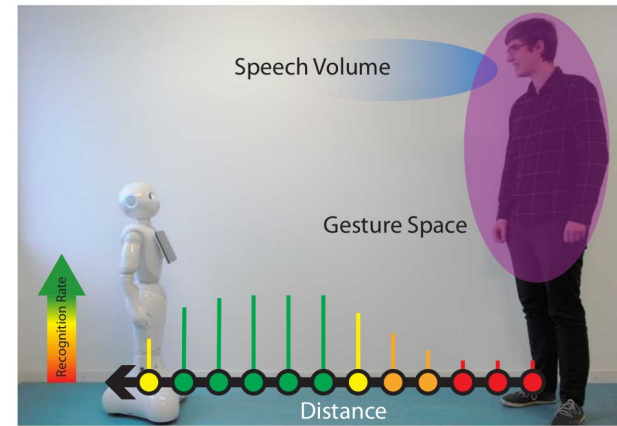
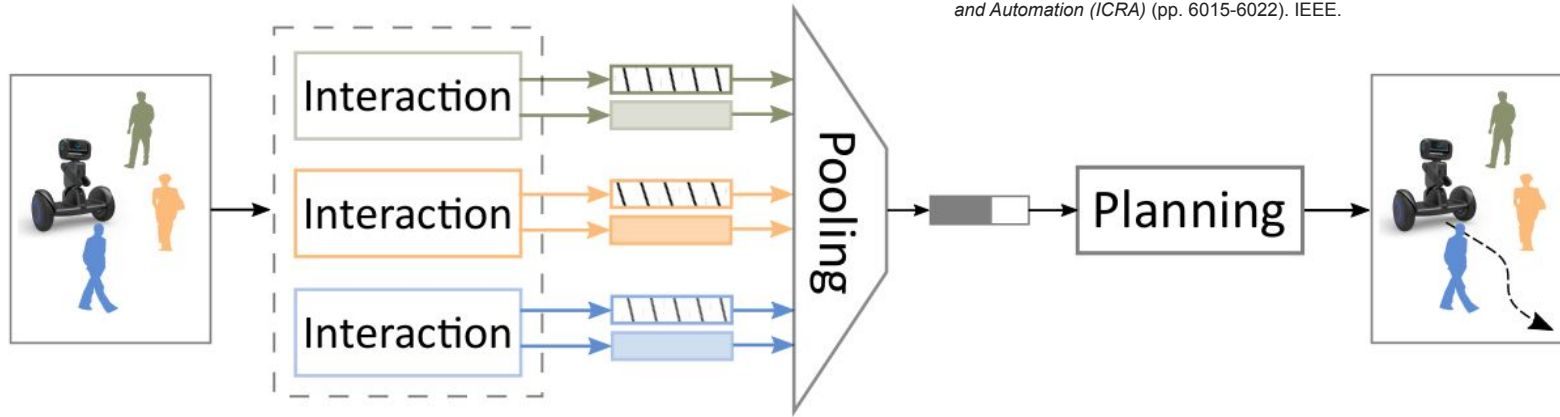


Fig. 5.6 in Bartneck, C., Belpaeme, T., Eyssel, F., Kanda, T., Keijsers, M., & Šabanović, S. (2020). *Human-Robot Interaction: An Introduction*. Cambridge University Press.

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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://CrowdBot.eu)

<http://u4y.fed.myftpupload.com/data-sets-sofwares/>

# Human or robot spatial zones?

- Most literature is concerned with robots not inappropriately invading human spatial zones - i.e. *human's comfort*.
- 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?

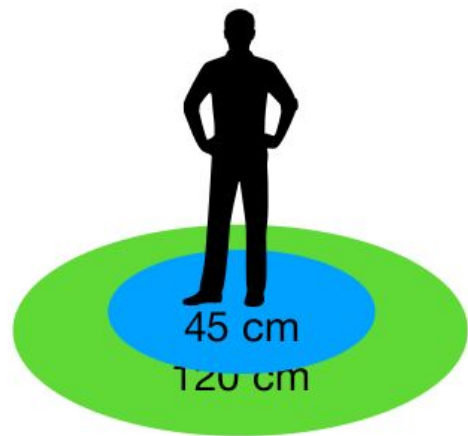
# Robot personal space



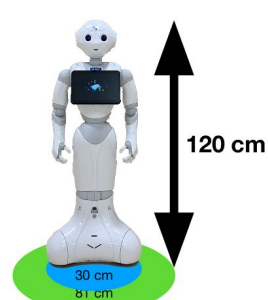
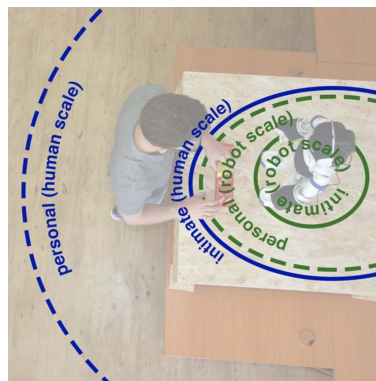
<https://youtu.be/gvICAkfK2CA>

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)'

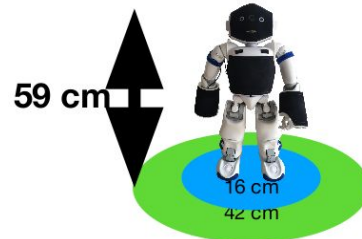
# Scaling of personal space to robot size?



intimate space  
personal space



Pepper



Nao

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

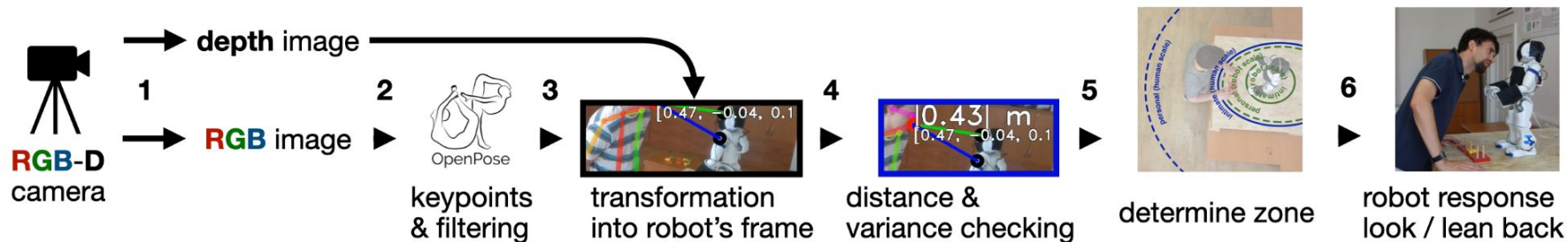
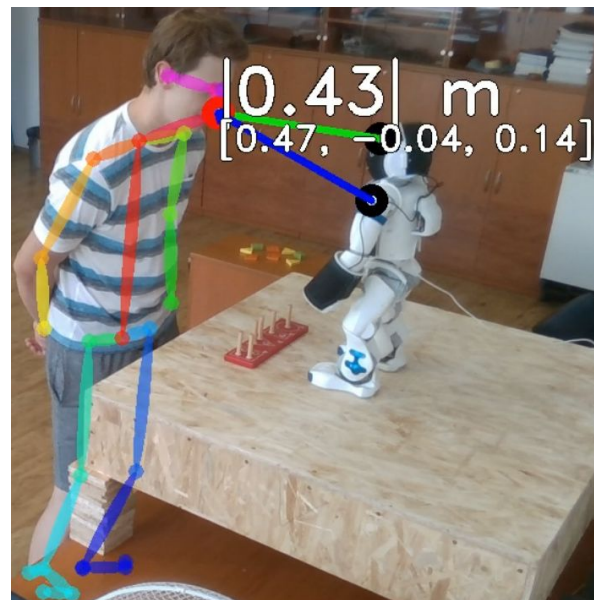


Experiment	Robot	Condition	Gaze distance	Lean-back distance	Differential lean-back distance
NAO-1	Nao	Robot	0.42 m	0.16 m	-
		Human	1.2 m	0.45 m	
Pepper	Pepper	Robot	0.81 m	-	0.3 m—0.1 m
		Human	1.2 m	0.45 m—0.1 m	
NAO-2	Nao	Robot	0.42 m	-	0.16 m—0.1 m
		Human	1.2 m	0.45 m—0.1 m	

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

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](#)]

# Perceiving the distance

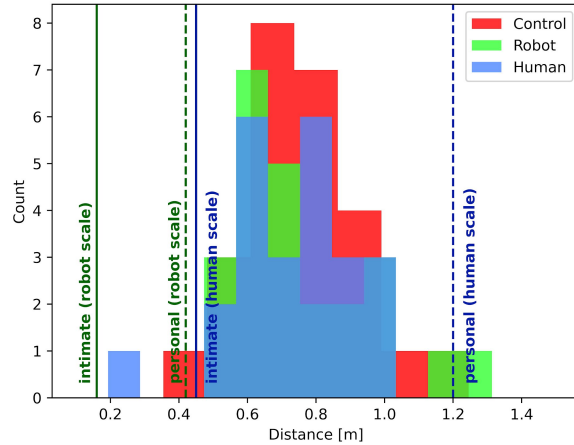


Lehmann, H.; Rojik, A. & Hoffmann, M. (2020), Should a small robot have a small personal space? Investigating personal spatial zones and proxemic behavior in human-robot interaction, in 'Cognitive Robotics for Interaction (CIRCE) Workshop at IEEE International Conference On Robot and Human Interactive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

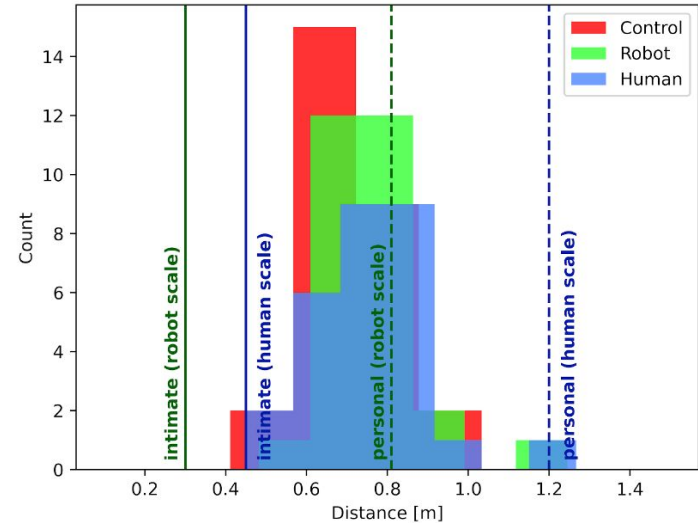


# Results - distance

Nao



Pepper



- people do not scale robot personal space with its size

Rojik, 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]

	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

# 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
<b>SUM</b>	<b>32.14%</b>	<b>42.86%</b>	<b>28.57%</b>	<b>28</b>

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

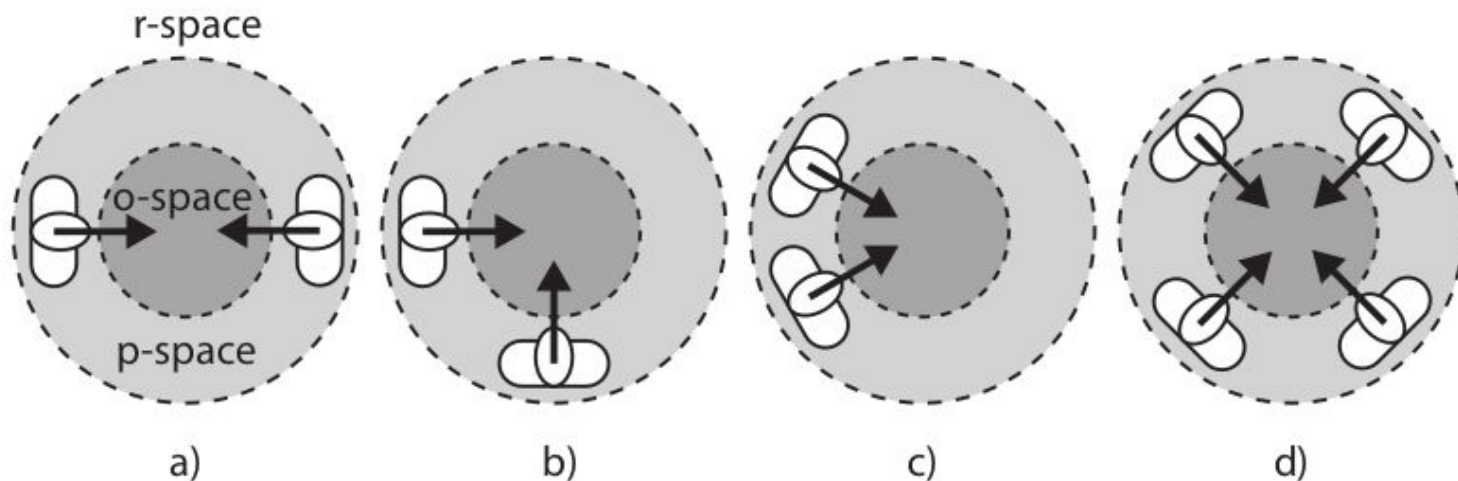
Lean-back meaning	C	R	H	Responses
keeping distance	16.00%	4.00%	16.00%	9
shock	8.00%	8.00%	4.00%	5
surprised	4.00%	8.00%	4.00%	3
curious	0.00%	0.00%	8.00%	2
distrust	0.00%	4.00%	4.00%	2
gazing	0.00%	4.00%	0.00%	1
odd	0.00%	0.00%	4.00%	1
respect	0.00%	4.00%	0.00%	1
tallness	0.00%	0.00%	4.00%	1
<b>SUM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

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., Eyssele, 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>

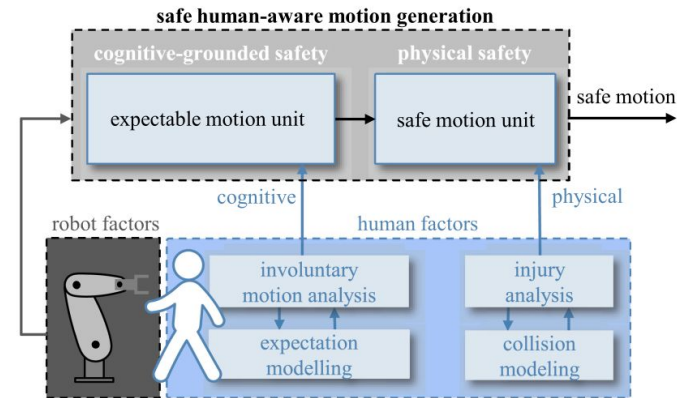


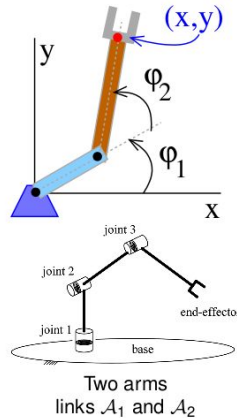
Fig. 1. Proposed framework for safe human-aware motion generation that combines cognitive-grounded safety aspects and well-established physical safety considerations and paradigms. The main contribution of this work is an experimental model of human involuntary motion (IM) occurrence in HRI and the derivation 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 Petřík) /  
Autonomous Robotics (B3M33ARO) - Vojtěch Vonásek

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

- $q = (\varphi_1, \dots, \varphi_n)$ ,  $n$  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  $\mathcal{A}_i(q)$

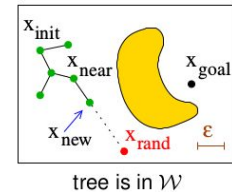
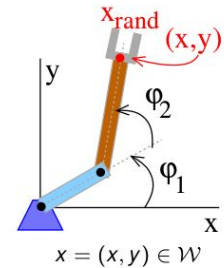


## Spaces:

- 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)

## 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 straight-line from  $x_{near}$  to  $x_{rand}$  with resolution  $\epsilon$
- 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

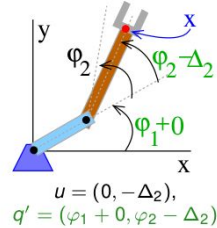
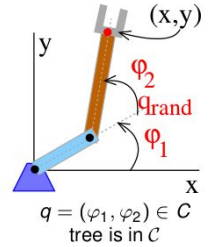


V. Vonásek: ARO, Motion Planning III - sampling-based motion planners, slides 12-13

<https://cw.fel.cvut.cz/b212/media/courses/b3m33aro/lectures/planning-sampling2.pdf>

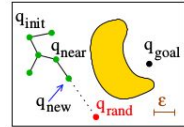
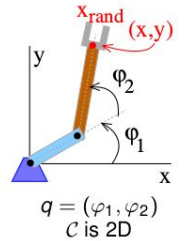
### Planning via forward kinematics

- 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.:  
 $\mathcal{U} = \{(-\Delta_1, 0), (\Delta_1, 0), (0, -\Delta_2), (0, \Delta_2), \dots\}$
- $q_{\text{rand}}$  is generated randomly in  $\mathcal{C}$
- $q_{\text{near}}$  is its nearest neighbor in  $\mathcal{T}$
- Tree expansion: for each  $u \in \mathcal{U}$ :
  - Apply  $u$  to  $q_{\text{near}}$ :  $q' = q_{\text{near}} + u$
  - Check collision of  $A_i(q')$
  - add to tree such  $q'$  that is collision-free and minimizes distance to  $q_{\text{rand}}$
- ✗ Goal state needs to be defined in  $\mathcal{C}$ !
- ✓ No issues with singularities
- ✓ Task/dynamics constraints can be easily checked



### 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
- $x_{\text{rand}}$  is generated randomly from  $\mathcal{W}$ ,
- $x_{\text{near}}$  is nearest node from  $\mathcal{T}$  towards  $x_{\text{rand}}$  measured in  $\mathcal{W}$
- Get joint angles:  $q_{\text{rand}} = IK(x_{\text{rand}})$  and  $q_{\text{near}} = IK(x_{\text{near}})$
- $q_{\text{new}}$  = straight-line expansion from  $q_{\text{near}}$  to  $q_{\text{rand}}$  (in  $\mathcal{C}$ )
- add  $q_{\text{new}}$  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



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

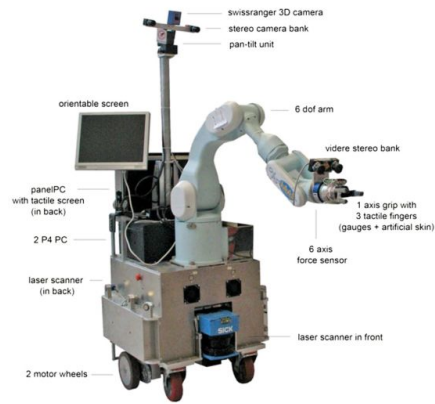
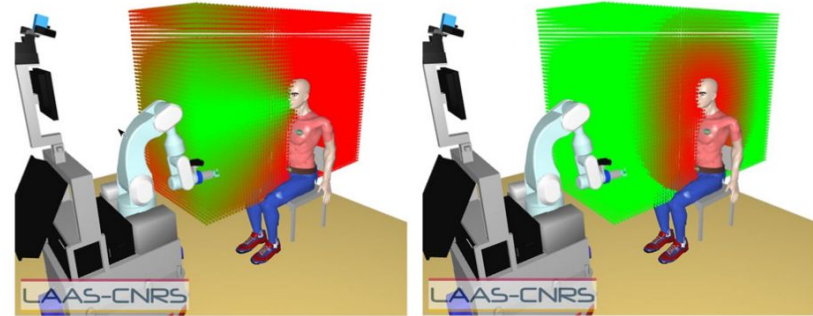


Fig. 1. Jido and a view from the experimental setup. The human is placed in front of the robot on a chair.

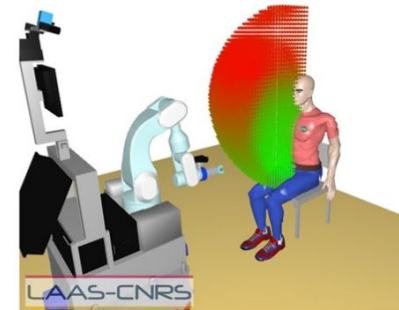
What is being optimized?

legibility (here ~ visibility)

safety



physical comfort



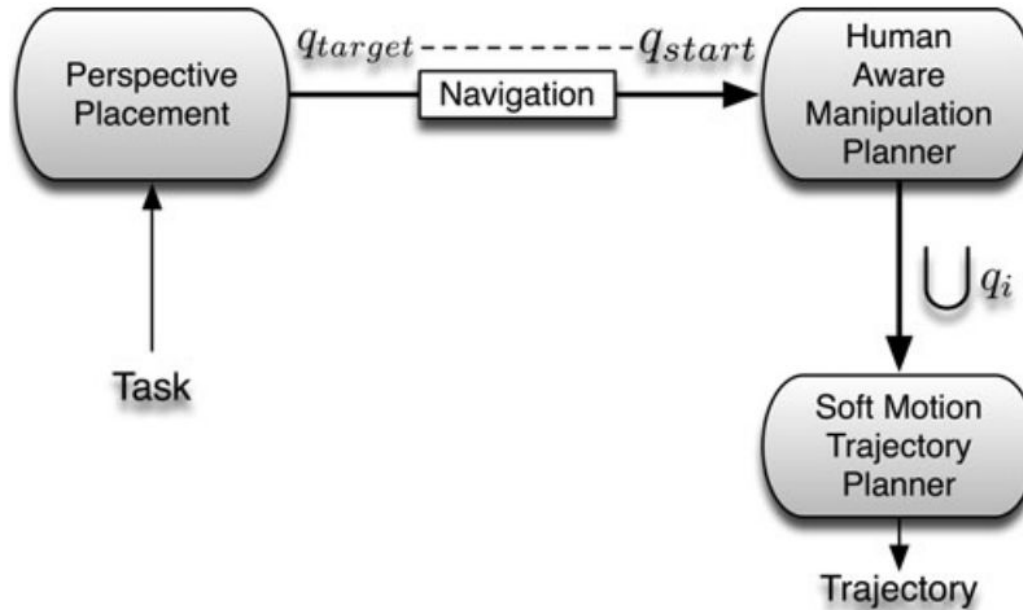
Dehais, F., Sisbot, E. A., Alami, R., & Cause, M. (2011). Physiological and subjective evaluation of a human-robot object hand-over task. *Applied ergonomics*, 42(6), 785-791.

# 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.

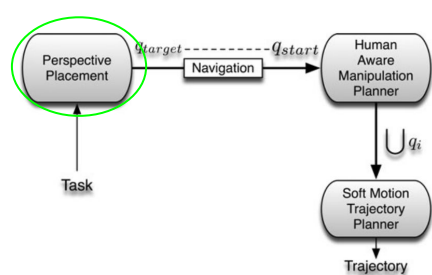
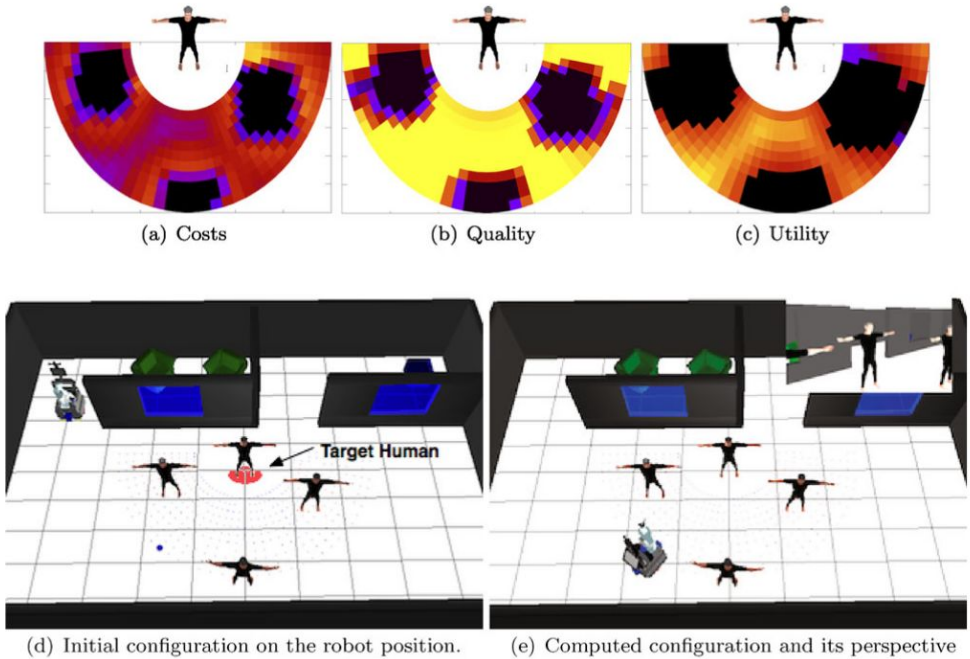


Fig. 2 The data flow between the three motion synthesis system components

**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.

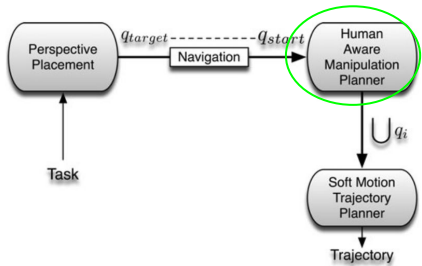


Fig. 2 The data flow between the three motion synthesis system components

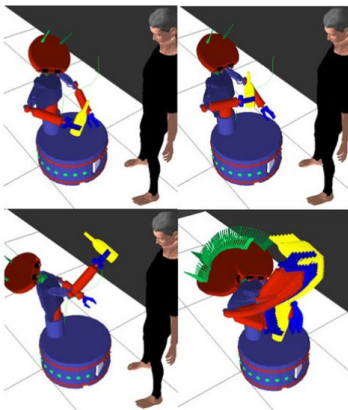


Fig. 7 Calculated path for a “handing over an object” scenario. The robot looks at the object during this motion, ensuring the clarity of its intention to the human. As seen in the final figure, a “simple” hand over task results in a quite complete robot motion involving almost all its upper body in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

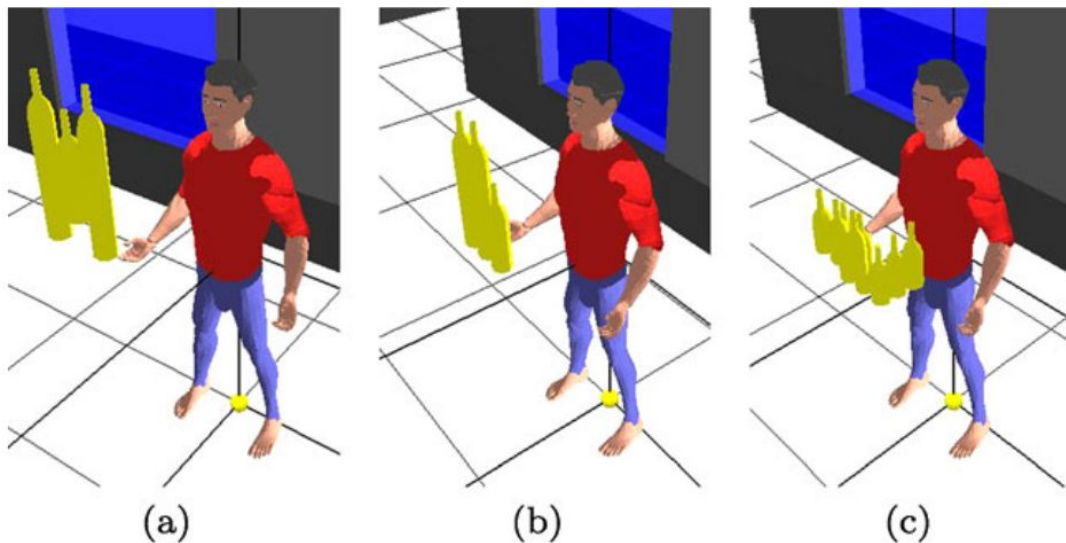


Fig. 6 10 points around the human having lowest costs to place the object. The order of weights change drastically the result of the process. The figure illustrates the case where (a) the safety is the most important. In case of figure (b) the visibility is dominant, in figure (c) the comfort of the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

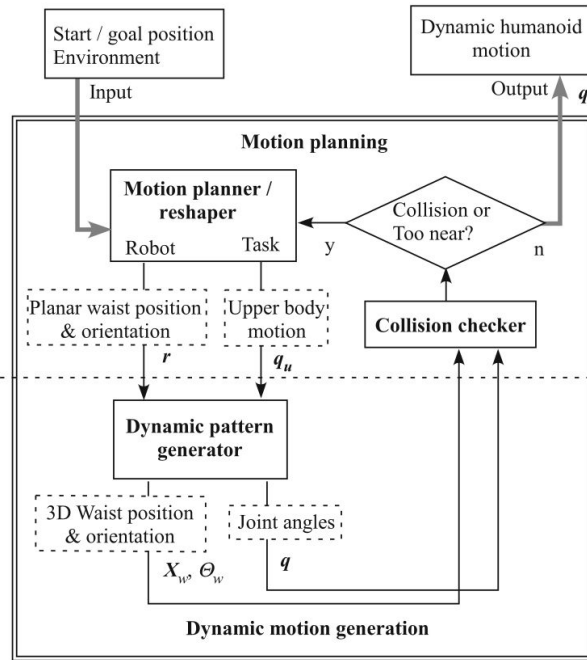


Most recently developed bipedal humanoid robots with a full humanoid body plan, from left to right, top to bottom: Asimo, Atlas, Atlas-Unplugged, Digit, HRP-5P, Hydra, Kengoro, NimRo-OP2X, TALOS, Toro, Valkyrie, WALK-MAN

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

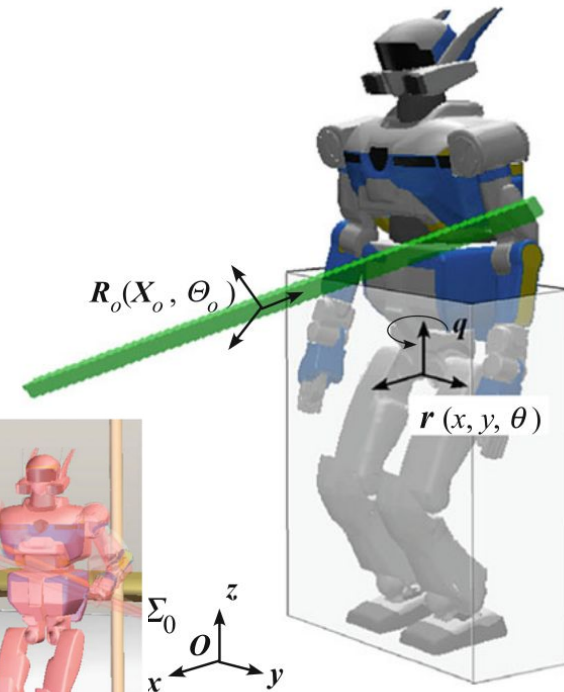
Ficht, G., & Behnke, S. (2021). Bipedal humanoid hardware design: A technology review. *Current Robotics Reports*, 2(2), 201-210.

# Decomposition: upper body: manipulation; lower body: walking

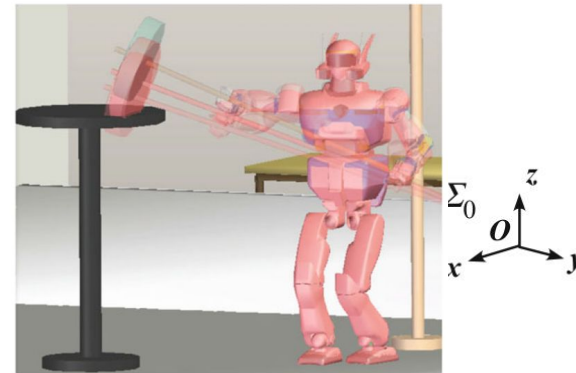


**Fig. 1** Two-stage motion planning framework. Based on kinematic and geometric motion planning, the first stage generates a collision-free path that is later converted into dynamic motion in the second stage. If collisions are detected the path is sent back to the first stage. This process is repeated 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 ( $r$ , 3-DOF) and object ( $R_o$ , 6-DOF)

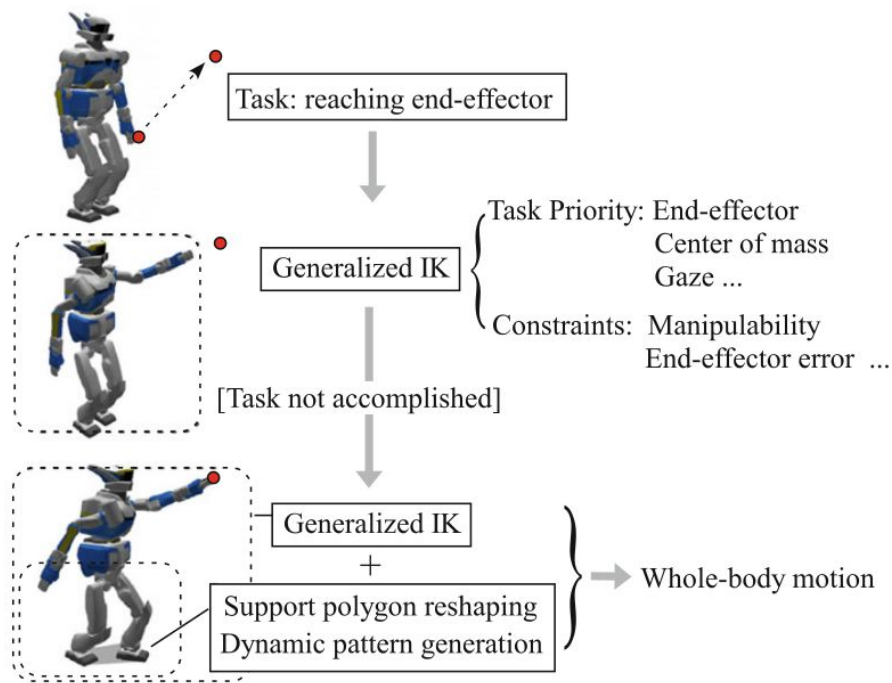


**Fig. 3** Transition of robot configurations during the reshaping. The colliding part of the carried object goes away from the obstacle by increasing tolerance

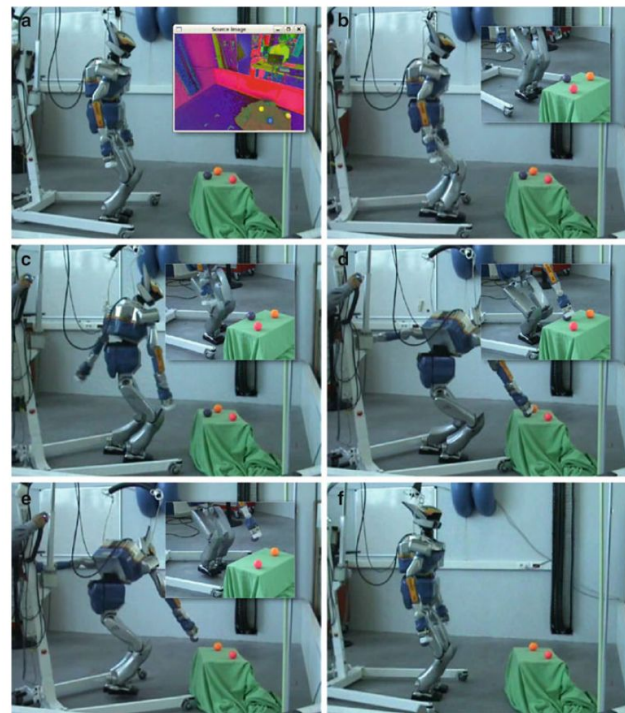


Yoshida, E., Kanehiro, F., & Laumond, J. P. (2017). Whole-body motion planning. *Humanoid Robotics: A Reference*, 1575-1599.

# 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

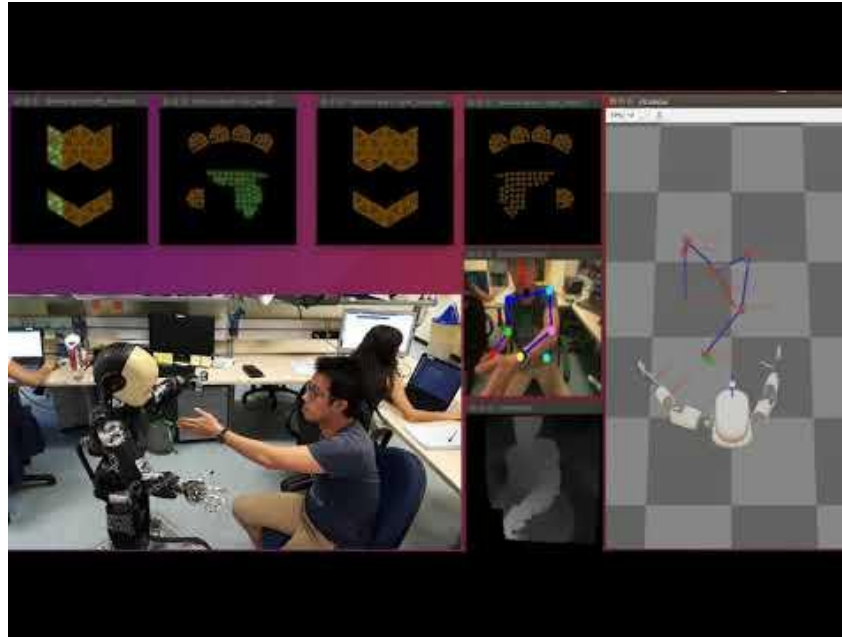


**Fig. 6** A whole-body grasping motion generated through task-priority generalized inverse kinematics [53]. Upper and lower bodies coordinate to achieve the desired grasping task while making a step and maintaining the balance

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



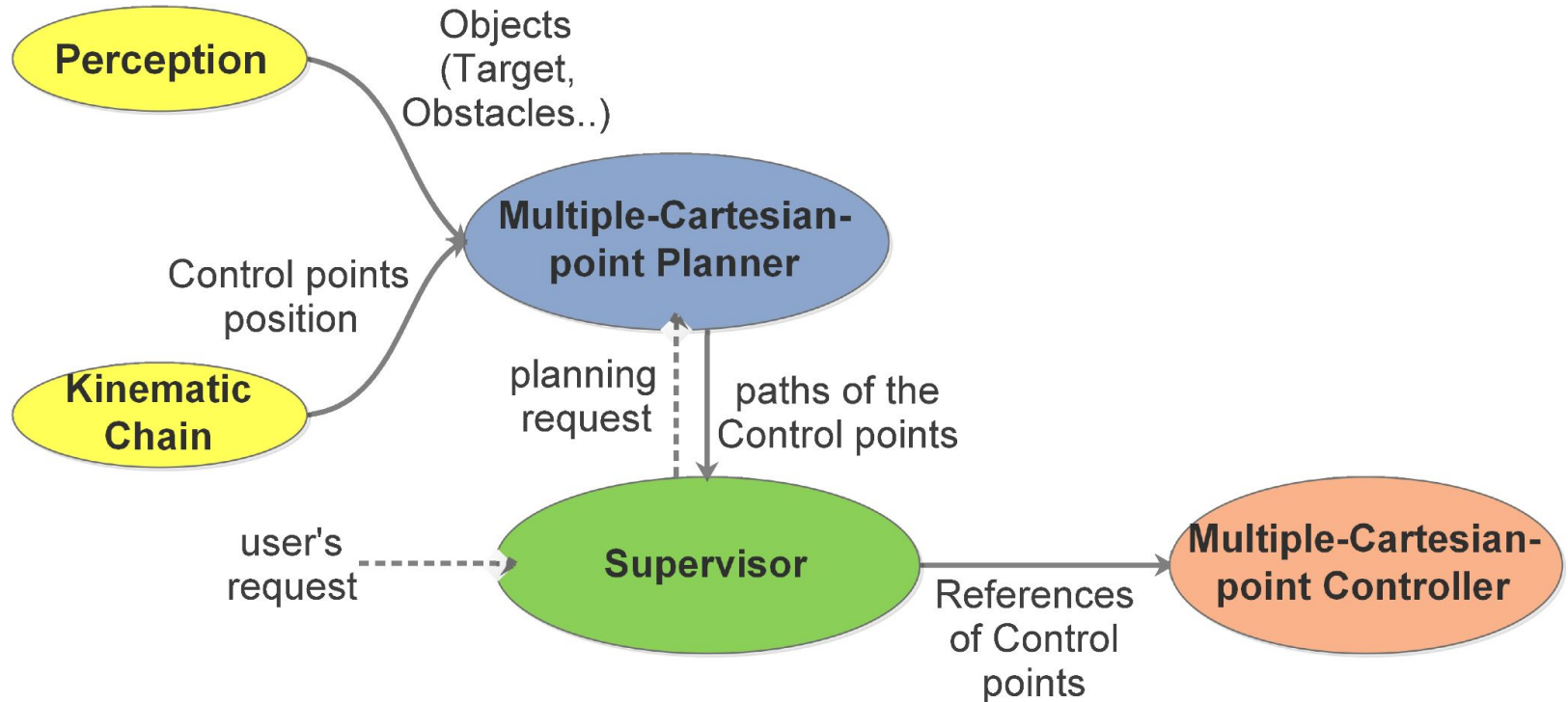
# Motion planning for dynamic environments



<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 algorithm



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

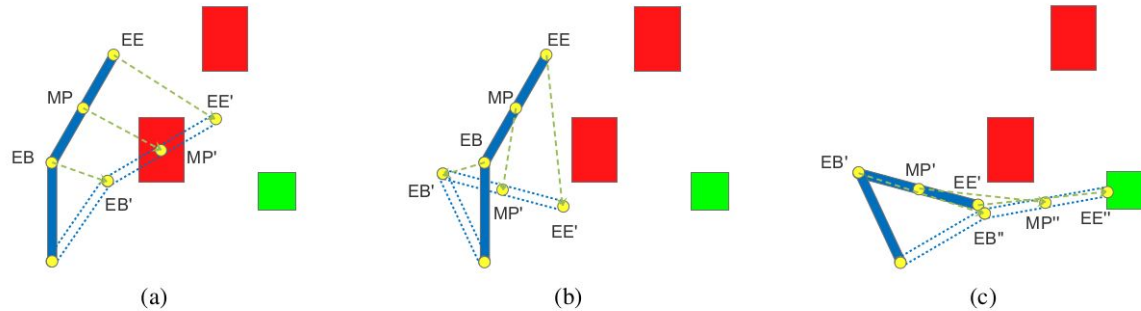
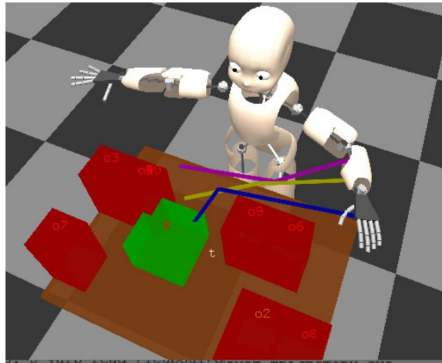
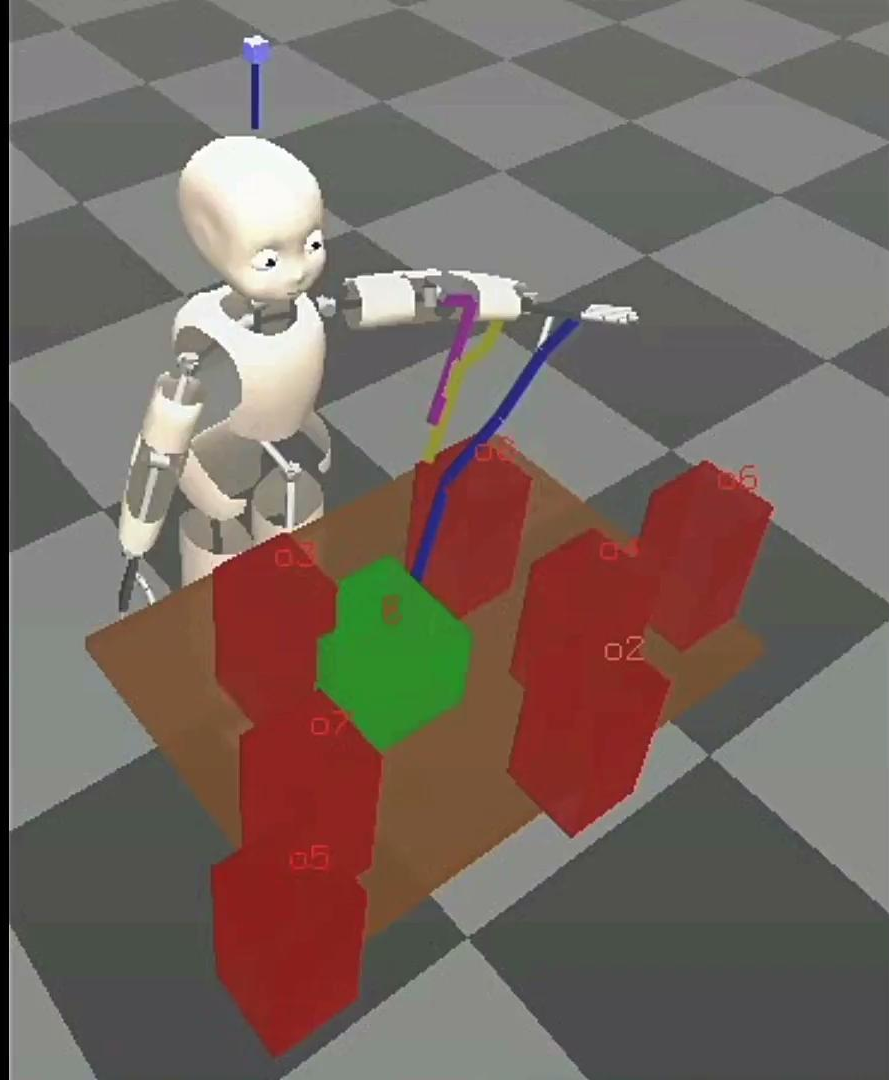


Fig. 3: Schematics of a 2 DoF planar manipulator with obstacles (red) and target (green). (a) Part of a plan for End-Effector and elbow (EB) illustrating that a collision-free path for the two control points does not guarantee that no collisions will occur for the whole manipulator occupancy (b) Introduction 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).

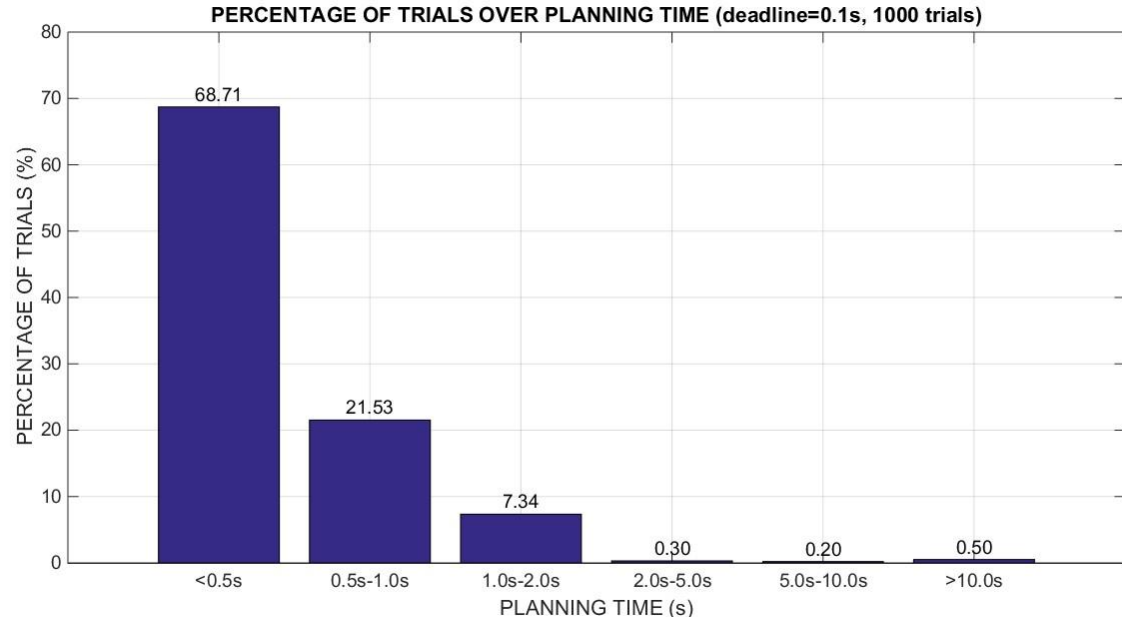
Nguyen, P. D.; Hoffmann, M.; Pattacini, U. & Metta, G. (2016), A fast heuristic Cartesian space motion planning algorithm for many-DoF robotic manipulators in dynamic environments, in 'Humanoid Robots (Humanoids), 2016 IEEE-RAS 16th International Conference on', IEEE, pp. 884-891.



# Fast heuristic Cartesian space motion planning algorithm

## Algorithm 1 Multiple Cartesian point planning Algorithm

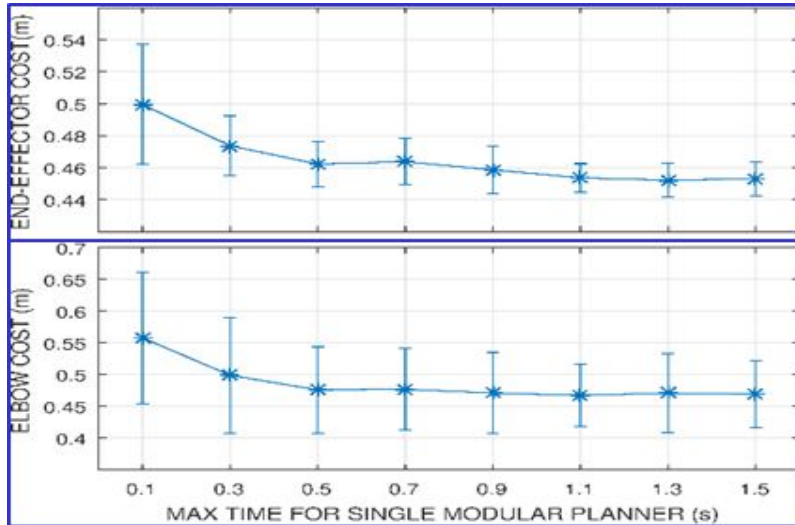
```
1: ESTIMATE – WORKSPACE
2: UPDATE – MANIPULATOR – POSE
3: OBTAIN – SCENE
4: repeat
5:   clear( $EE - path$ )
6:   while ( $\neg EE - path$ ) do
7:     MODULAR – PLANNER( $EE, EE - pos, GOAL$ )
8:   end while
9:   if ( $EE - path$ ) then
10:    for all  $w_i \in (EE - path)$  do
11:      DILATE – OBSTACLE( $w_i$ )
12:    end for
13:    repeat
14:       $i = 0$ 
15:       $s_{MP} = MP - pos$ 
16:      repeat
17:        PICK – VIAPOINT( $w_i, w_{i+1}$ )
18:         $g_{MP} = goal_{MP} \leftarrow w_{i+1}$ 
19:        MODULAR – PLANNER( $MP, s_{MP}, g_{MP}$ )
20:        if ( $size(MP - path) > 2$ ) then
21:          success  $\leftarrow$  PAD – VIAPOINT( $EE$ )
22:        end if
23:         $i \leftarrow i + 1$ 
24:      until  $size(EE - path) = size(MP - path)$ 
25:      FIND – ELBOW
26:      success  $\leftarrow$  CHECK – COLLISION – ELBOW
27:    until ( $\neg EB - collisions$ )
28:  end if
29: 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 algorithm

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!

# Further reading and resources

- Books / book sections
  - Bartneck, C., Belpaeme, T., Eyssele, 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.