

PLANNING OPTIMAL MOTIONS FOR ANTHROPOMORPHIC SYSTEMS

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Under the supervision of
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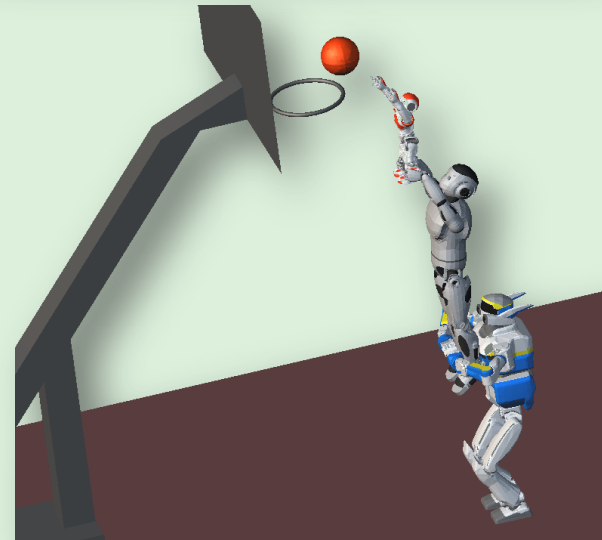
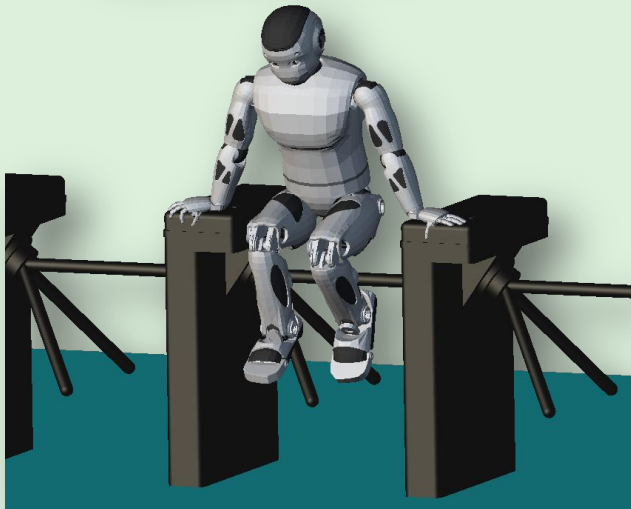
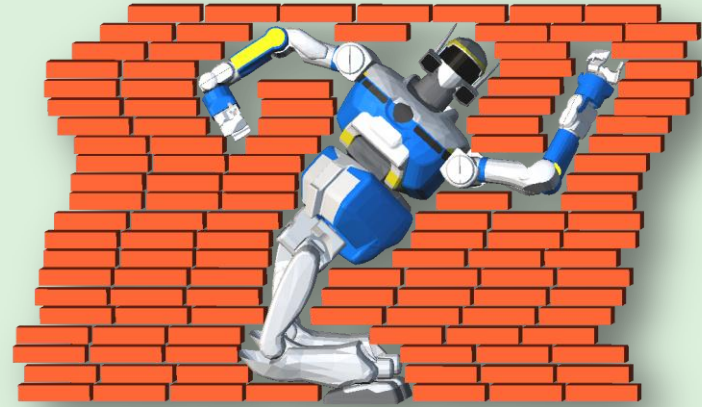
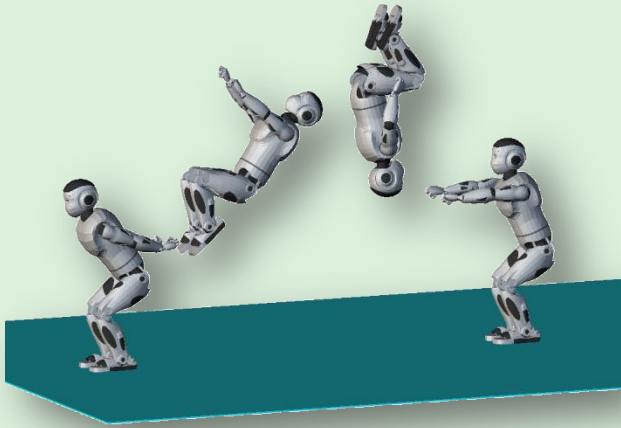
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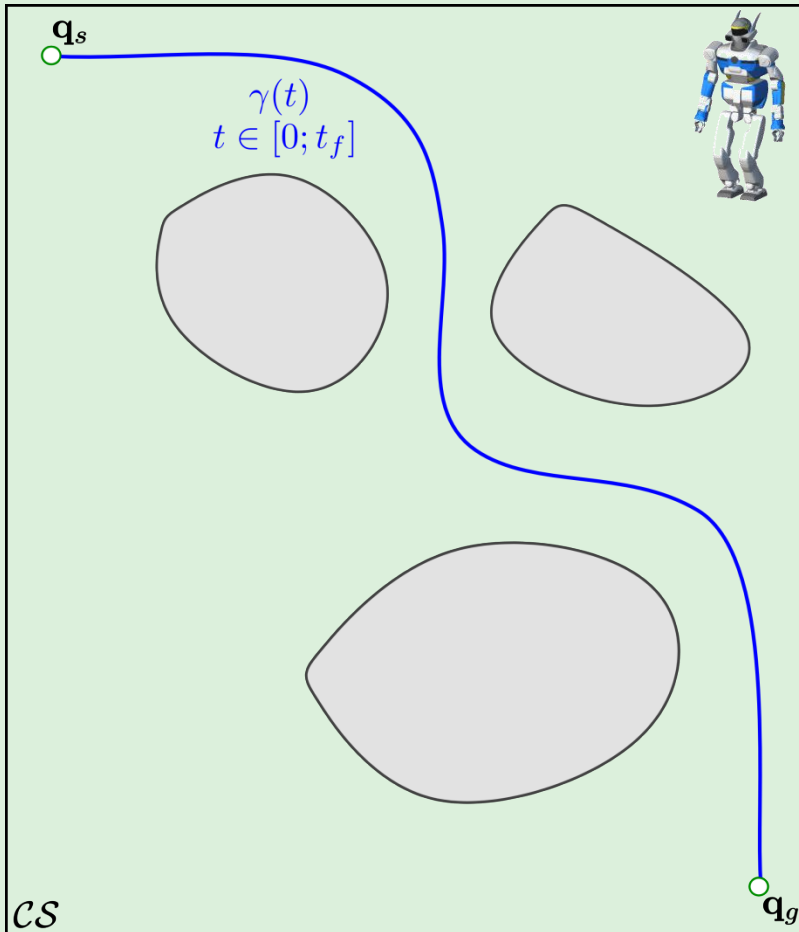
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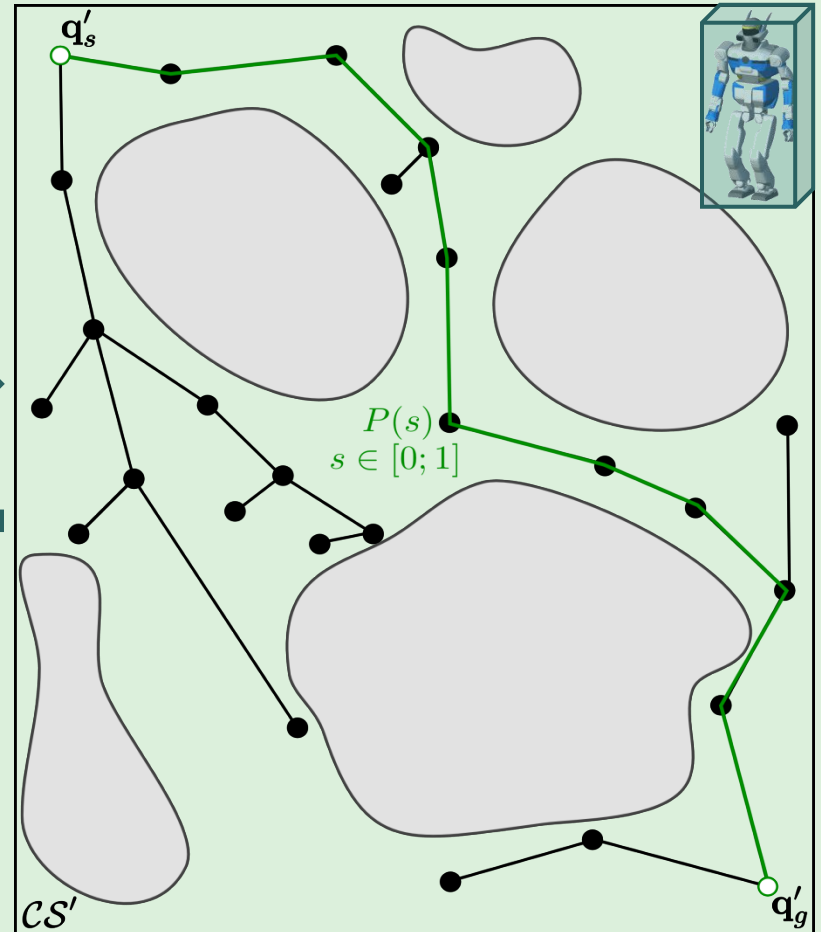
THE MOTION PLANNING PROBLEM



A DECOUPLED APPROACH FOR MOTION PLANNING



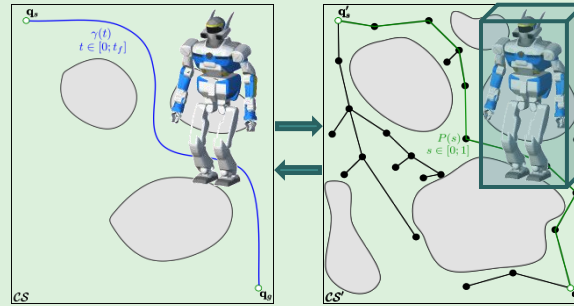
[Lozano-Perez (TRO 1983)]



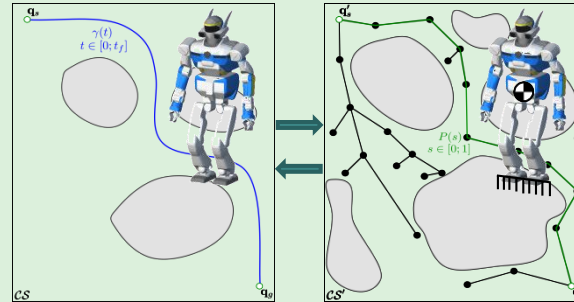
[Kuffner et al. (ICRA 2000)]

OUTLINE

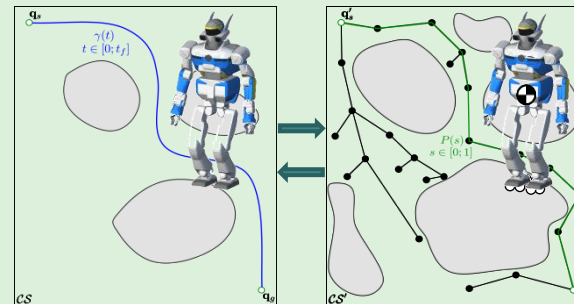
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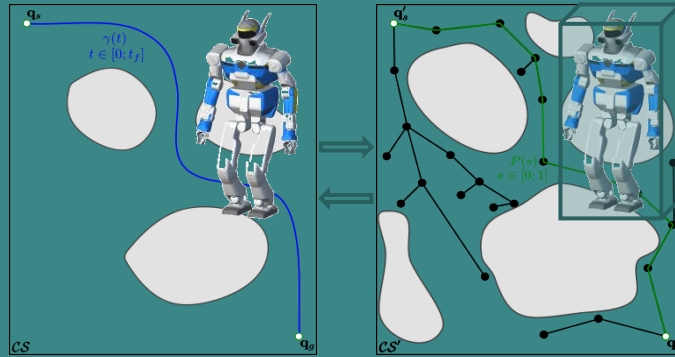


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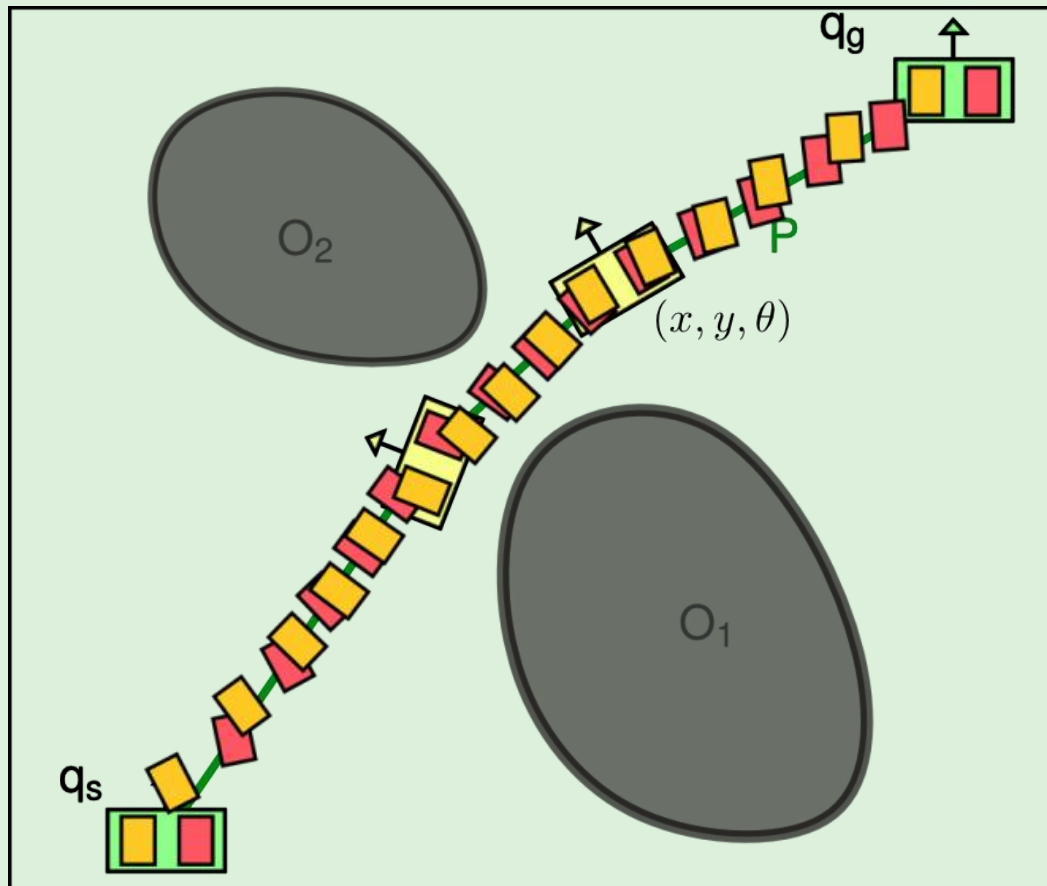


PATH OPTIMIZATION FOR THE BOUNDING BOX APPROACH

1

PROBLEM SIMPLIFICATION: THE BOUNDING BOX APPROACH

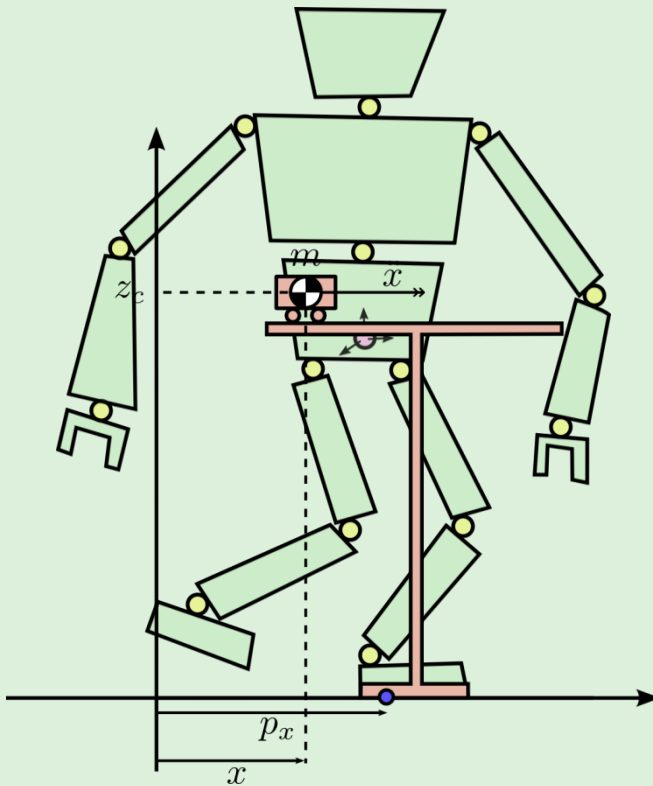
- Simplification of planning: 3-DoF bounding box of the robot



[Yoshida et al. (TRO 2008)]

CART-TABLE MODEL

- Dynamic balance criterion for walking robots on a flat surface: the **Zero-Moment Point (ZMP)** [Vukobratovic et al. (TBE 1969)]

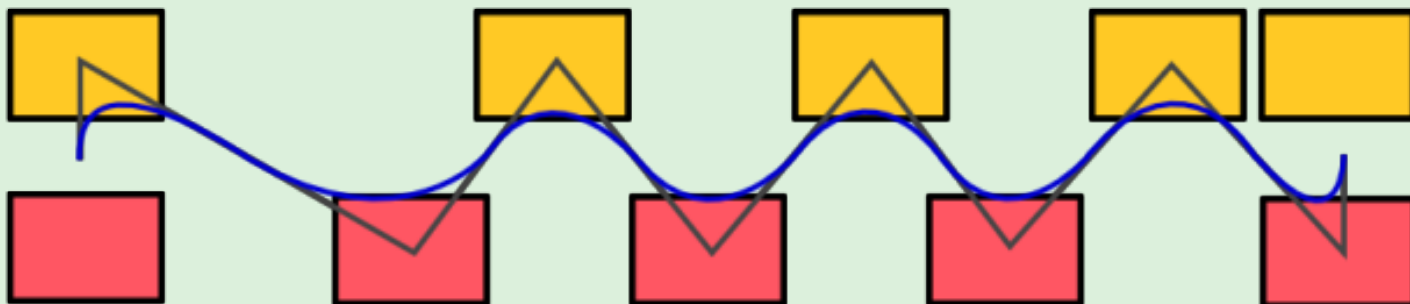


$$\begin{pmatrix} p_x \\ p_y \end{pmatrix} = \begin{pmatrix} x - \frac{z_c}{g} \ddot{x} \\ y - \frac{z_c}{g} \ddot{y} \end{pmatrix}$$

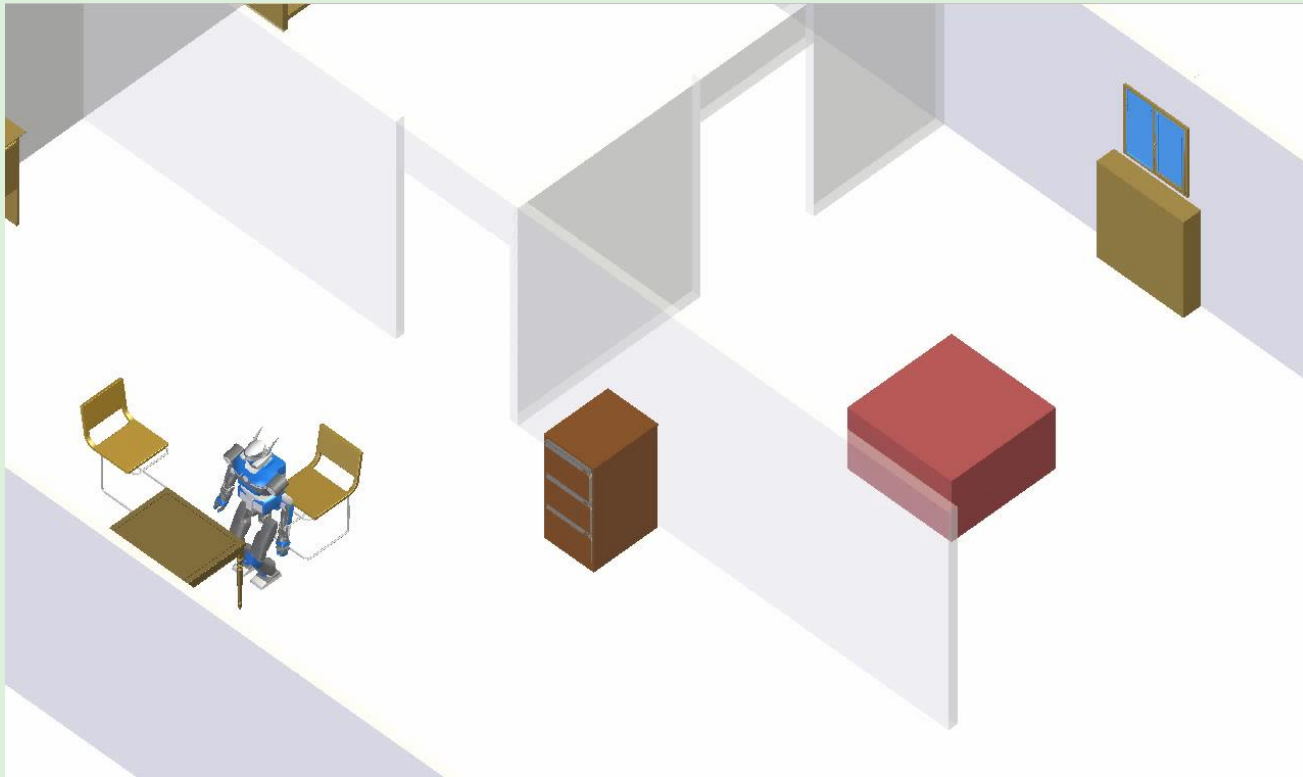
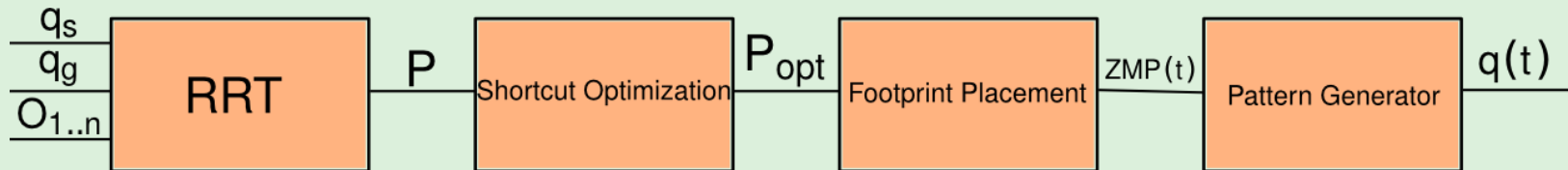
PREVIEW-CONTROL-BASED PATTERN GENERATOR

- The **Center of Mass (CoM)** trajectory is generated from a desired ZMP trajectory for the cart-table model

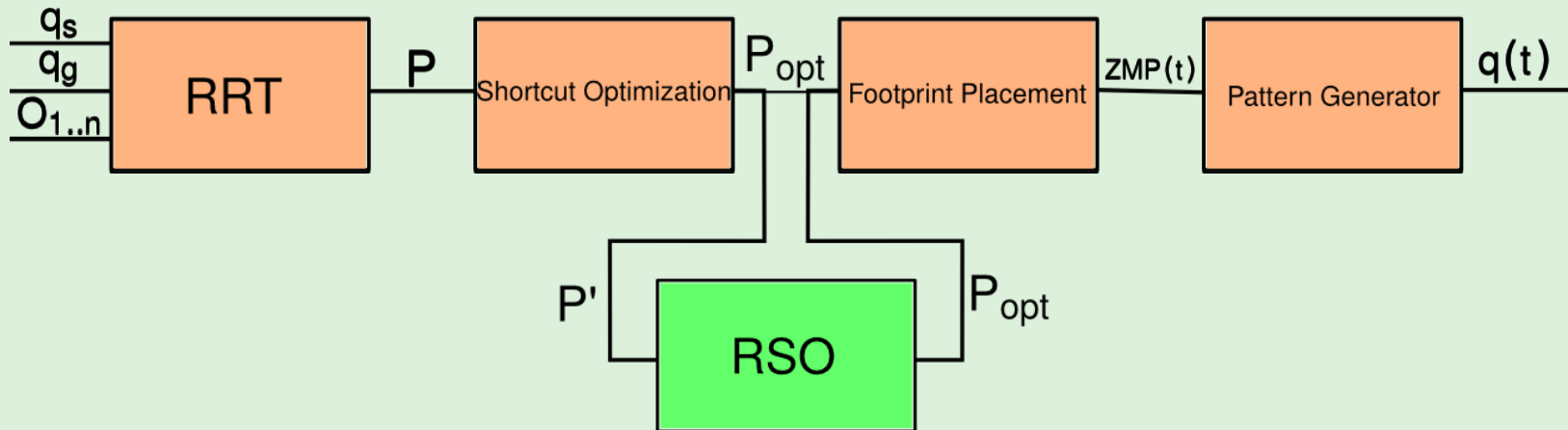
— Desired ZMP trajectory
— CoM trajectory



SO WHAT'S WRONG?

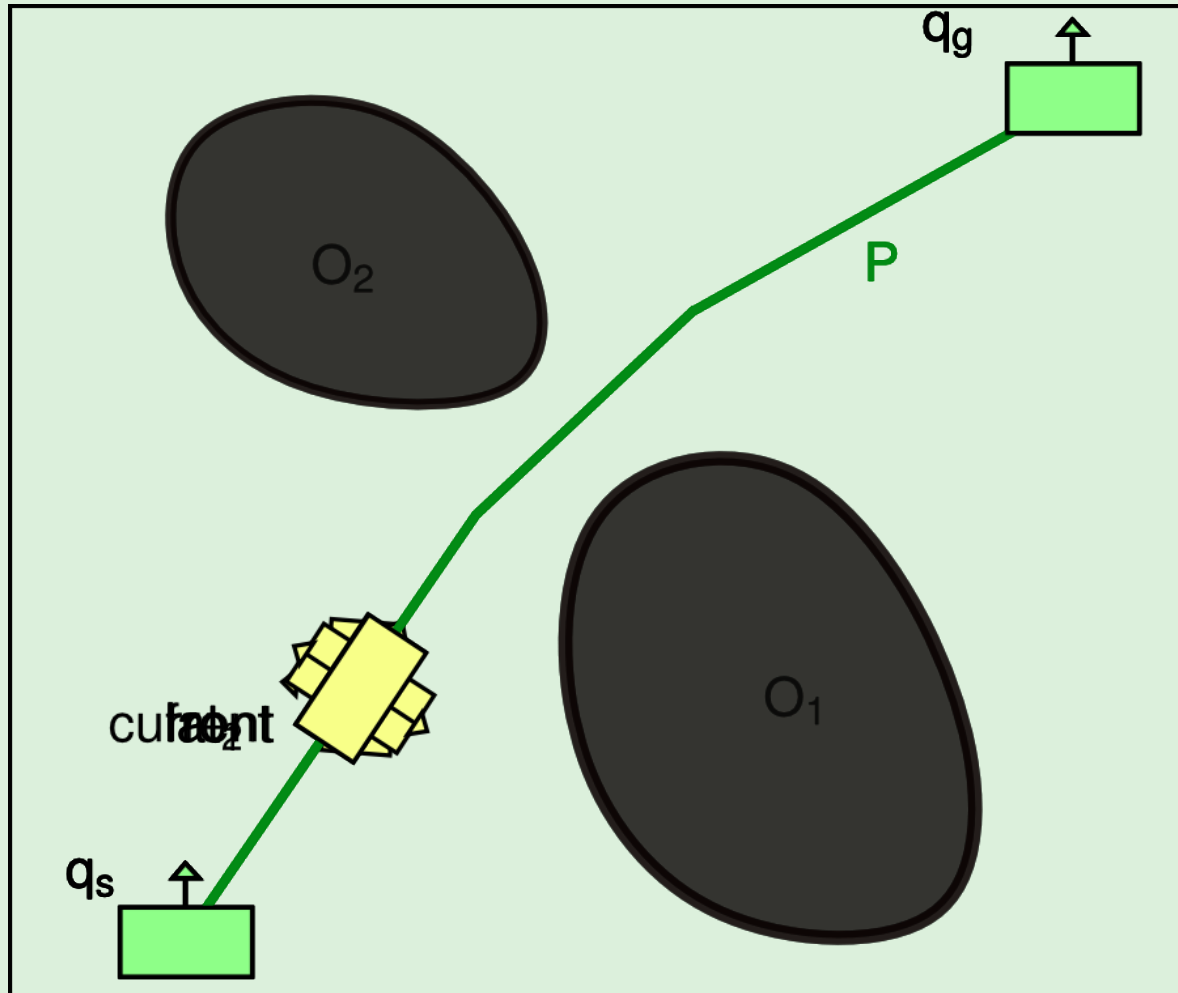


CONTRIBUTION: REGULAR SAMPLING OPTIMIZATION (RSO)

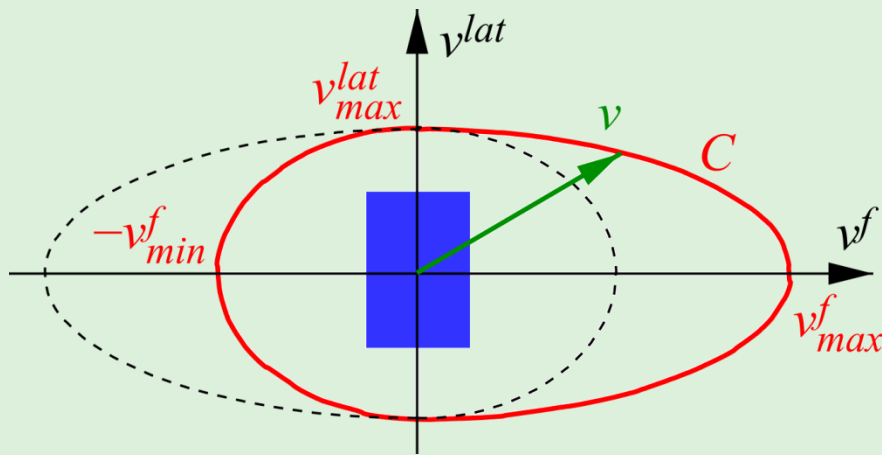


- What is wrong with the current scheme?
 - Random nature of RRT \Rightarrow Random path
 - Even after shortcut optimization, robot orientation is still random
- Need for frontal walking
 - Shorter trajectories (in time)
 - Camera facing the walking direction

REGULAR SAMPLING OPTIMIZATION (RSO)



COST FUNCTION

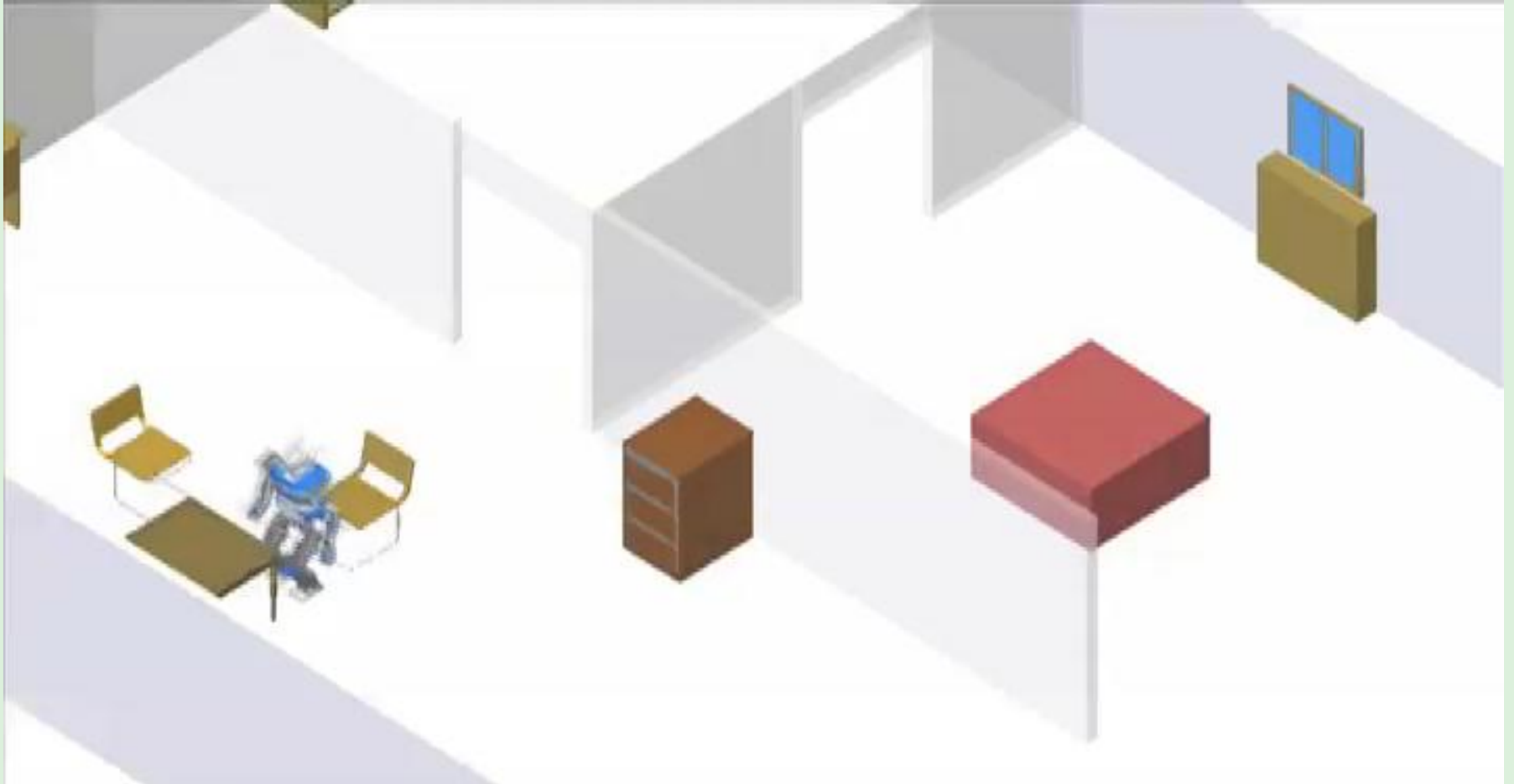


$$C = \begin{cases} \left(\frac{v^f}{v_{max}^f} \right)^2 + \left(\frac{v^{lat}}{v_{max}^{lat}} \right)^2 - 1 & \text{if } v^f \geq 0 \\ \left(\frac{v^f}{v_{min}^f} \right)^2 + \left(\frac{v^{lat}}{v_{max}^{lat}} \right)^2 - 1 & \text{if } v^f < 0 \end{cases}$$

$$cost(\mathbf{q}_i, \mathbf{q}_j) = \int_0^L \frac{1}{v(s)} ds \quad (\text{Walking time})$$

- Heuristic function: cost of walking frontally from \mathbf{q}_i to \mathbf{q}_g while staying on P

APARTMENT SCENARIO



PERFORMANCE OF REGULAR SAMPLING OPTIMIZATION

■ Computation time (s)

	RRT	Shortcut Optimization	RSO	Total
Chairs	4.0	1.9	2.1	8.0
Boxes	0.092	2.5	0.24	2.8
Apartment	1.2	2.4	2.4	6.0

■ Walking time (s)

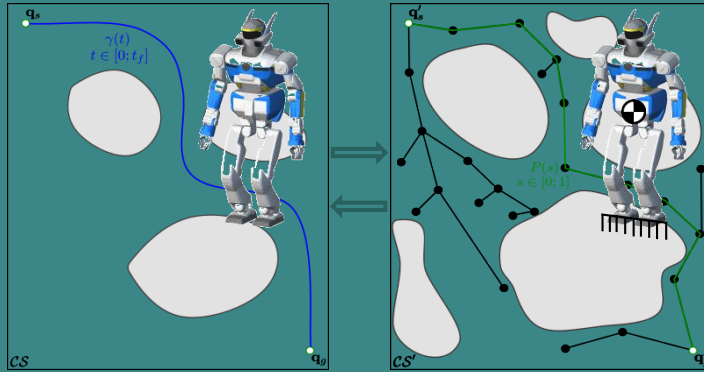
	Shortcut Optimization	Shortcut Optimization + RSO
Chairs	40	35
Boxes	66	57
Apartment	200	120

SUMMARY

- **Summary of RSO**
 - Regular sampling of path
 - Four orientations states for each sample configuration
 - A* search with time as cost function
- **Discussion of results**
 - Optimized trajectories are shorter with respect to walk time
 - Very low computational overhead to the planning scheme when compared to walking time gain

BUT...

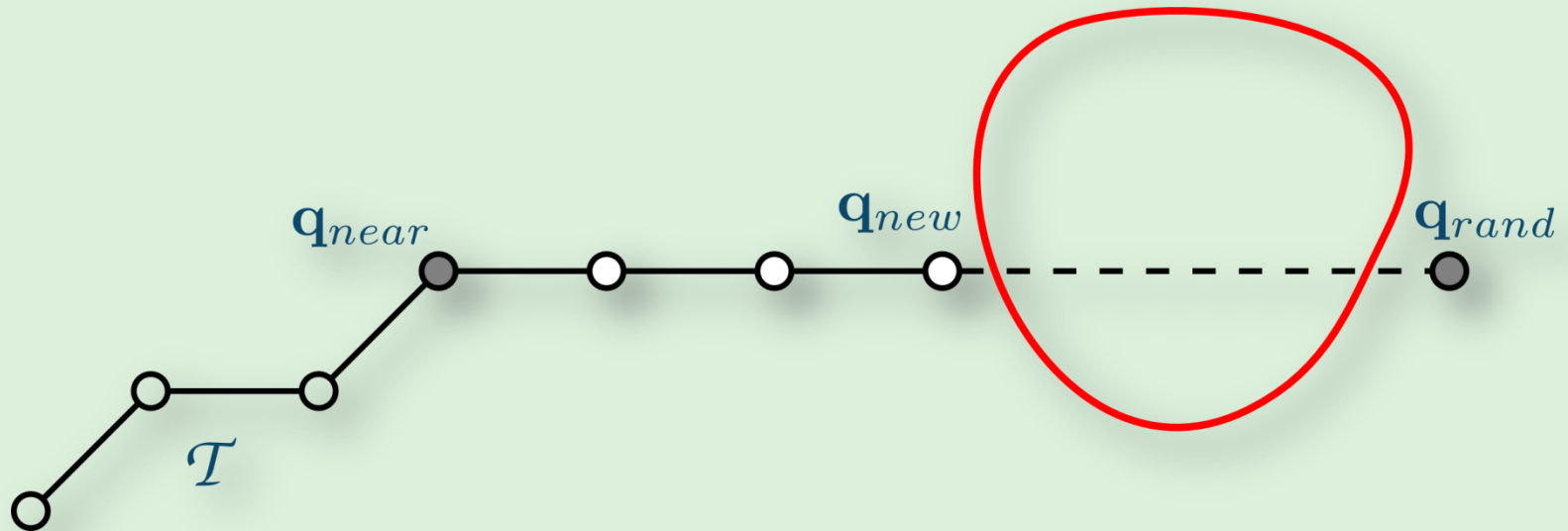




WHOLE-BODY OPTIMAL MOTION PLANNING

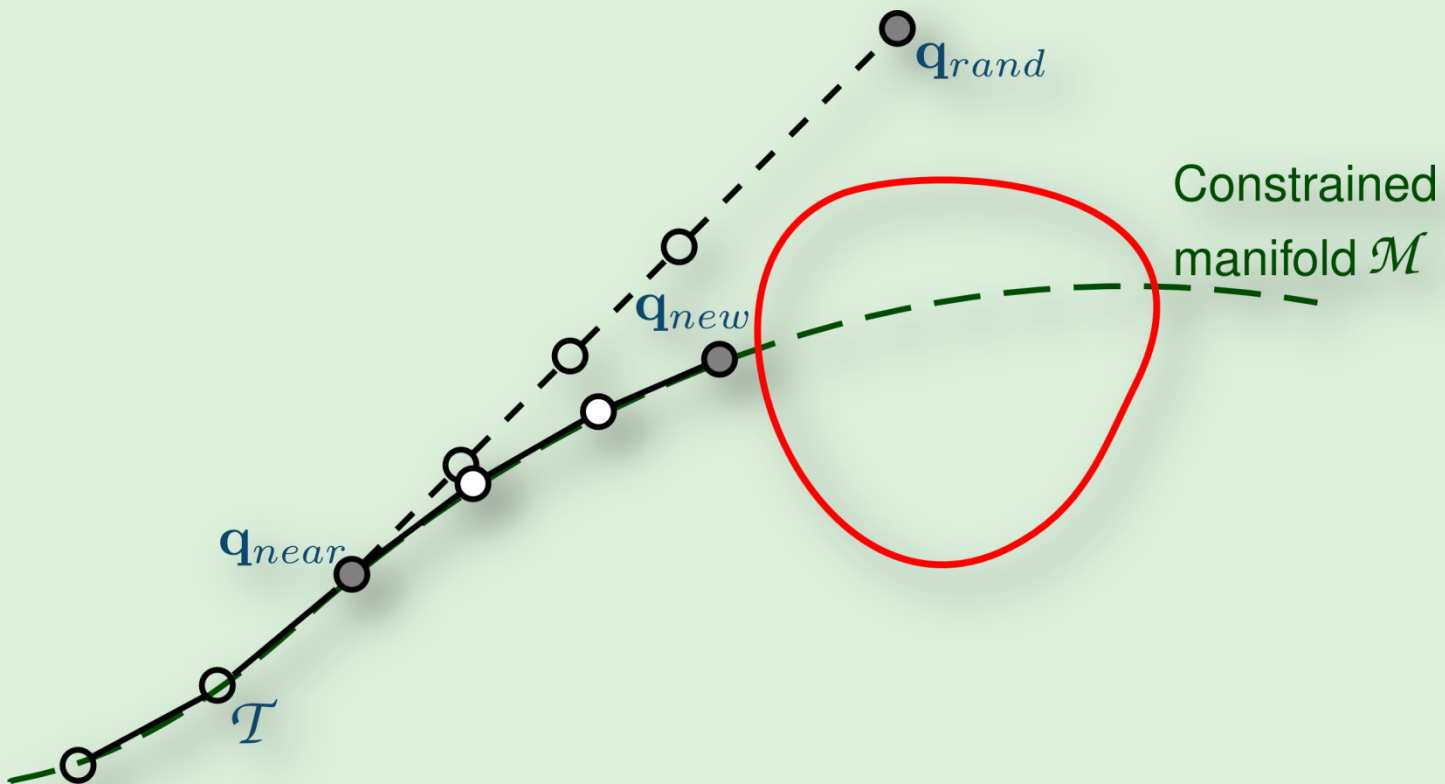
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RRT EXTENSION



PLANNING ON A CONSTRAINED MANIFOLD

- Contact and static balance constraints: plan on a zero-measure manifold $\mathbf{f}(\mathbf{q}) = \mathbf{0}$



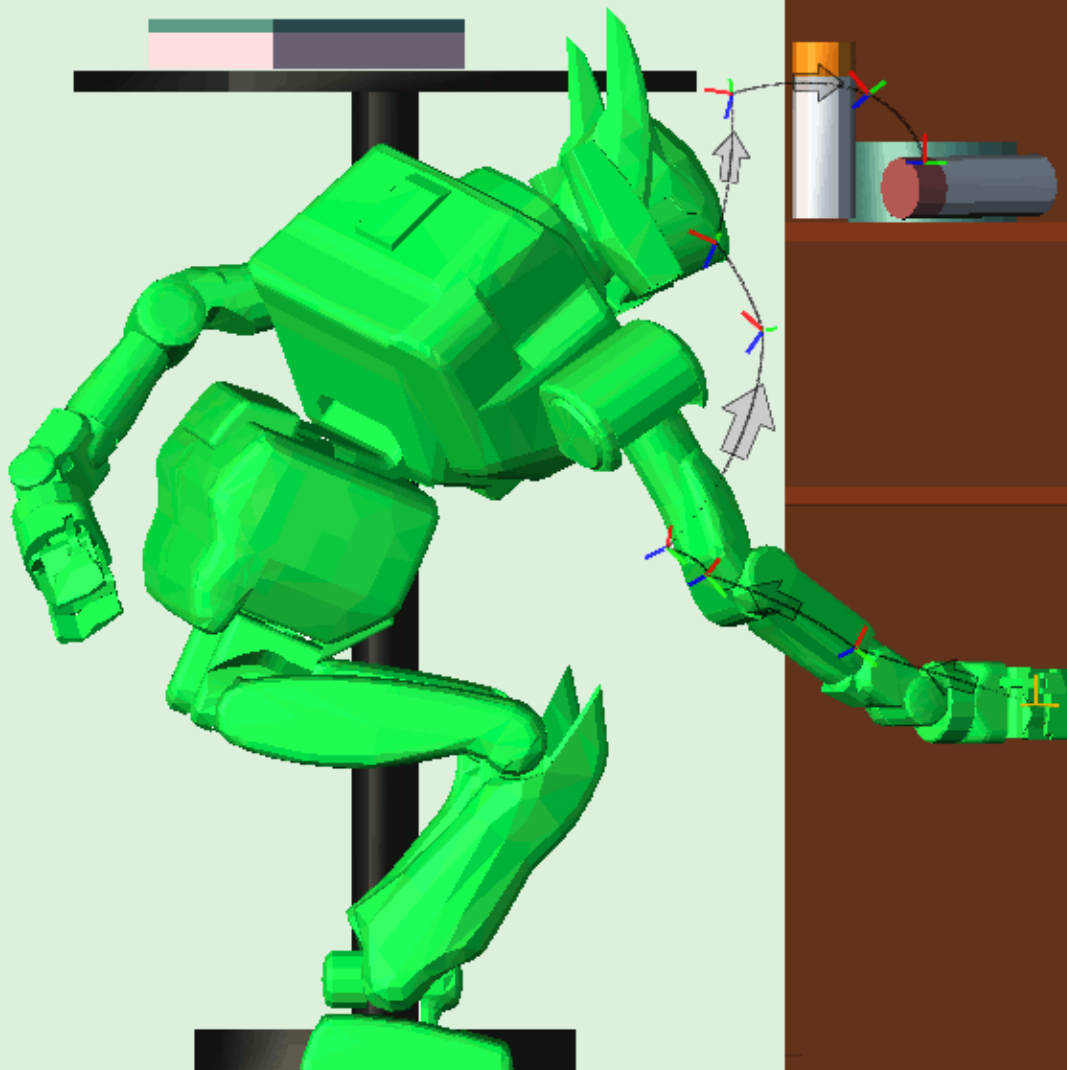
STATICALLY BALANCED PATH PLANNING

Planning
manifold:

Fixed right foot
6D position

Fixed left foot
6D position

Center of mass
projection at
support polygon
center



CONSTRAINED RRT: PROPERTIES AND DRAWBACKS

■ Properties

- Generation of quasi-static collision-free paths.
- Probabilistic completeness.
- Geometric local minima avoidance.

■ Drawbacks

- Random and long paths.
- No time parametrization.
- Additional processing needed to obtain a feasible trajectory.

NUMERICAL OPTIMIZATION FOR OPTIMAL CONTROL PROBLEMS (NOC)

$$\min_{\mathbf{x}(\cdot), \mathbf{u}(\cdot), T} J(\mathbf{x}(t), \mathbf{u}(T), T) = \int_0^T L(\mathbf{x}(t), \mathbf{u}(t)) dt + \Phi(\mathbf{x}(T))$$

$$\begin{aligned}\dot{\mathbf{x}}(t) &= \mathbf{f}(t, \mathbf{x}(t), \mathbf{u}(t)), & t \in [0, T], \\ \mathbf{g}(t, \mathbf{x}(t), \mathbf{u}(t)) &= \mathbf{0}, & t \in [0, T], \\ \mathbf{h}(t, \mathbf{x}(t), \mathbf{u}(t)) &\geq \mathbf{0}, & t \in [0, T], \\ \mathbf{r}(\mathbf{x}(0), \mathbf{x}(T)) &= \mathbf{0}.\end{aligned}$$

- \mathbf{x}, \mathbf{u} : state and control vectors
- \mathbf{f} : differential equation of the model
- $\mathbf{g}, \mathbf{h}, \mathbf{r}$: constraint vector functions

NOC: PROPERTIES AND DRAWBACKS

■ Properties

- Generation of locally optimal trajectories.
- Enforcement of equality and inequality constraints.

■ Drawbacks

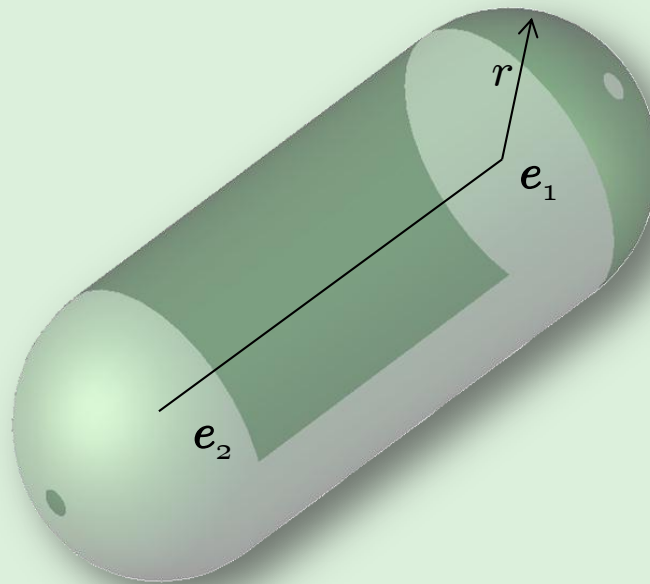
- Possible failure if stuck in local minima.
- Success depends of the “initial guess”.
- Prior processing needed to guarantee optimization success.

A DECOUPLED APPROACH FOR OPTIMAL MOTION PLANNING

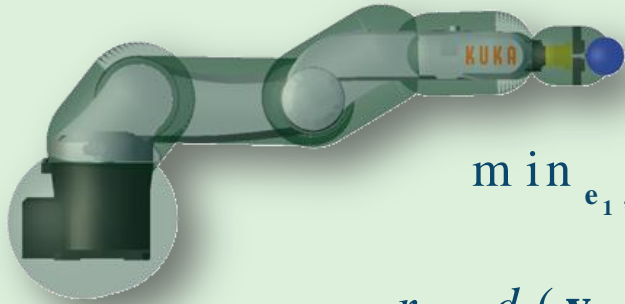
- Optimal motion planning two-stage scheme:
 first plan draft path, then optimize
- Locally optimal collision-free trajectory generation
- Application to a humanoid robot with fixed coplanar contact points

(SELF-)COLLISION AVOIDANCE: CAPSULE BOUNDING VOLUMES

- Capsule: Set of points lying at a distance r from a segment
- Simple to implement
- Fast distance and penetration computation

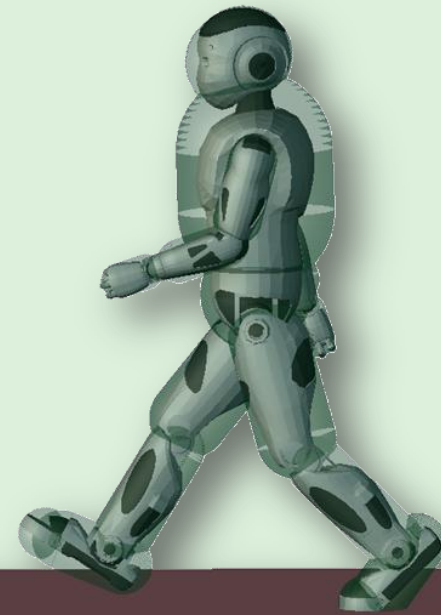
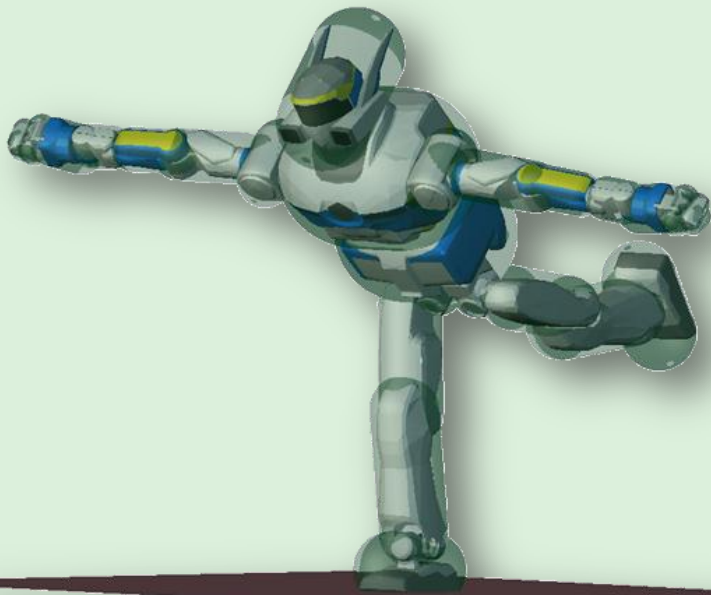


MINIMUM BOUNDING CAPSULE OVER A POLYHEDRON



$$\min_{\mathbf{e}_1, \mathbf{e}_2, r} \left\| \mathbf{e}_2 - \mathbf{e}_1 \right\| \pi r^2 + \frac{4}{3} \pi r^3$$

$$r - d(\mathbf{v}, \mathbf{e}_1 \mathbf{e}_2) \geq 0, \text{ for all } \mathbf{v} \in \mathcal{P}$$



OPTIMAL CONTROL PROBLEM FORMULATION

$$\mathbf{x}(t) = [\mathbf{q}(t), \dot{\mathbf{q}}(t), \ddot{\mathbf{q}}(t)]^T$$

$$\mathbf{u}(t) = [\ddot{\mathbf{q}}(t)]^T$$

$$J = \int_0^T \ddot{\mathbf{q}}(t)^T \ddot{\mathbf{q}}(t) dt$$

$$\underline{\mathbf{q}} \leq \mathbf{q}(t) \leq \overline{\mathbf{q}}$$

$$\underline{\dot{\mathbf{q}}} \leq \dot{\mathbf{q}}(t) \leq \overline{\dot{\mathbf{q}}}$$

$$\underline{\boldsymbol{\tau}} \leq \boldsymbol{\tau}(t) \leq \overline{\boldsymbol{\tau}}$$

$$\mathbf{p}_{lf}(\mathbf{q}(t)) = \mathbf{p}_{lf}(\mathbf{q}(0))$$

$$\mathbf{p}_{rf}(\mathbf{q}(t)) = \mathbf{p}_{rf}(\mathbf{q}(0))$$

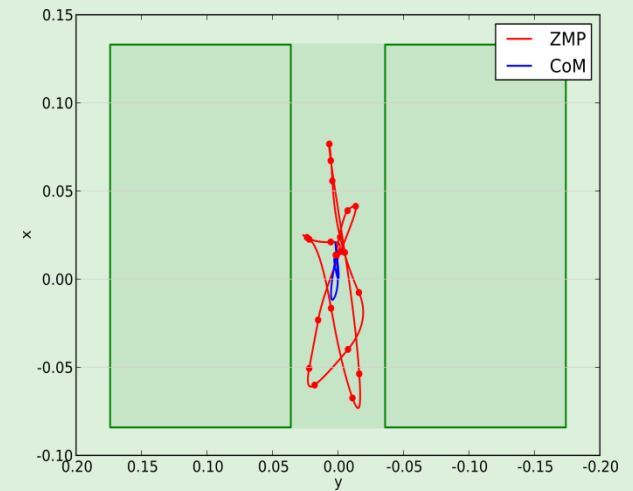
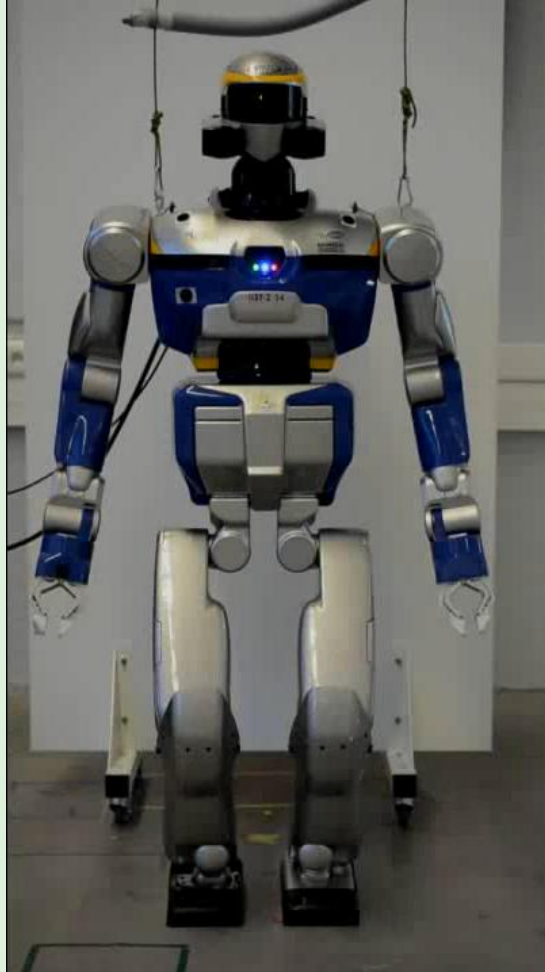
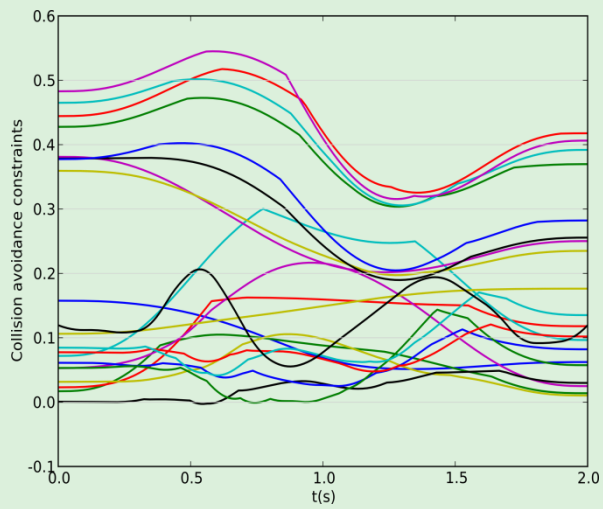
$$\mathbf{p}_{zmp}(\mathbf{q}(t), \dot{\mathbf{q}}(t), \ddot{\mathbf{q}}(t)) \in \mathcal{P}_{sup}$$

$$\mathbf{d}_{min}(t) \geq \mathbf{0}$$

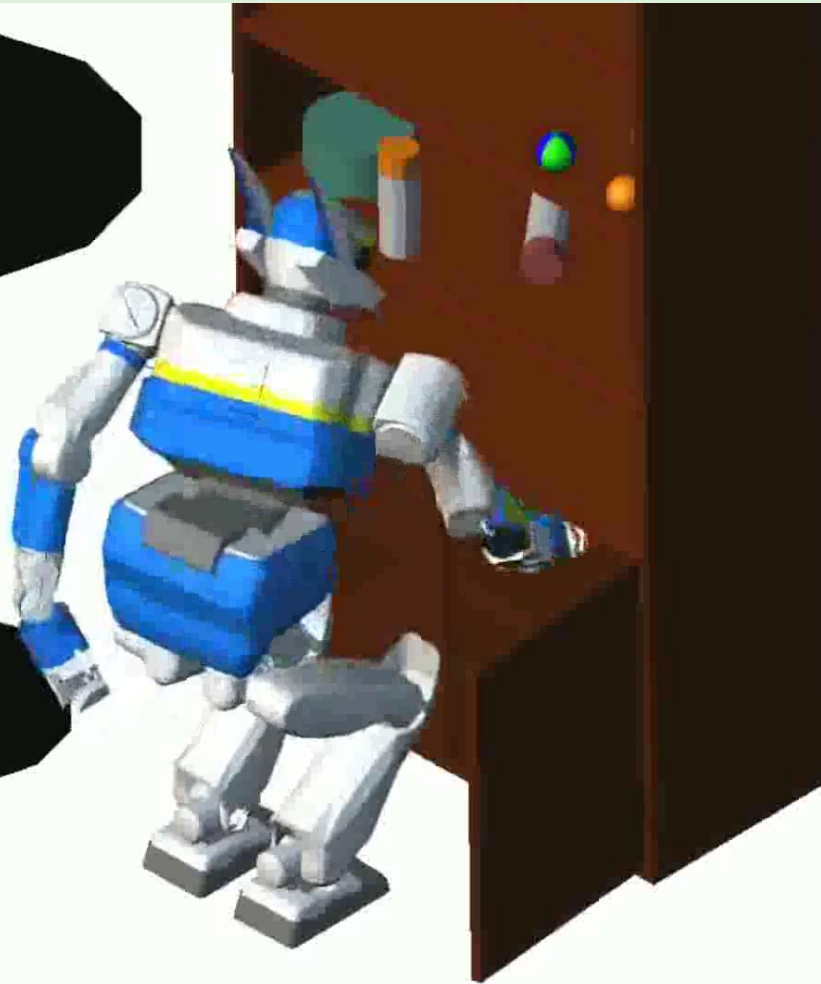
OPTIMAL CONTROL PROBLEM SOLVER

- MUSCOD-II: specially tailored SQP solver.
- Trajectory search space: $\ddot{q}(t)$ (or jerk) piecewise linear.
- Discretized constraints: 20 nodes over trajectory.

MARTIAL ARTS MOTION



SHELVES SCENARIO

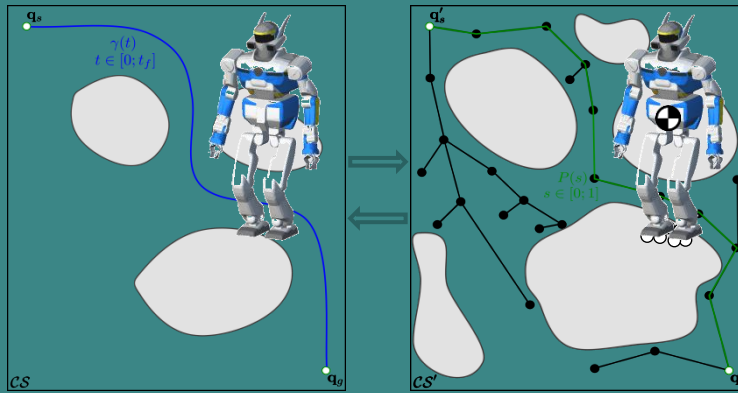


SUMMARY

- Decoupled approach: first plan, then optimize.
- Draft path provided by constrained planner.
- Path used as initial guess by numerical optimal control solver
- Generated trajectories are locally optimal, feasible, and collision-free.

BUT...

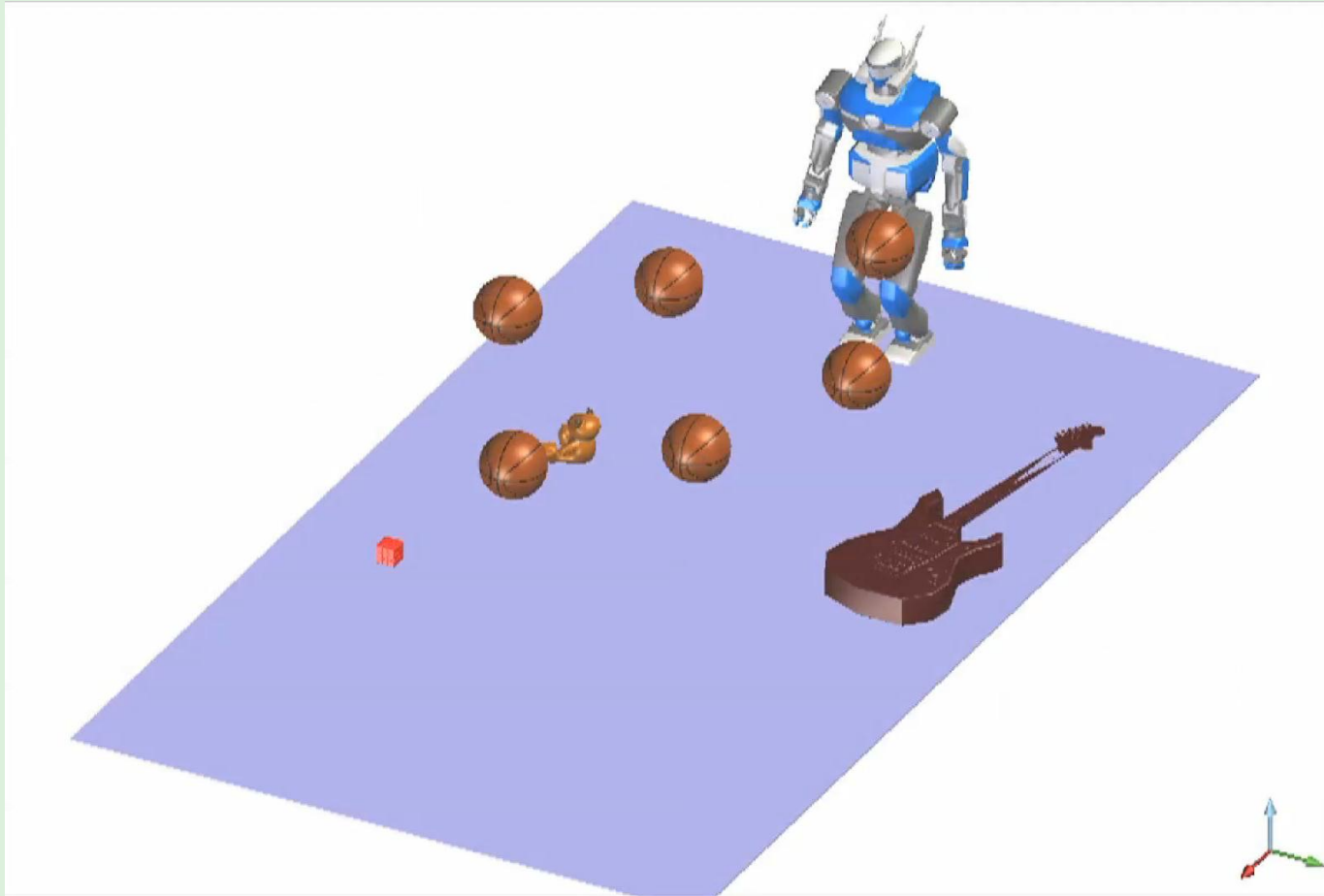
- **Optimal control solver: black box**
 - Even with a proper initial guess and duration, solver fails sometimes
 - Difficult to tune
- **Problems are sensitive to scaling**
- **Very long computation time**
- **Difficult to extend to walking motions**



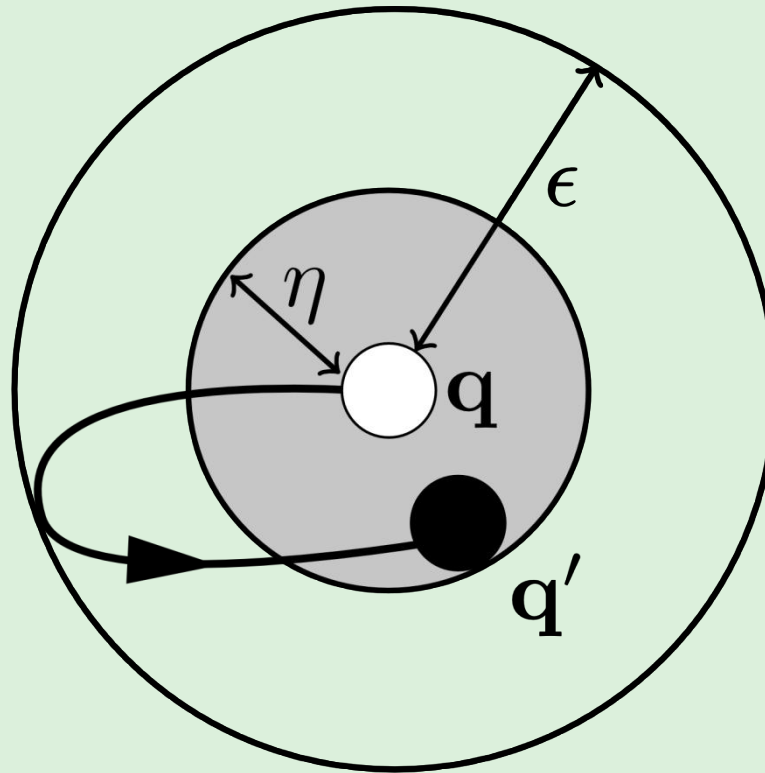
A WHOLE-BODY MOTION PLANNER FOR DYNAMIC WALKING

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PLANNING ON A CONSTRAINED MANIFOLD

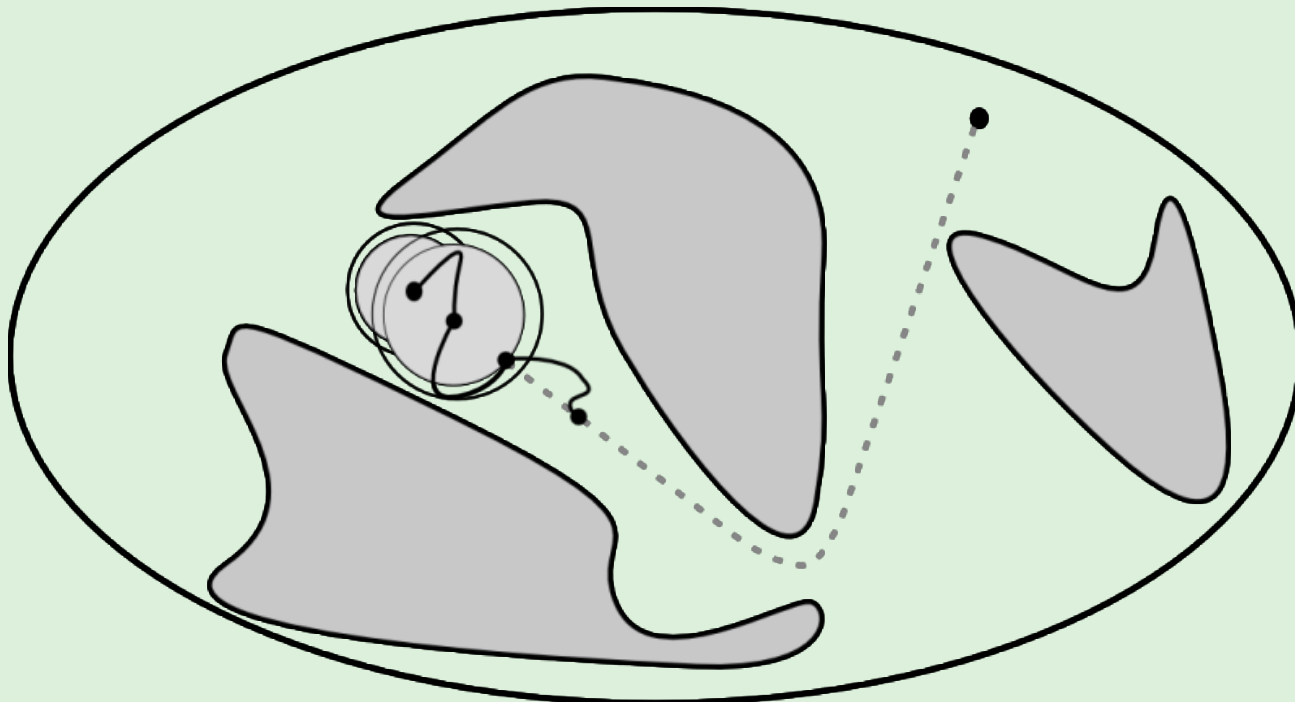


SMALL-SPACE CONTROLLABILITY

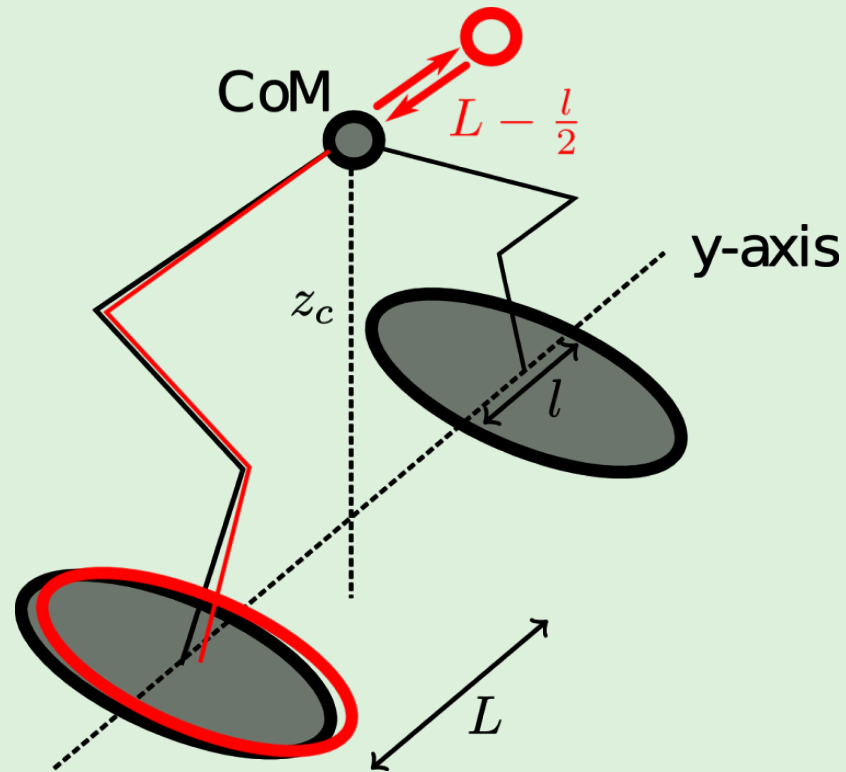


SMALL-SPACE CONTROLLABILITY

- For small-space controllable systems any collision-free path can be approximated by a sequence of collision-free feasible trajectories



SMALL-SPACE CONTROLLABILITY OF A WALKING HUMANOID ROBOT



- A quasi-statically walking humanoid robot is not small-space controllable

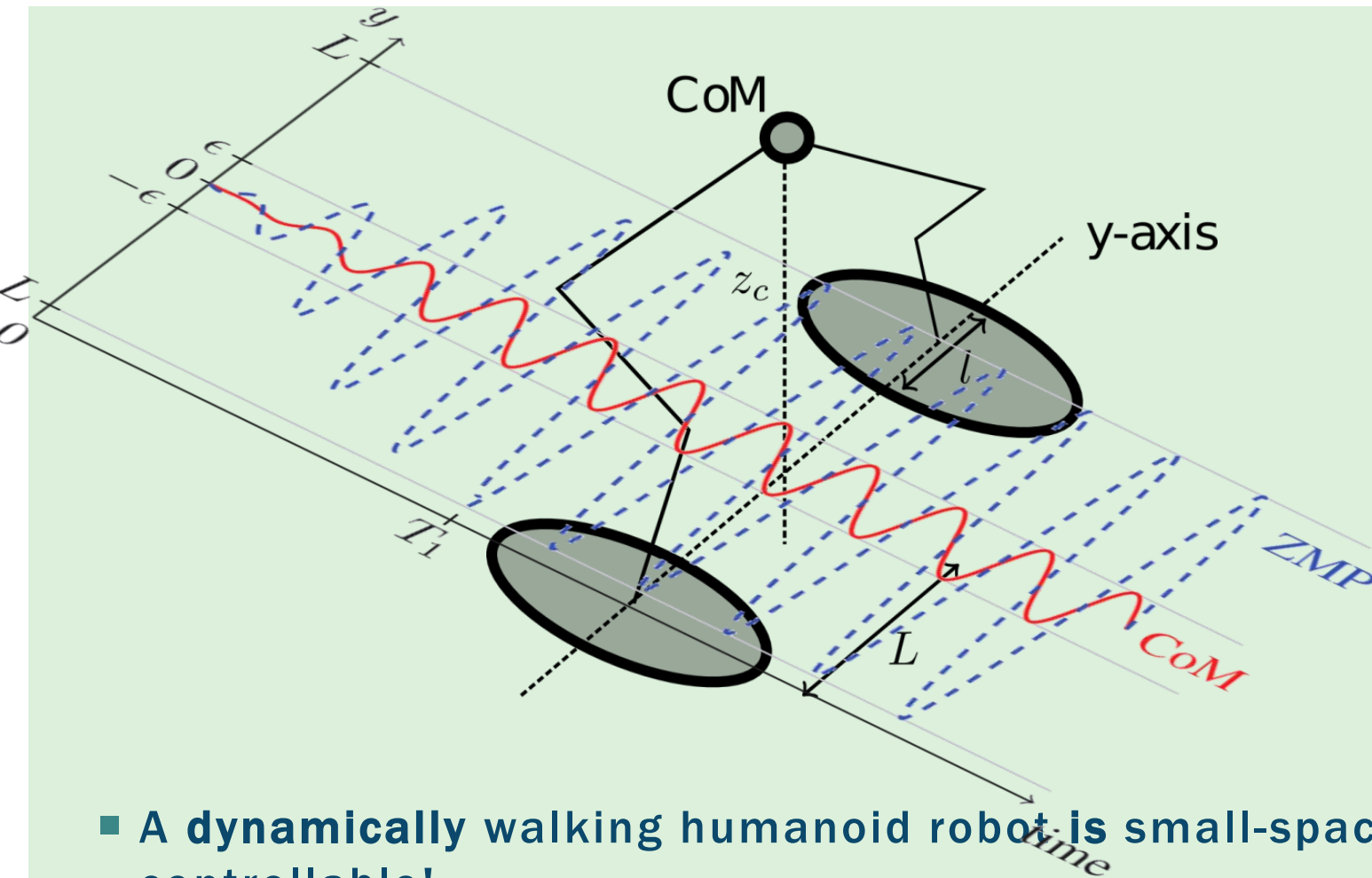
SMALL-SPACE CONTROLLABILITY OF A WALKING HUMANOID ROBOT

■ Cart-table model:
$$\begin{pmatrix} p_x \\ p_y \end{pmatrix} = \begin{pmatrix} x - \frac{1}{\omega_0^2} \ddot{x} \\ y - \frac{1}{\omega_0^2} \ddot{y} \end{pmatrix}, \quad \omega_0^2 = \frac{g}{z_c}$$

■ $y(t) = \epsilon \sin(\omega t) \longrightarrow p_y(t) = \left(1 + \left(\frac{\omega}{\omega_0}\right)^2\right) \epsilon \sin(\omega t)$

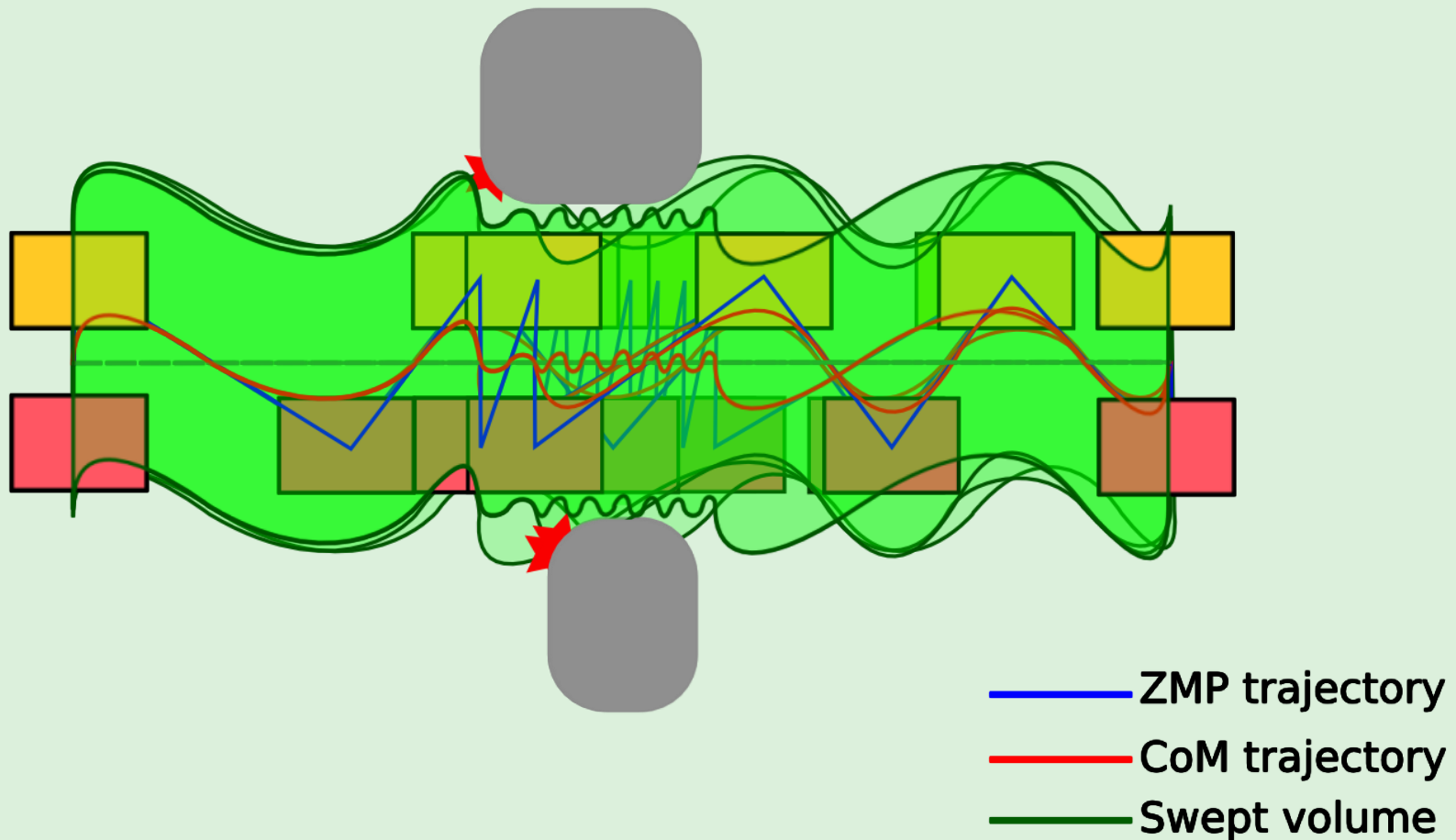
- Moving the CoM fast enough in an arbitrarily small neighborhood generates dynamically balanced walk

SMALL-SPACE CONTROLLABILITY OF A WALKING HUMANOID ROBOT

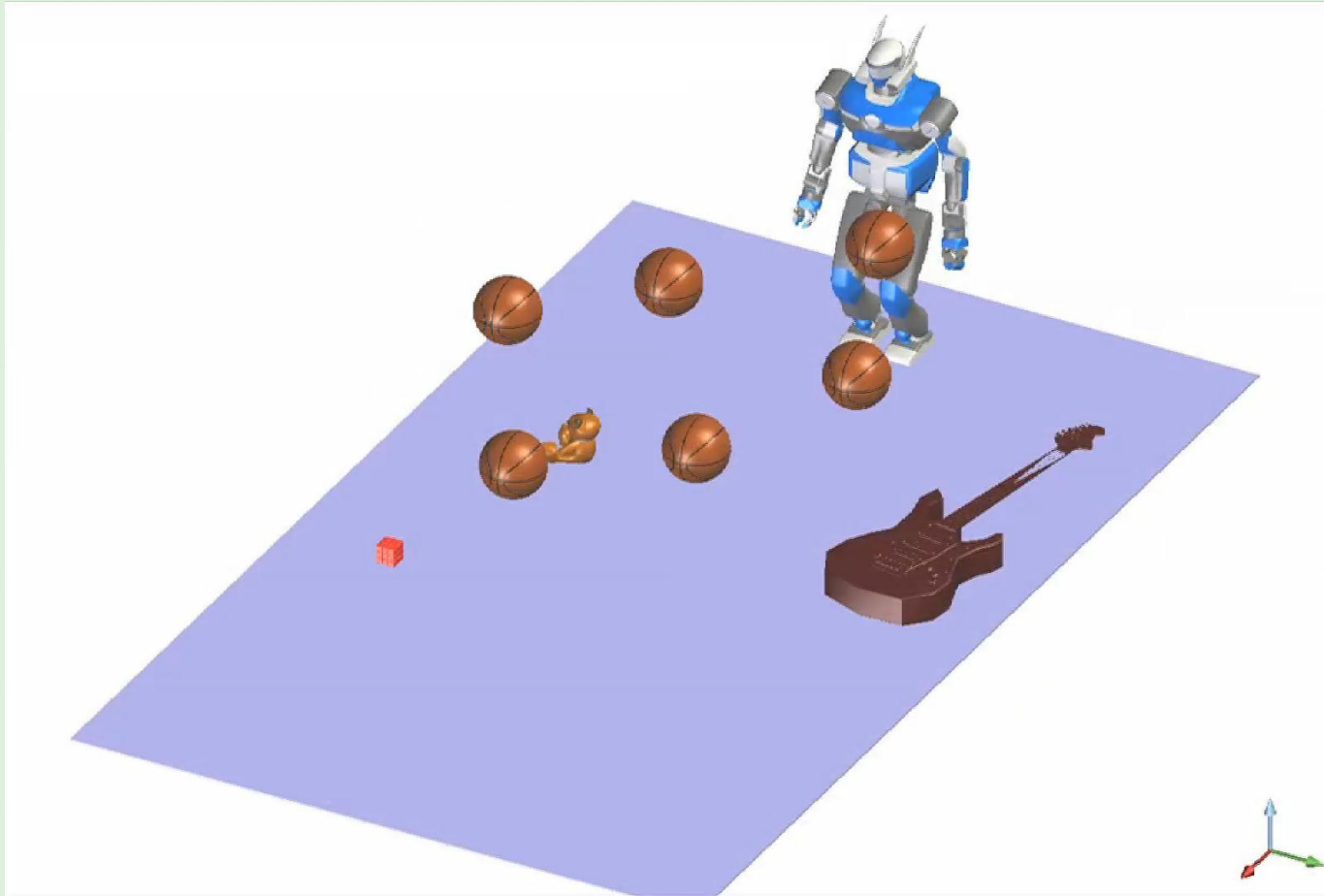


- A dynamically walking humanoid robot is small-space controllable!

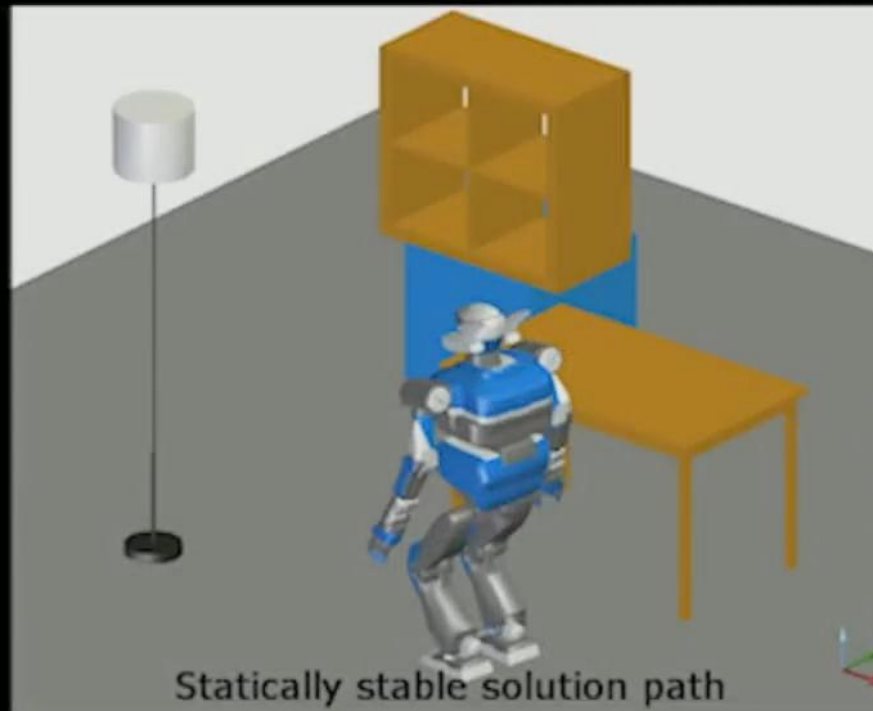
A TWO-STEP WHOLE-BODY MOTION PLANNING ALGORITHM



WHOLE-BODY MOTION PLANNING IN A CLUTTERED ENVIRONMENT



APPLICATION ON THE HRP-2



SUMMARY

- A dynamically-walking humanoid robot is small-space controllable
- A two-step well-grounded algorithm for whole-body motion planning on a flat surface
 - Plan a draft sliding quasi-static path
 - Use the small-space controllability property to approximate it with a sequence of collision-free steps
- Combine navigation and manipulation seamlessly
- Simpler, more reliable and faster than whole-body optimal control

CONCLUSION

SUMMARY OF CONTRIBUTIONS

- Efficient path optimization method for humanoid walk planning when using a bounding box approach [ICINCO 2011]
- Combining constrained path planning and optimal control methods for the generation of locally optimal collision-free trajectories [ICRA 2013]
- Generalization of constrained path planning to walk planning [Humanoids 2011, IJRR 2013]
- All contributions used to generate motions on the HRP-2 humanoid robot

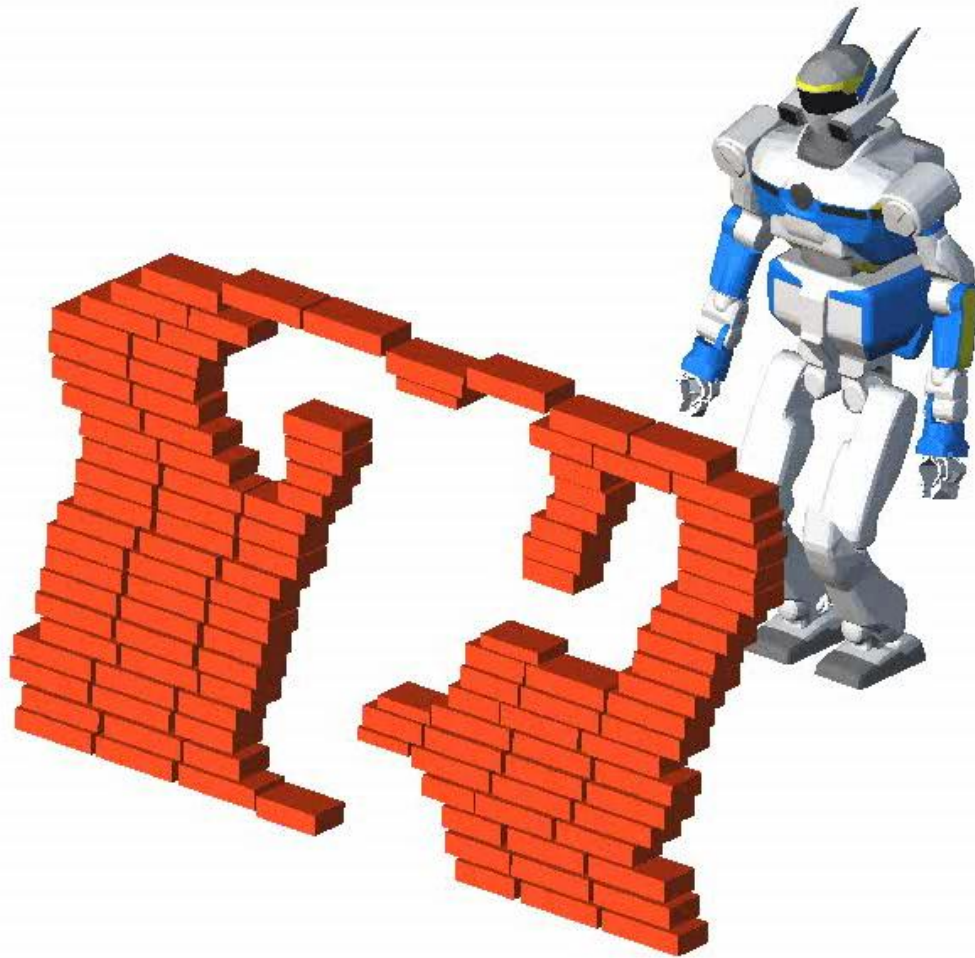
CONCLUSION

- **Decoupled approach for motion planning**
 - Easy
 - Fast
 - Sound

- **Instead of generating complex motions for complex dynamics**
 - Focus on simpler systems
 - Find equivalence properties
 - Solve efficiently and reliably a particular class of motion planning problems

OPEN QUESTIONS

- How can we execute trajectories **reliably** in uncertain environments?
- Can we extend the small-space controllability property to **multi-contact** motion?



THANK YOU
FOR YOUR
ATTENTION