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Humanoid Dance Simulation Using Hybrid Model Predictive Control

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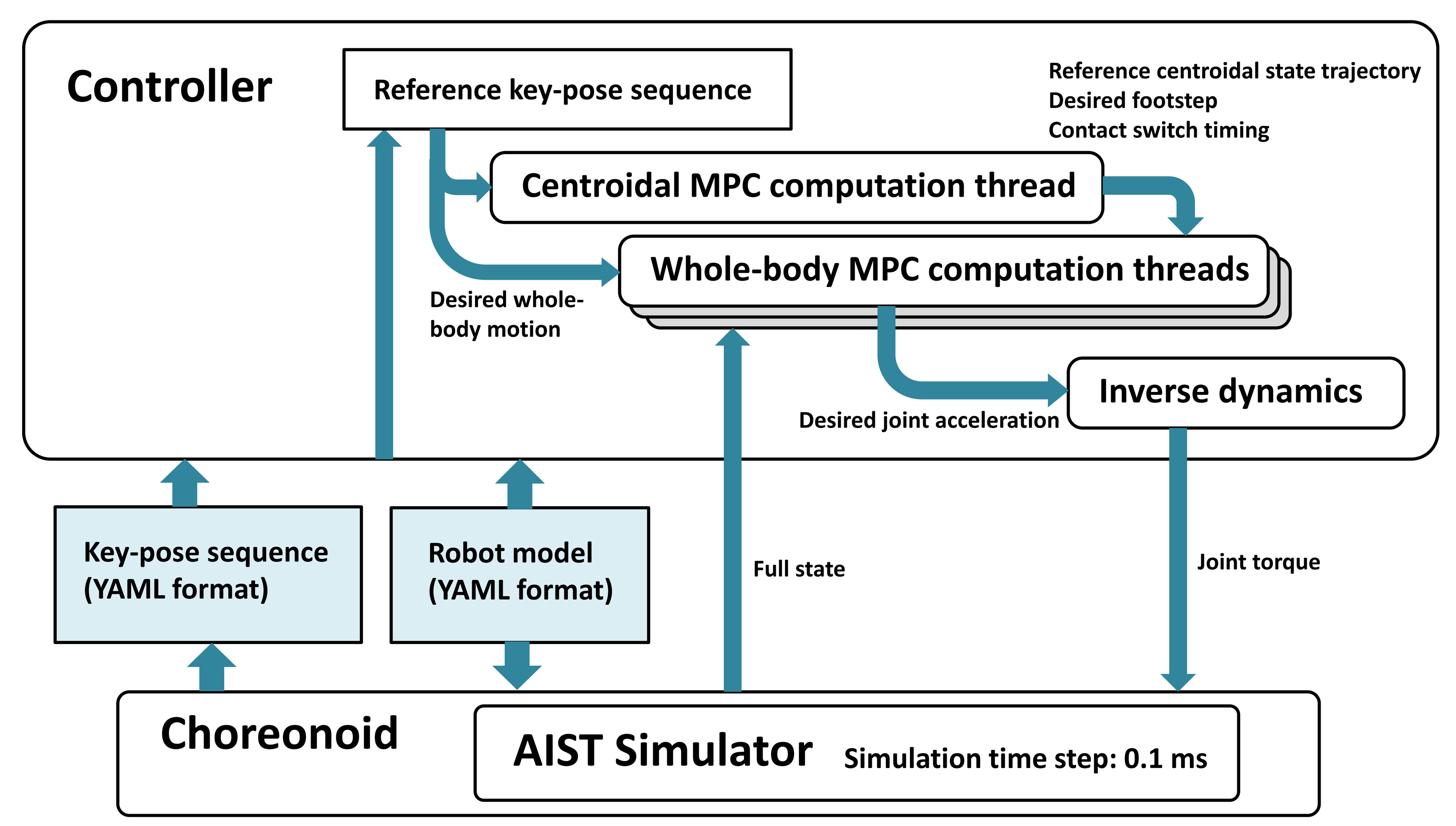
This paper proposes a method that realizes dynamic dancing motion of humanoid robots based on hybrid model predictive control. The proposed control method runs two types of model predictive controllers with different fidelity and time scale in parallel; one performs long-horizon prediction by making use of a closed-form solution of the centroidal dynamics, and the other performs short-horizon prediction based on the whole-body dynamics. A reference key-pose sequence of more than 100 key frames including stepping and fast upper-body movement was edited using Choreonoid and input to the controller. In closed-loop simulation of a torque-controlled 32-DoF humanoid robot, the controller was able to track the reference sequence by attenuating large angular momentum.

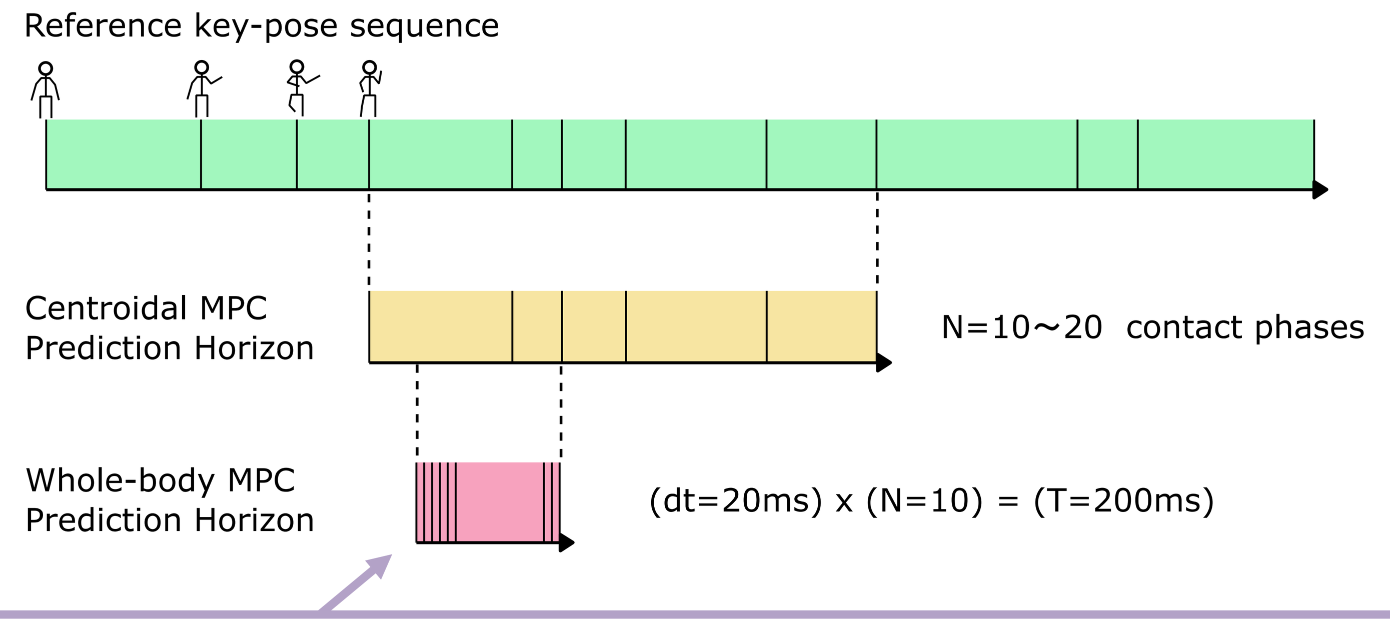
Summary

- **Realization of dynamic (large angular momentum) and complex (include steps and jumps) dance movement in simulation using MPC**
- **Combination of long-horizon Centroidal MPC and short-horizon Wholebody MPC for reference motion tracking**

Control System Architecture



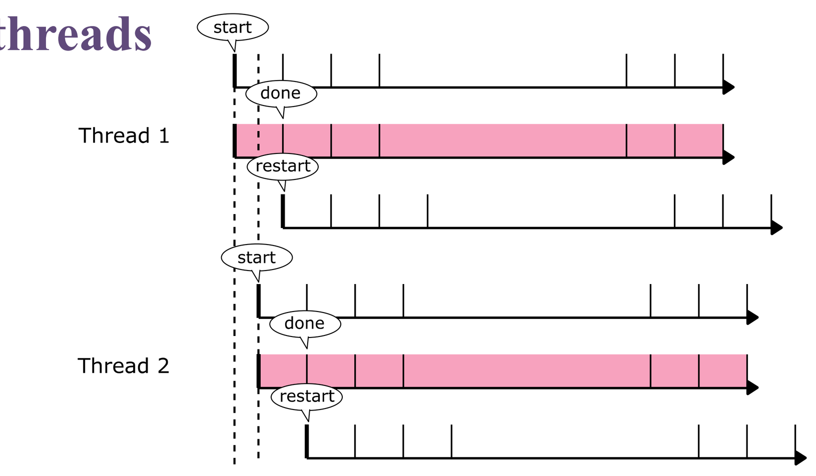
Coordination of multiple MPC threads



Latency reduction by parallel MPC threads

Multiple whole-body MPC threads are run in parallel with shifted timing

e.g., 5 threads (each with 20ms computation delay) gives 4ms update rate



Centroidal MPC

Y. Tazaki, Trajectory Generation for Legged Robots Based on a Closed-Form Solution of Centroidal Dynamics, IEEE Robotics and Automation Letters, Vol. 9, No. 11, pp. 9239-9246, 2024.

Centroidal dynamics

$$\begin{cases} \ddot{\boldsymbol{p}} = \frac{1}{m}\sum_l \boldsymbol{f}_l - \boldsymbol{g} \\ \dot{L} = \sum_l [(\boldsymbol{p}_l - \boldsymbol{p}) \times \boldsymbol{f}_l + \boldsymbol{\eta}_l] \end{cases}$$

$$\boldsymbol{x} = \begin{bmatrix} \boldsymbol{p} \\ \boldsymbol{v} \\ \boldsymbol{q} \\ \boldsymbol{L} \\ t \\ \boldsymbol{p}_l \\ \boldsymbol{q}_l \end{bmatrix} \begin{matrix} \text{CoM position} \\ \text{CoM velocity} \\ \text{Base orientation} \\ \text{Angular momentum} \\ \text{Timing} \\ \text{Foot position} \\ \text{Foot orientation} \end{matrix} \Bigg\} \text{25D}, \quad l \in \{\mathrm{r}, \mathrm{l}\}$$

$$\boldsymbol{u} = \begin{bmatrix} \tau \\ \boldsymbol{v}_l \\ \boldsymbol{\omega}_l \\ \lambda_l \\ \boldsymbol{r}_l \\ \hat{\boldsymbol{\eta}}_l \end{bmatrix} \begin{matrix} \text{Duration} \\ \text{Foot velocity} \\ \text{Foot angular velocity} \\ \text{Foot stiffness} \\ \text{Foot CMP} \\ \text{Foot moment} \end{matrix} \Bigg\} \text{25D}, \quad l \in \{\mathrm{r}, \mathrm{l}\}$$

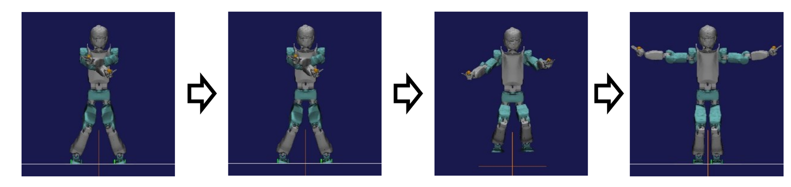
Stiffness-based parametrization **of contact wrench**

$$\boldsymbol{f}_l = m\lambda_l^2(\boldsymbol{p} - (\boldsymbol{p}_l + \boldsymbol{r}_l))$$

$$\boldsymbol{\eta}_l = m\lambda_l^2 \hat{\boldsymbol{\eta}}_l$$

- **Zero-order hold to the stiffness parameters** yields a **closed-form solution** of the centroidal dynamics
- Enables long-horizon planning with fewer variables.

- Jumps can be realized by inserting flight phases to key frames.
- CD-MPC works as a dynamics filter to generate vertical CoM motion and contact forces required for jumping.



Whole-body MPC

- Centroidal-dynamics + full-kinematics
- Euler stepping to derive discrete-time prediction model

$$\begin{cases} \ddot{\boldsymbol{p}} = \frac{1}{m}\sum_l \boldsymbol{f}_l - \boldsymbol{g} \\ \dot{\boldsymbol{\omega}} = I^{-1}\left(-(\dot{I}\boldsymbol{\omega} + \boldsymbol{\omega} \times \boldsymbol{q}\hat{\boldsymbol{L}} + \boldsymbol{q}\dot{\hat{\boldsymbol{L}}} + \sum_l (\boldsymbol{\eta}_l + (\boldsymbol{p}_l - \boldsymbol{p}) \times \boldsymbol{f}_l)\right) \end{cases}$$

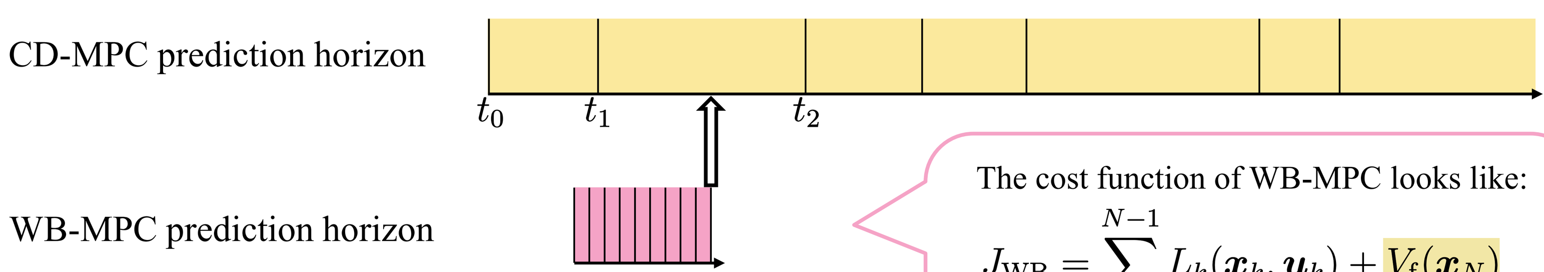
$$\boldsymbol{x} = \begin{bmatrix} \boldsymbol{p} \\ \boldsymbol{v} \\ \boldsymbol{q} \\ \boldsymbol{\omega} \\ \boldsymbol{\theta} \\ \dot{\boldsymbol{\theta}} \end{bmatrix} \begin{matrix} \text{CoM position} \\ \text{CoM velocity} \\ \text{Base orientation} \\ \text{Base ang. vel.} \\ \text{Joint angle} \\ \text{Joint vel.} \end{matrix} \Bigg\} \text{76D}$$

$$\boldsymbol{u} = \begin{bmatrix} \ddot{\boldsymbol{\theta}} \\ \boldsymbol{f}_l \\ \boldsymbol{\eta}_l \end{bmatrix} \begin{matrix} \text{Joint acc.} \\ \text{Foot wrench} \\ \text{Foot moment} \end{matrix} \Bigg\} \text{50D}, \quad l \in \{\mathrm{r}, \mathrm{l}\}$$

Decomposition of angular momentum into base link rotation and "local" angular momentum

$$\boldsymbol{L} = I(\boldsymbol{\theta})\boldsymbol{\omega} + \boldsymbol{q}\hat{\boldsymbol{L}}(\boldsymbol{\theta}, \dot{\boldsymbol{\theta}})$$

Using the value function of CD-MPC as the terminal cost of WB-MPC



The cost function of WB-MPC looks like:

$$J_{\mathrm{WB}} = \sum_{k=0}^{N-1} L_k(\boldsymbol{x}_k, \boldsymbol{u}_k) + V_t(\boldsymbol{x}_N)$$

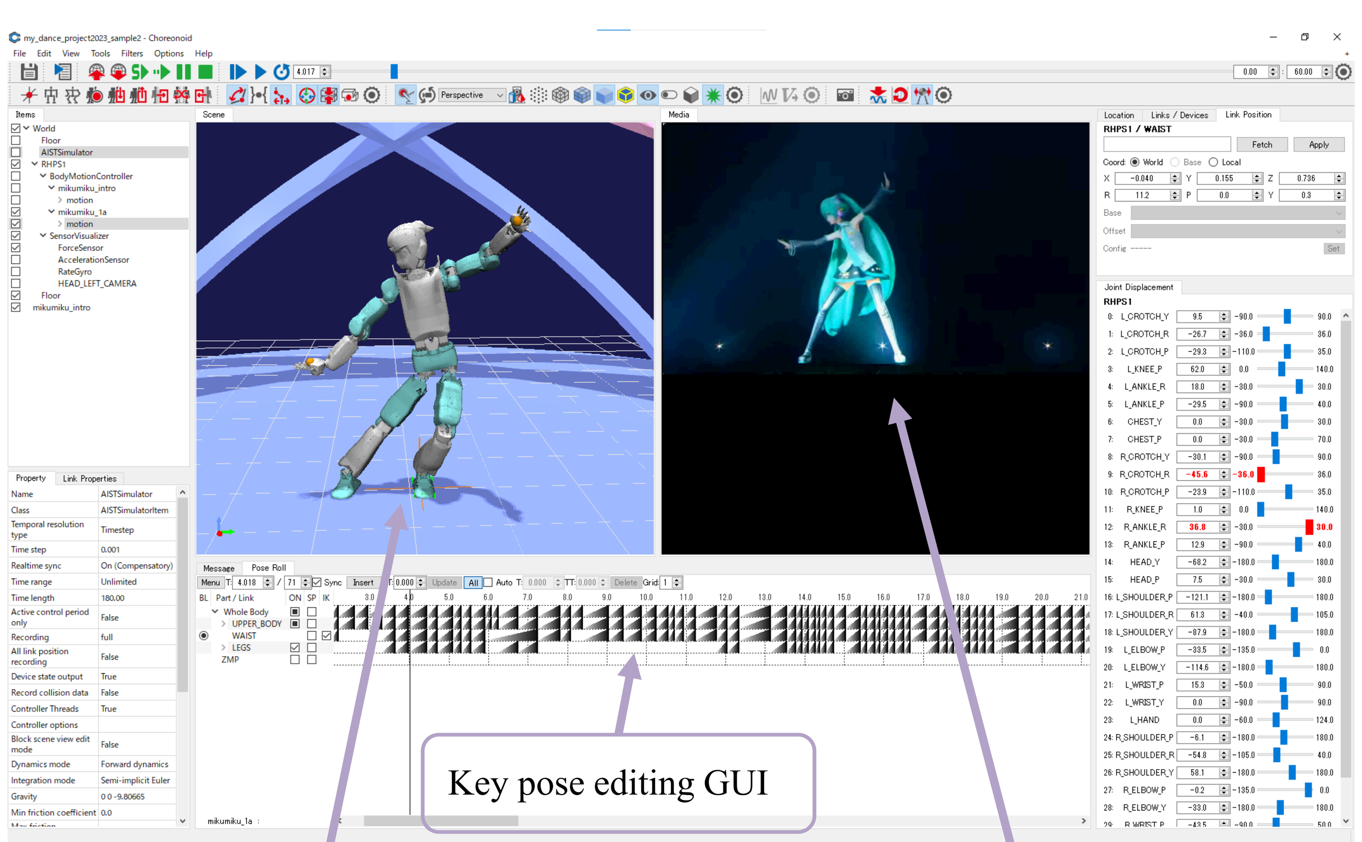
Terminal cost obtained from the value function of CD-MPC

The prediction horizon of WB-MPC is effectively extended to the end of the prediction horizon of CD-MPC.

** This part is our recent work and not included in the proceedings.*

Simulation Results

Choreography GUI of Choreonoid https://github.com/choreonoid



Key pose editing GUI

Visualization of robot model

RHP Friends (Kawasaki Heavy Industry)

Project Kaleido (in Japanese) https://p-kaleido.com

Kakiuchi Y, Kamon M, Shimomura N, et al. Development of life sized humanoid robot platform with robustness for falling down, long time working and error occurrence. IEEE/RSJ International Conference on Intelligent Robots and Systems (IROS), pp.689-696, 2017.

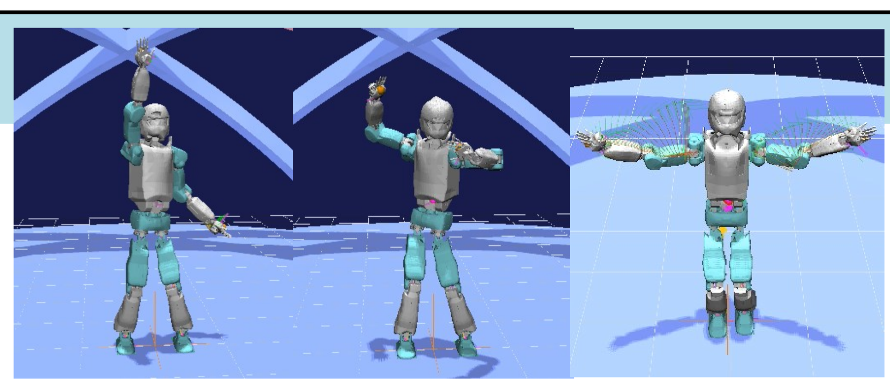
Original CG animation video clip

Hatsune Miku Magical Mirai 2017

https://www.youtube.com/watch?v=RU-OAZas1Ps

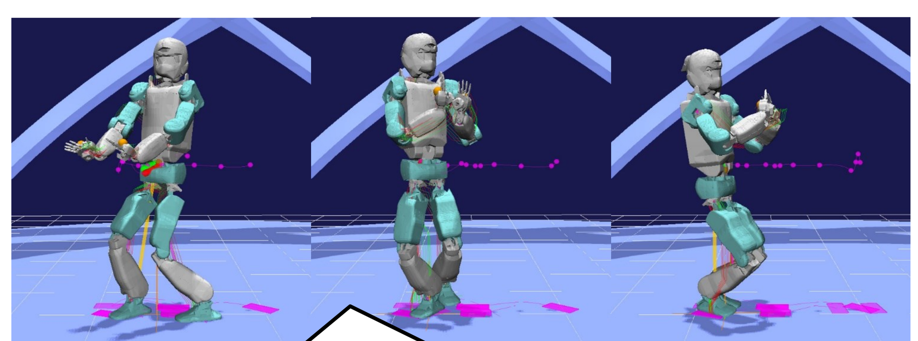
Edited key-pose sequence is exported in YAML format

Part	# of key-frames	Duration [s]	Comments
Intro	27	12	Arm swinging only
Verse	81	24	Includes stepping
Pre-verse	56	13	Includes jumps
Chorus	152	35	Includes jumps



Stepping while swinging arms

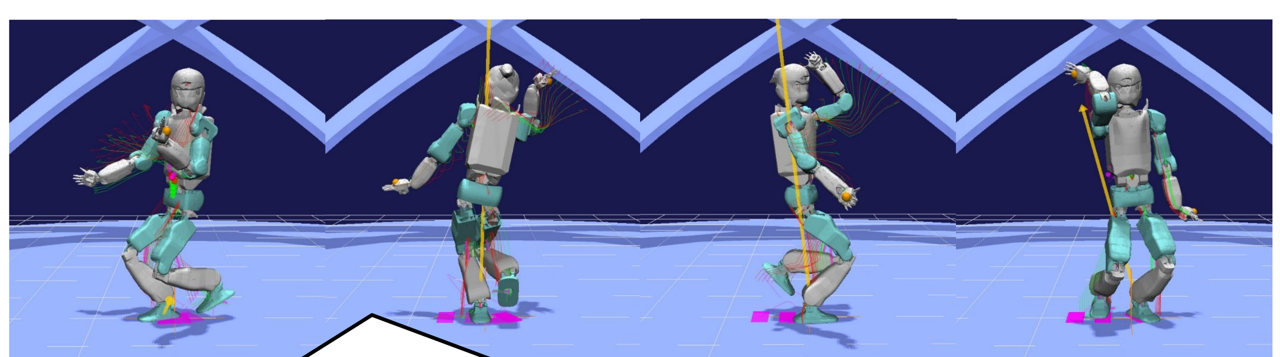
Footsteps and CoM trajectory generated by CD-MPC



180 degree turn with small jump

Computation time [ms]

	Average	Max
CD-MPC	12	14
WB-MPC	14	16



360 degree turn with 4 steps (flight in between)

See also

- **dymp/dymp_mpc** https://github.com/ytazz/dymp|_mpc|
  A trajectory optimization and MPC library
- **Humanoid Virtual Athletics Challenge** https://ytazz.github.io/vnoid/
  Simulation-based humanoid robot competition featuring athletics and dance