# Planning and Executing Humanoid Gaits in a World of Stairs

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January 21, 2020

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Abstract. Humanoid Robot Locomotion Problem.

# Block Scheme

- `elevation_mapping`: autonomously build a map $\mathcal{M}_z$
- RRT-based footstep planner: generate a footstep sequence $\{f^j\}$ together with swing foot trajectories $\{p^*_{\mathrm{swg}}\}$
- variable-height CoM IS-MPC: realize a stable trajectory $p^*_{\mathrm{CoM}}$

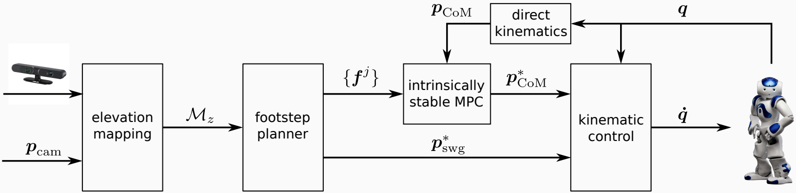


Figure 1: Block scheme of the approach.

# Variable Height CoM IS-MPC: 3D Motion Model

- **LIP** model not suitable for gait generation over **uneven terrain**
- constraint vertical motion such that

$$\frac{\ddot{z}_c + g}{z_c - z_z} = \omega^2$$

- CoM dynamics become

$$\ddot{x}_c = \omega^2(x_c - x_z)$$
$$\ddot{y}_c = \omega^2(y_c - y_z)$$
$$\ddot{z}_c = \omega^2(z_c - z_z) - g$$

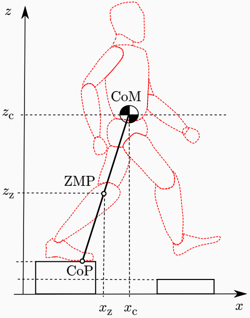


Figure 2: ZMP, CoP and COM are colinear.

# Variable Height CoM IS-MPC: MPC Formulation

- **constrain ZMP** into subregion of polyhedral cone (box)

$$R_{k+i}^{T}\begin{pmatrix} x_z^{k+i} - x_f^{k+i} \\ y_z^{k+i} - y_f^{k+i} \\ z_z^{k+i} - y_f^{k+i} \end{pmatrix} \leq \frac{1}{2}\begin{pmatrix} \tilde{d}_x^z \\ \tilde{d}_y^z \\ d_z^z \end{pmatrix}$$

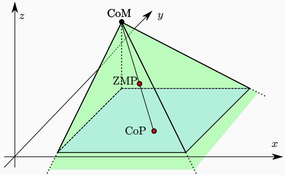


Figure 3: CoP internal to support polygon equivalent to ZMP internal to polyhedral cone.

- bound CoM wrt ZMP (**LIP stability**)

$$\frac{1}{\omega}\frac{1-e^{-\delta\omega}}{1-e^{-N\delta\omega}}\sum_{i=0}^{N-1} e^{-i\delta\omega}\dot{x}_z^{k+i} = x_c^k + \frac{\dot{x}_c^k}{\omega} - x_z^k$$

- solve **QP problem** using **MPC** scheme

# Variable Height CoM IS-MPC: Stair Climbing

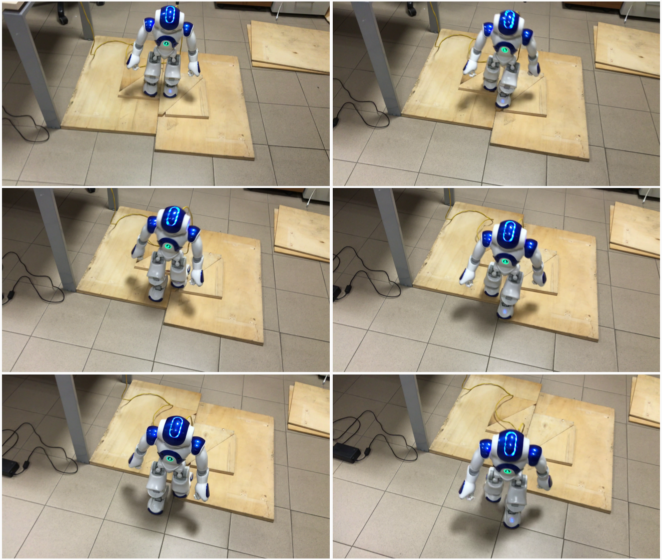

Figure 4: NAO going down the stairs.

# Variable Height CoM IS-MPC: Stair Climbing

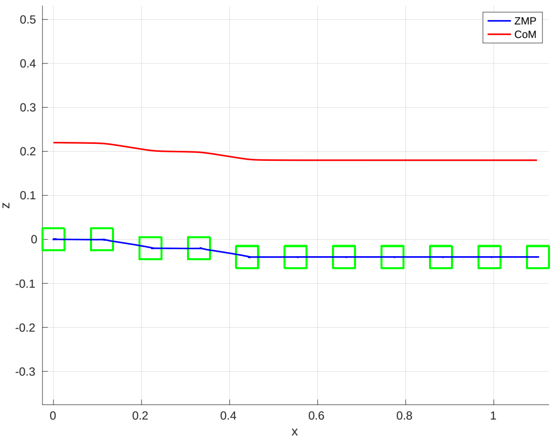


Figure 5: CoM/ZMP plot ($z$-axis).

- Rapidly-Exploring Random Tree
  - R1 maximum footsteps height variation $|z_{\mathrm{f}}^{j} - z_{\mathrm{f}}^{j-1}| \leq \Delta z_{\mathsf{max}}$
  - R2 footstep is fully in contact with the ground
  - R3 swing foot trajectory $\boldsymbol{p}_{\mathrm{swg}}^{j}$ is collision free
- footstep planner iteration
  1. $\boldsymbol{p}_{\mathrm{rand}} \leftarrow Rand(\mathcal{M}_z)$
  2. $v_{\mathrm{near}} \leftarrow Nearest(\boldsymbol{p}_{\mathrm{rand}}, \gamma, \mathcal{T})$
  3. $\boldsymbol{f}_{\mathrm{cand}} \leftarrow Rand(U)$
  4. **if** $\boldsymbol{f}_{\mathrm{cand}}$ feasible wrt R1-R2 **then**
  5. $\quad \boldsymbol{p}_{\mathrm{swg}}^{\mathrm{cand}} \leftarrow \mathrm{BuildTrajectory}(\cdot)$
  6. $\quad \mathcal{T}.\mathrm{add}(v_{\mathrm{new}}, v_{\mathrm{near}})$ **if** $\boldsymbol{p}_{\mathrm{swg}}^{\mathrm{cand}}$ satisfies R3

# RRT-based Footstep Planning: Catalogue of Primitives

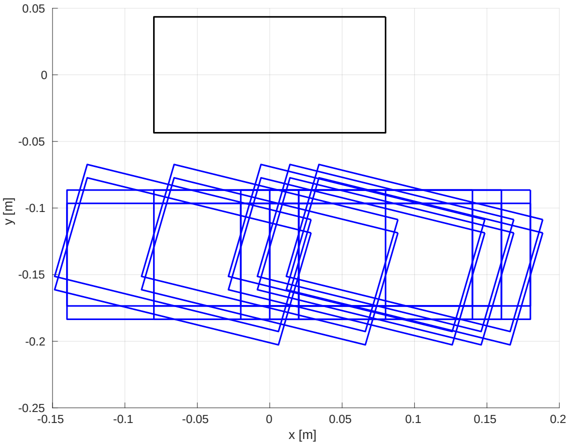


Figure 6: NAO's catalogue of primitives $U$.

# RRT-based Footstep Planning: Obstacle Avoidance

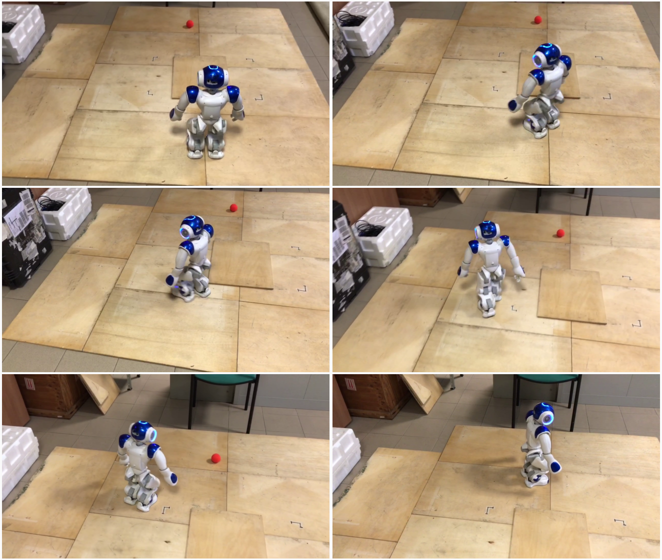

Figure 7: NAO avoiding an obstacle.

# Elevation Map Generation

`elevation_mapping`, features, how it works (briefly). Settings: NAO + Xtion + *World of Stairs*.

Experiments: Generated Map + Stair Climbing in Unknown Environment.

Video

# Conclusion

Results. Future Works.

# Q&A

# References


- A. Zamparelli, N. Scianca, L. Lanari, and G. Oriolo, “Humanoid Gait Generation on Uneven Ground using Intrinsically Stable MPC,” *IFAC-PapersOnLine*, vol. 51, pp. 393–398, 01 2018.
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- P. Fankhauser, M. Bloesch, and M. Hutter, “Probabilistic terrain mapping for mobile robots with uncertain localization,” *IEEE Robotics and Automation Letters (RA-L)*, vol. 3, no. 4, pp. 3019–3026, 2018.