

Planning and Executing Humanoid Gaits in a World of Stairs

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Master Degree in Artificial Intelligence and Robotics

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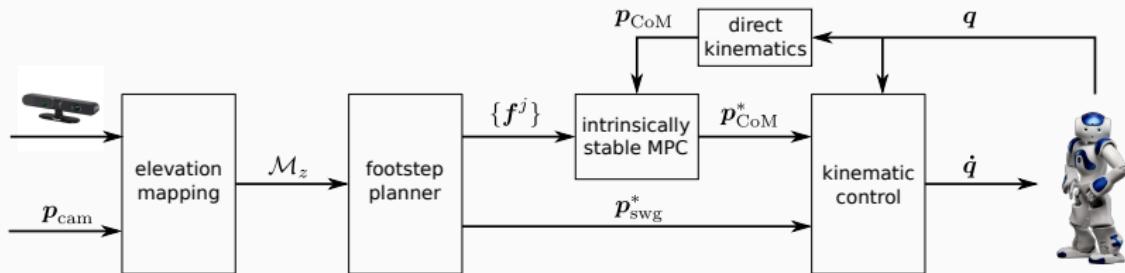
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Introduction

- goal: humanoid robot locomotion in a *World of Stairs*
- assumption: humanoid is equipped with a depth sensor
- assumption: humanoid knows its location



Proposed Approach



- **elevation map building**: autonomously build a map \mathcal{M}_z
- **footstep planner**: generates a footstep sequence $\{f^j\}$ on \mathcal{M}_z together with swing foot trajectories $\{p_{swg}^*\}$
- **variable-height IS-MPC**: computes a stable gait along the planned footsteps $\{f^j\}$

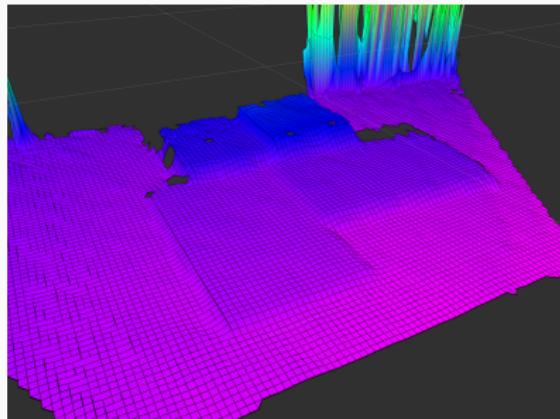
Elevation Map Building: Framework

`elevation_mapping` [Fankhauser et al., 2018]

- robot-centric grid-based map: \mathcal{M}_z
- height estimate $\mathcal{N}(\hat{h}_i, \sigma_{h_i}^2)$ for each cell i
- Kalman filter given new height and motion measurements
- map fusion: $(\hat{h}_i, h_{i,\min}, h_{i,\max})$ such that $h_i \in [h_{i,\min}, h_{i,\max}]$ with 95% confidence
- dynamic environments using visibility check based on ray tracing

Elevation Map Building: Results

- ASUS Xtion Pro (**depth sensor**)
- working range: 0.5–3.5 m



Variable Height CoM IS-MPC: 3D Motion Model

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

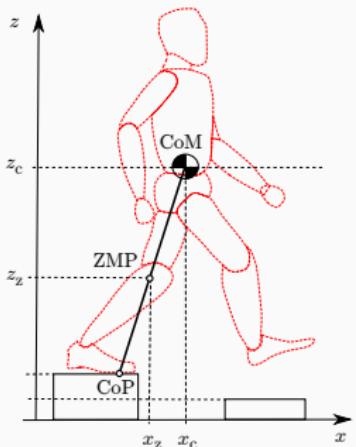
$$\frac{\ddot{z}_c + g}{z_c - z_z} = \omega^2$$

- CoM dynamics become

$$\ddot{x}_c = \omega^2(x_c - x_z)$$

$$\ddot{y}_c = \omega^2(y_c - y_z)$$

$$\ddot{z}_c = \omega^2(z_c - z_z) - g$$



Variable Height CoM IS-MPC: MPC Formulation

- constrain ZMP into subregion of polyhedral cone (box)

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

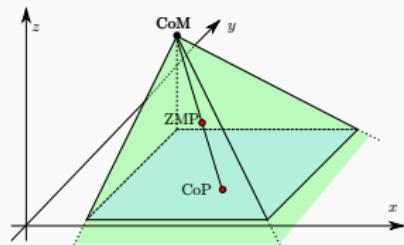
- bound CoM wrt ZMP (LIP stability)

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

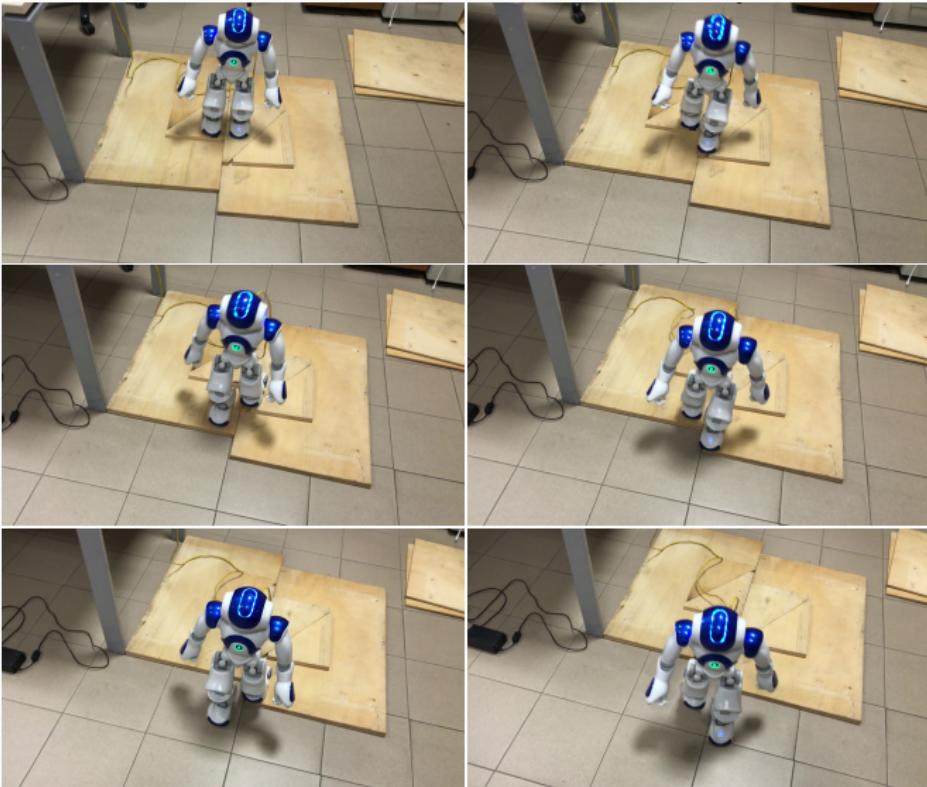
- solve QP problem using MPC scheme

$$\min_{\dot{x}_z^k, \dot{y}_z^k, \dot{z}_z^k} \|\dot{x}_z^k\|_2^2 + \|\dot{y}_z^k\|_2^2 + \|\dot{z}_z^k\|_2^2 + \beta(\|\Delta x_f^{k+1}\|_2^2 + \|\Delta y_f^{k+1}\|_2^2 + \|\Delta z_f^{k+1}\|_2^2)$$

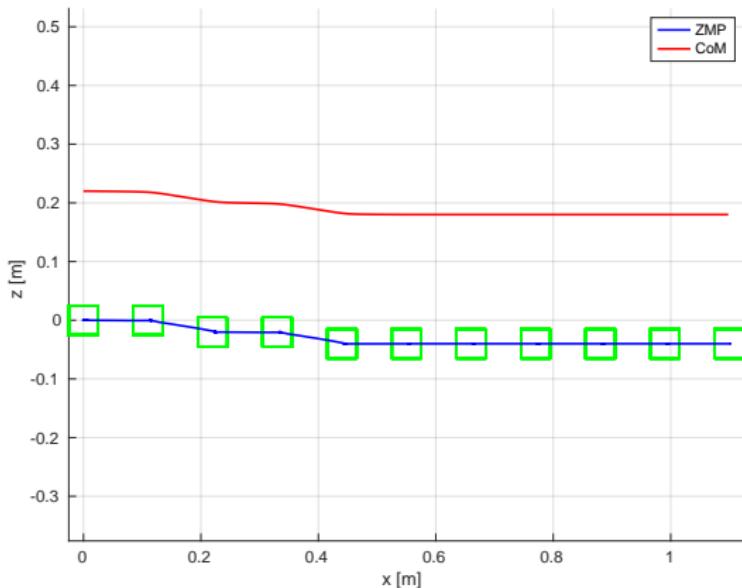
s.t. ZMP and stability constraints



Variable Height CoM IS-MPC: Stair Climbing



Variable Height CoM IS-MPC: Stair Climbing



RRT-based Footstep Planning

- Rapidly-Exploring Random Tree

- R1 maximum footsteps height variation $|z_f^j - z_f^{j-1}| \leq \Delta z_{\max}$

- R2 footstep is fully in contact with the ground

- R3 swing foot trajectory p_{swg}^j is collision free

- footstep planner iteration

1. $p_{\text{rand}} \leftarrow \text{Rand}(\mathcal{M}_z)$
2. $v_{\text{near}} \leftarrow \text{Nearest}(p_{\text{rand}}, \gamma, \mathcal{T})$
3. $f_{\text{cand}} \leftarrow \text{Rand}(U)$
4. if f_{cand} feasible wrt R1-R2 then
5. $p_{\text{swg}}^{\text{cand}} \leftarrow \text{BuildTrajectory}(\cdot)$
6. $\mathcal{T}.\text{add}(v_{\text{new}}, v_{\text{near}})$ if $p_{\text{swg}}^{\text{cand}}$ satisfies R3

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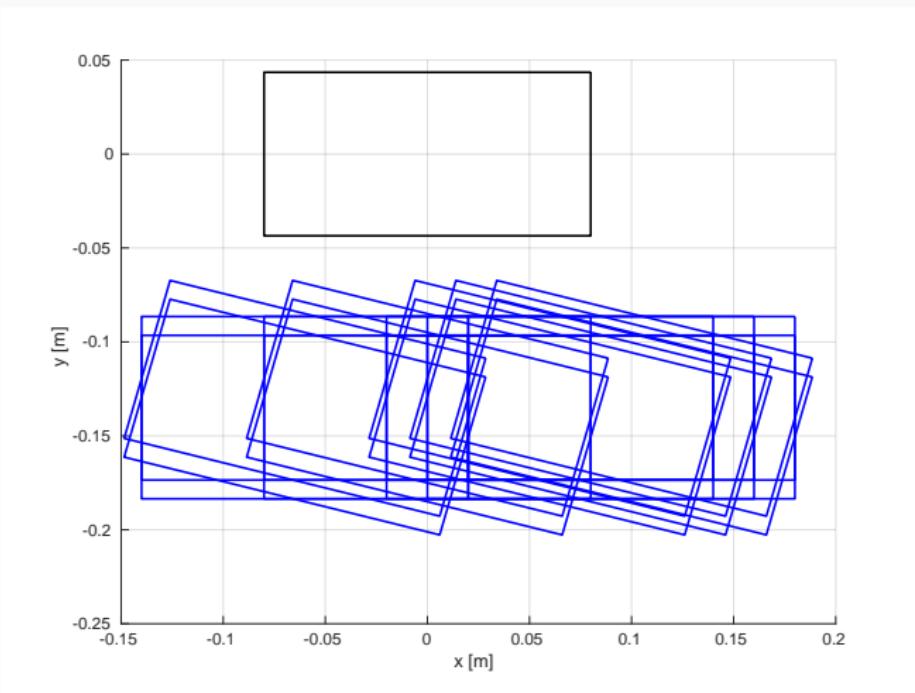
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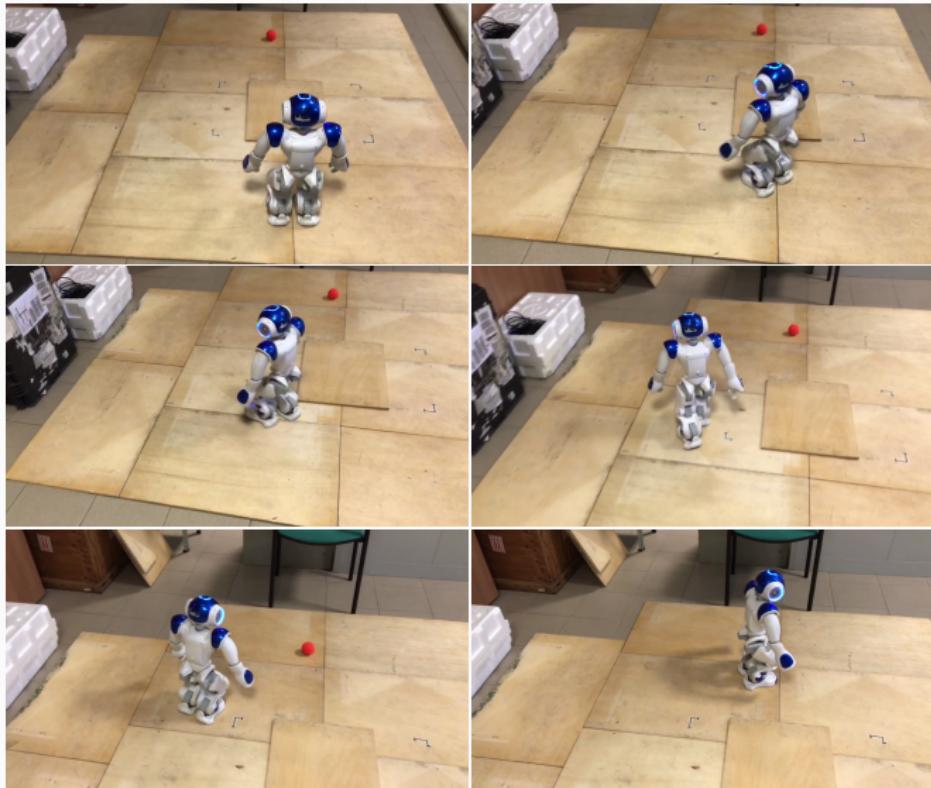
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RRT-based Footstep Planning: Catalogue of Primitives

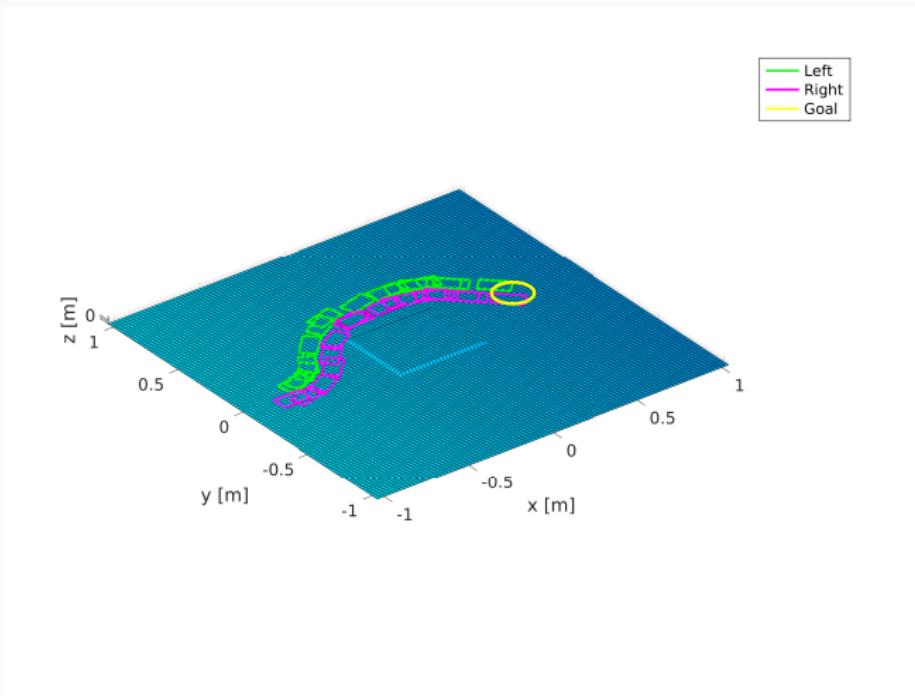


RRT-based Footstep Planning: Obstacle Avoidance



RRT-based Footstep Planning: Obstacle Avoidance

tree size: 488 – solution size: 31 – runtime: 70 ms



Elevation Map Generation: Framework

elevation_mapping

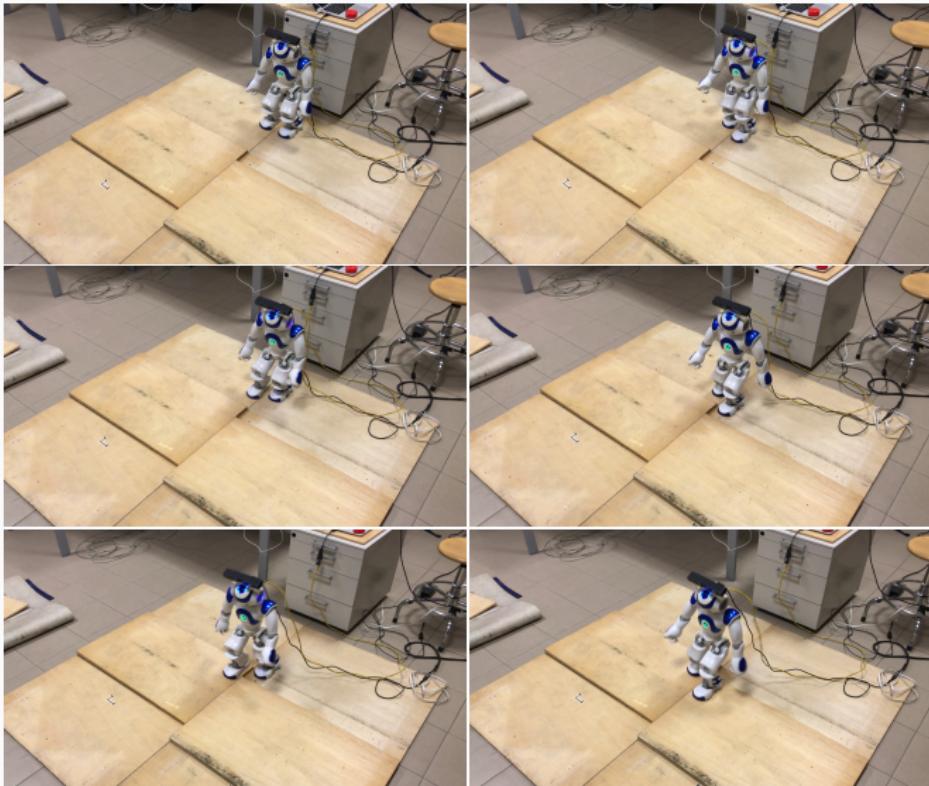
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Elevation Map Generation: Settings

- NAO humanoid robot
- ASUS Xtion Pro (**depth sensor**)
- working range: 0.5–3.5 m
- elevation map extended with **safe zone**
- *unknown World of Stairs* environment

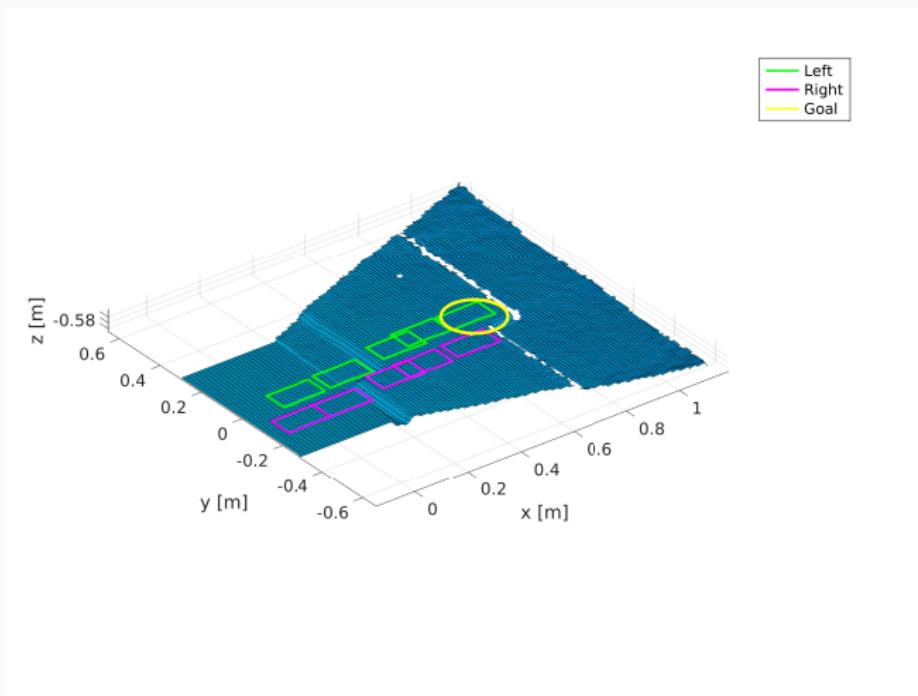


Stair Climbing in Unknown Environment



Stair Climbing in Unknown Environment: Footstep Plan

tree size: 454 – solution size: 10 – runtime: 331 ms



Video

Conclusion: Results and Future Works

- NAO is able to autonomously climb the stairs in an unknown *World of Stairs* environment
- **localization** module and **continuous mapping**
- **replanning** phase
- dynamic and rough environments

Q&A

References

-  Fankhauser, P., Bloesch, M., and Hutter, M. (2018).
Probabilistic terrain mapping for mobile robots with uncertain localization.
IEEE Robotics and Automation Letters (RA-L), 3(4):3019–3026.
-  Ferrari, P., Scianca, N., Lanari, L., and Oriolo, G. (2019).
An integrated motion planner/controller for humanoid robots on uneven ground.
In *18th European Control Conference, ECC 2019, Naples, Italy, June 25-28, 2019*, pages 1598–1603.
-  Zamparelli, A., Scianca, N., Lanari, L., and Oriolo, G. (2018).
Humanoid Gait Generation on Uneven Ground using Intrinsically Stable MPC.
IFAC-PapersOnLine, 51:393–398.