Planning and Executing Humanoid Gaits in a World of Stairs

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Introduction

- humanoid robot locomotion in an unknown *World of Stairs*
- **mapping:** perceive the surrounding world
- **planning:** generate a sequence of motion primitives
- **control:** correctly execute the motion
- NAO humanoid robot equipped with a **depth** sensor
- **goal:** make NAO autonomously climb stairs in an unknown *World of Stairs* environment

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^*_{CoM}

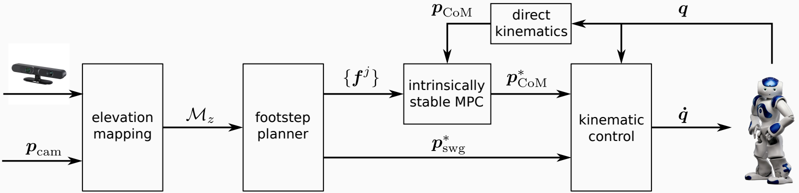

Figure 1: Block scheme of the approach.

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

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

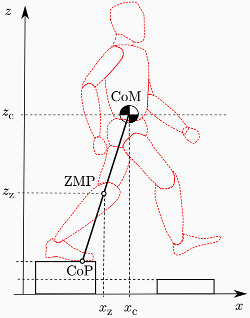

Figure 2: ZMP, CoP and COM are colinear.

Variable Height CoM IS-MPC: MPC Formulation

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

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

- 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

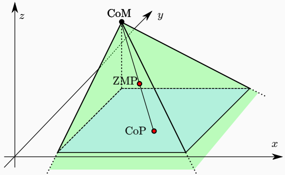

Figure 3: CoP internal to support polygon equivalent to ZMP internal to polyhedral cone.

Variable Height CoM IS-MPC: Stair Climbing

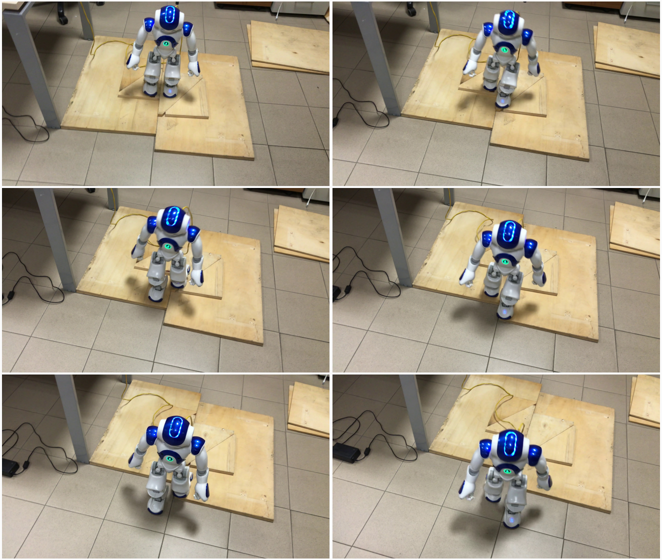

Figure 4: NAO going down the stairs.

Variable Height CoM IS-MPC: Stair Climbing

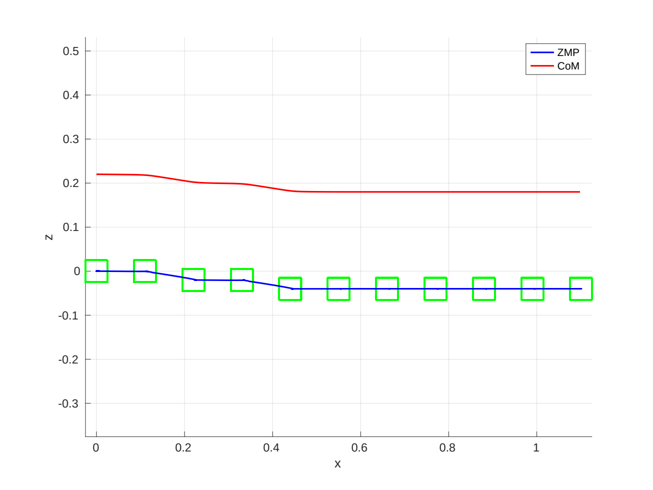

Figure 5: CoM/ZMP plot (z-axis).

RRT-based Footstep Planning

- 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

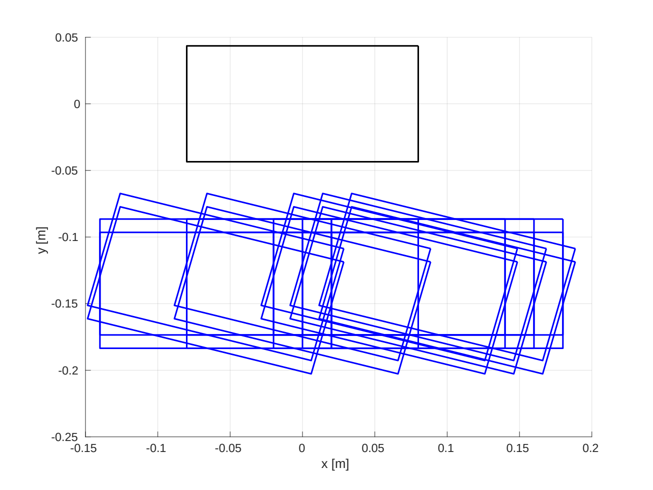

Figure 6: NAO's catalogue of primitives *U*.

RRT-based Footstep Planning: Obstacle Avoidance

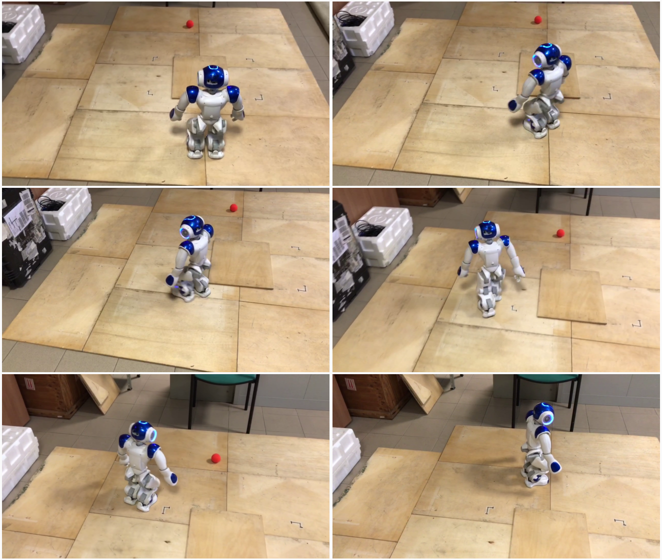

Figure 7: NAO avoiding an obstacle.

RRT-based Footstep Planning: Obstacle Avoidance

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

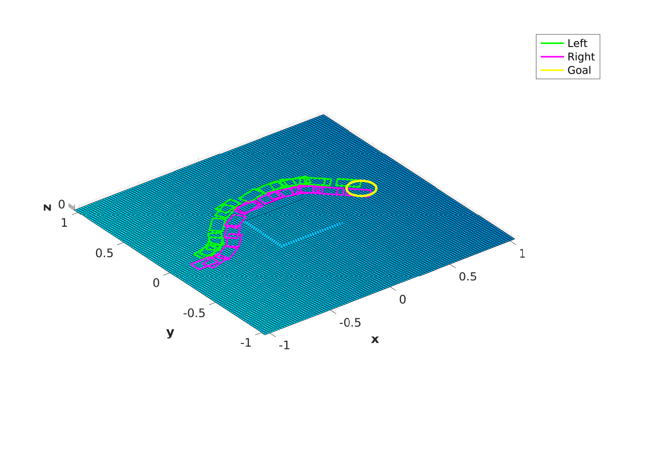

Figure 8: Footstep plan generated for the scenario “Obstacle Avoidance”.

Elevation Map Generation: Framework

`elevation_mapping`

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

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

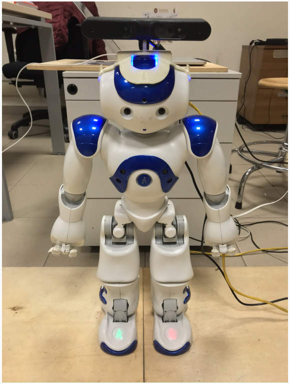

Figure 9: NAO with ASUS Xtion Pro placed on its head.

Stair Climbing in Unknown Environment

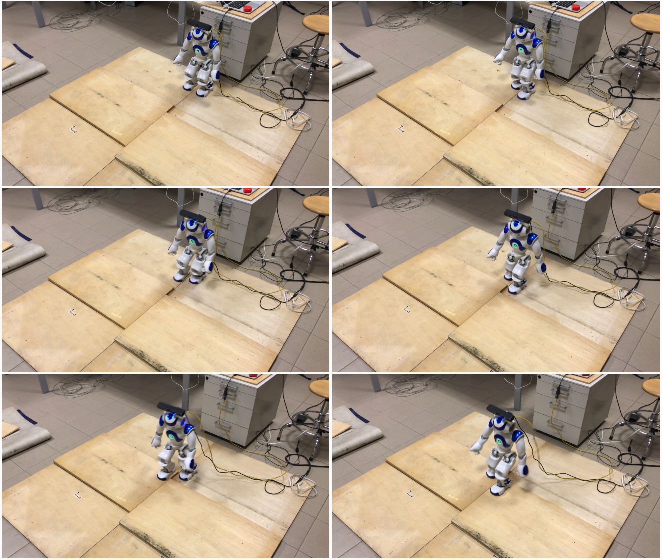

Figure 10: NAO climbing the stairs in an unknown environment.

Stair Climbing in Unknown Environment: Footstep Plan

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

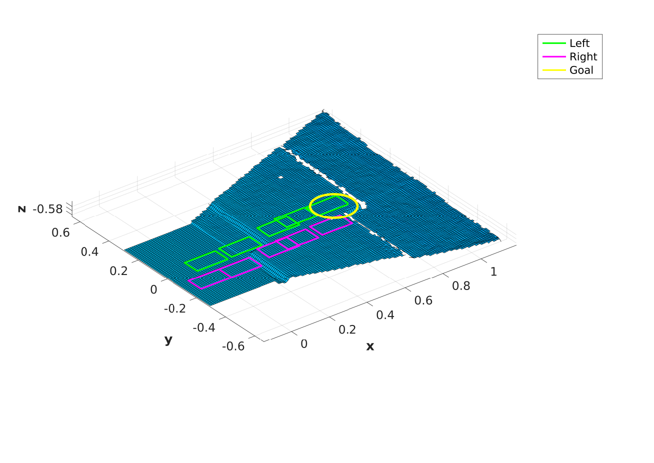

Figure 11: Footstep plan generated for the scenario “Stair Climbing in Unknown Environment”.

Video

Conclusion

Results. Future Works.

Q&A

References

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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.