

Planning and Executing Humanoid Gaits in a World of Stairs

Candidate: Michele Cipriano

Thesis Advisor: Prof. Giuseppe Oriolo

January 21, 2020



Master Degree in Artificial Intelligence and Robotics

Department of Computer, Control and Management Engineering

Sapienza University of Rome

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 $\{p_{\text{swg}}^*\}$
- variable-height CoM IS-MPC: realize a stable trajectory p_{CoM}^*

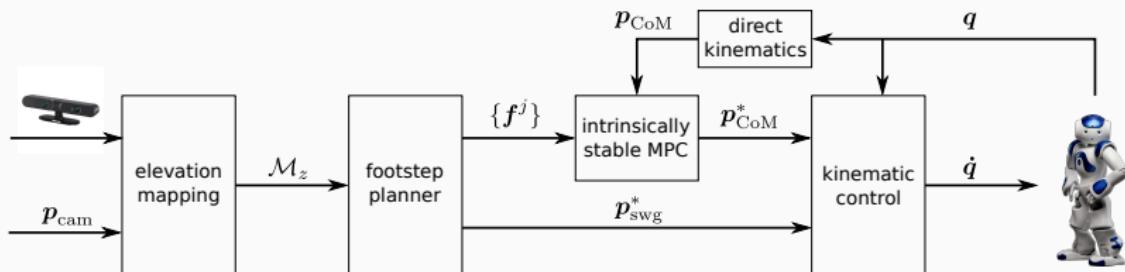


Figure 1: Block scheme of the approach.

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

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

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

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

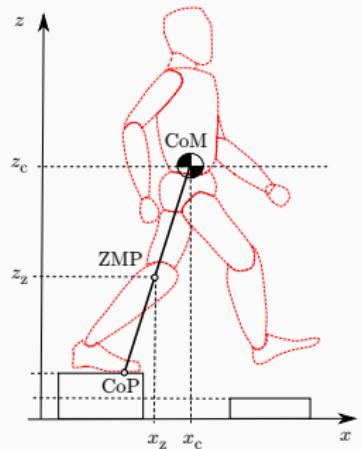
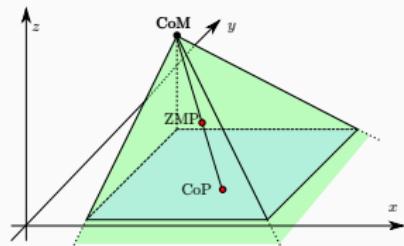


Figure 2: ZMP, CoP and COM are colinear.

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

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

s.t. ZMP and stability constraints

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

Variable Height CoM IS-MPC: Stair Climbing

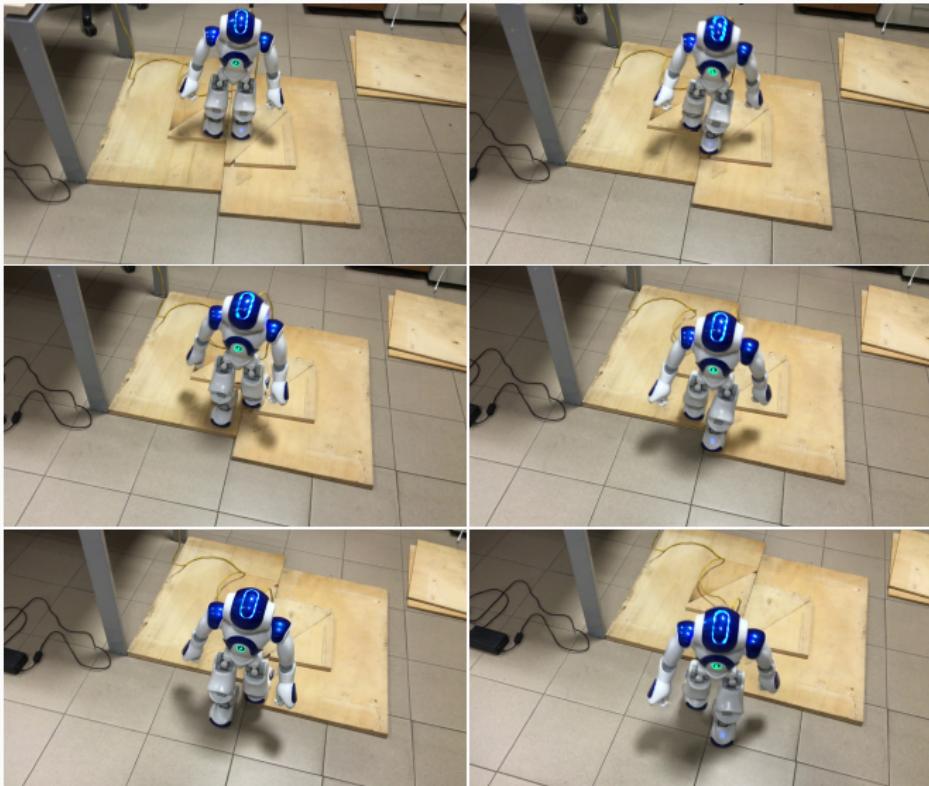


Figure 4: NAO going down the stairs.

Variable Height CoM IS-MPC: Stair Climbing

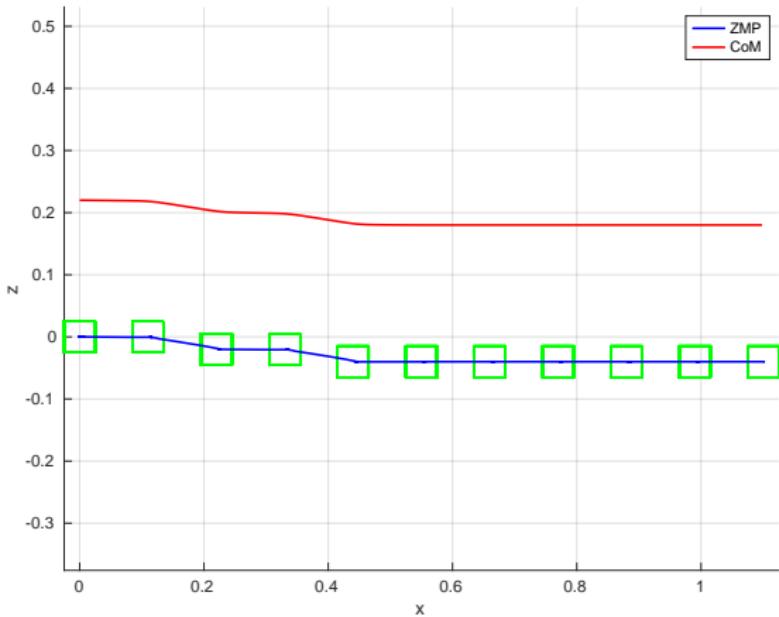


Figure 5: CoM/ZMP plot (z-axis).

RRT-based Footstep Planning

- Rapidly-Exploring Random Tree

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

- 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

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 footprint 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

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

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

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

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

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

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

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

RRT-based Footstep Planning: Catalogue of Primitives

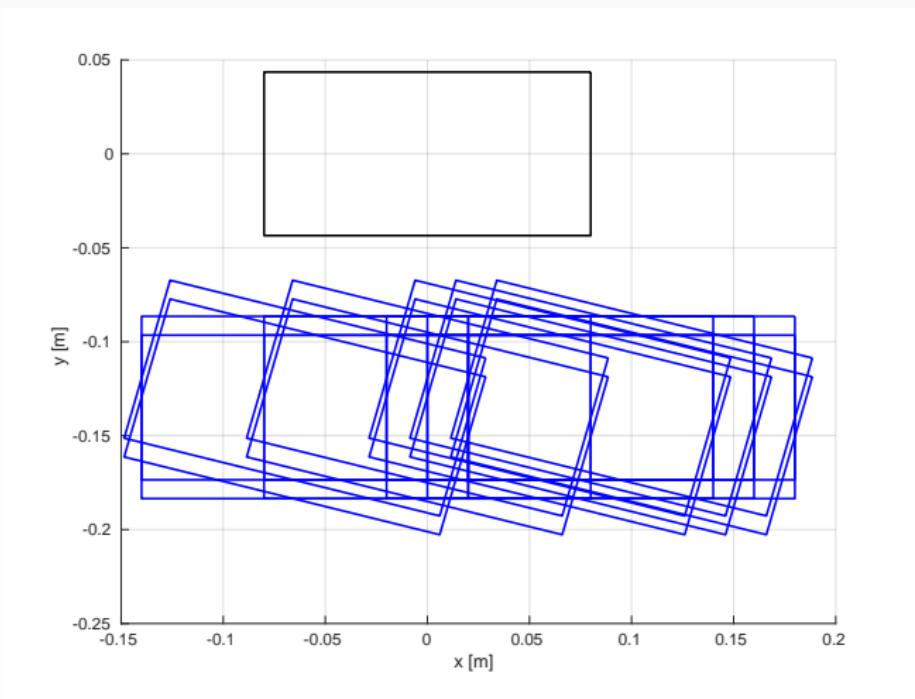


Figure 6: NAO's catalogue of primitives U .

RRT-based Footstep Planning: Obstacle Avoidance

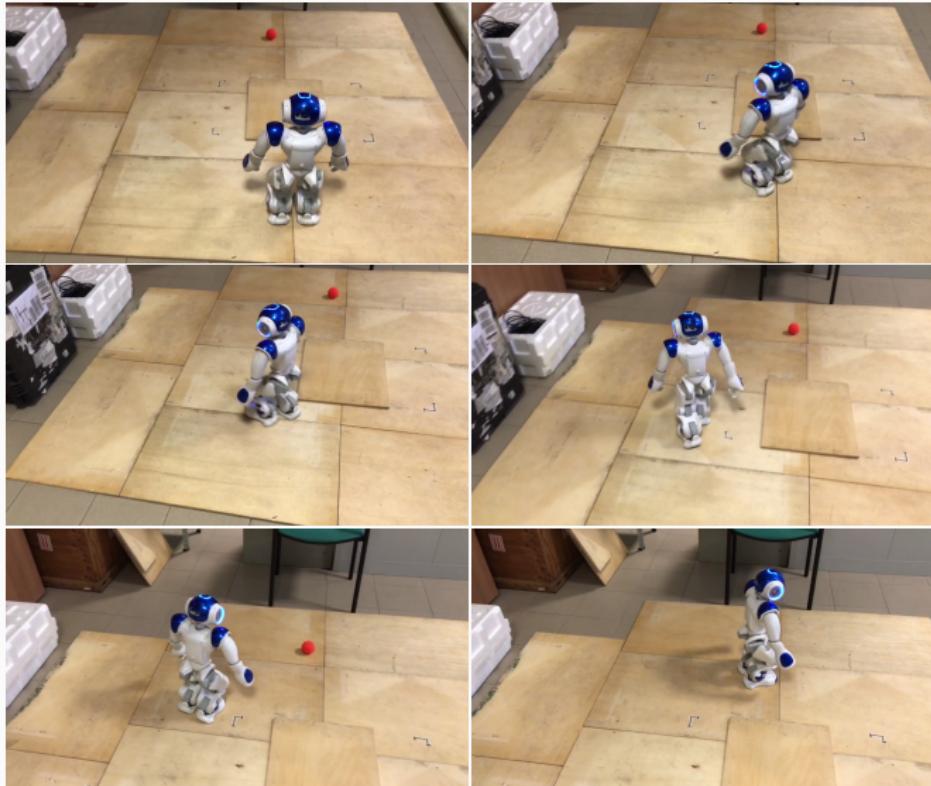


Figure 7: NAO avoiding an obstacle.

RRT-based Footstep Planning: Obstacle Avoidance

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

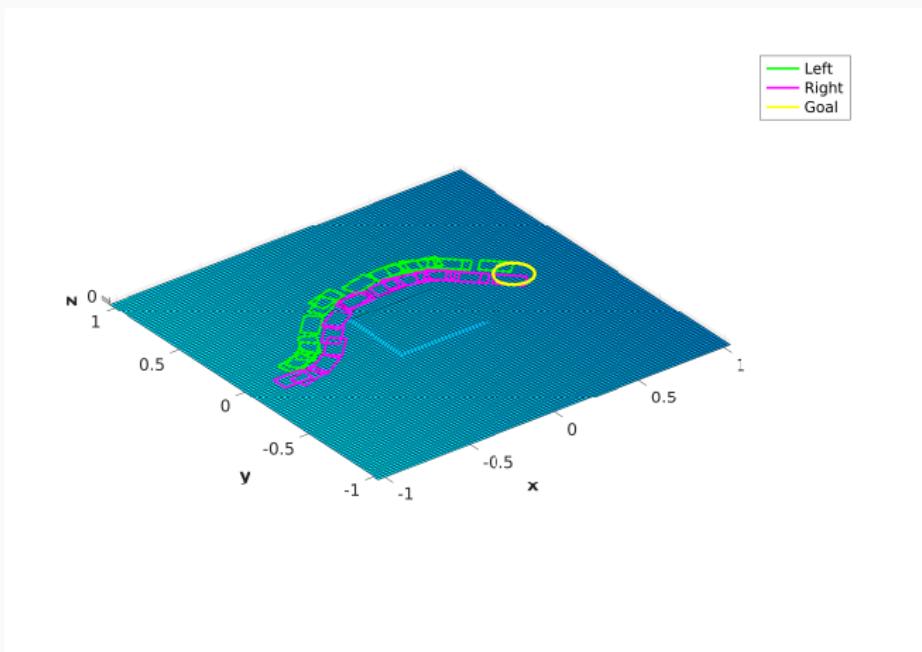


Figure 8: Footstep plan generated for the scenario “Obstacle Avoidance”.

Elevation Map Generation: Framework

elevation_mapping

- robot-centric grid-based map: \mathcal{M}_z
- height estimate $\mathcal{N}(\hat{h}_i, \sigma_{h_i}^2)$ 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 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

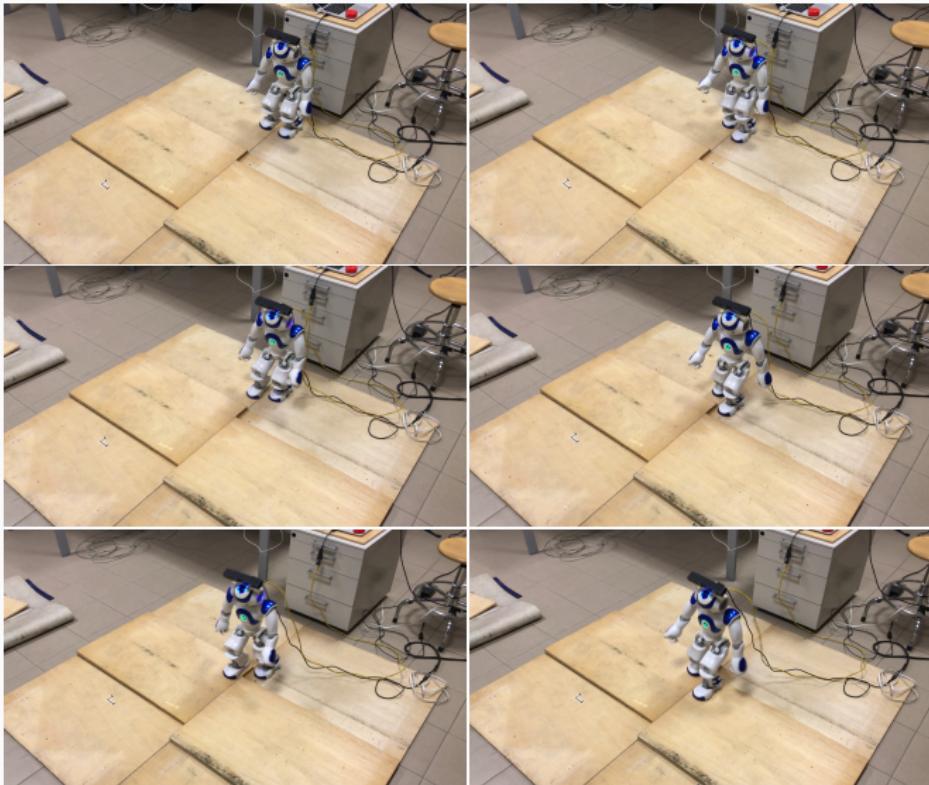


Figure 10: NAO climbing the stairs in an unknown environment.

Stair Climbing in Unknown Environment: Footstep Plan

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

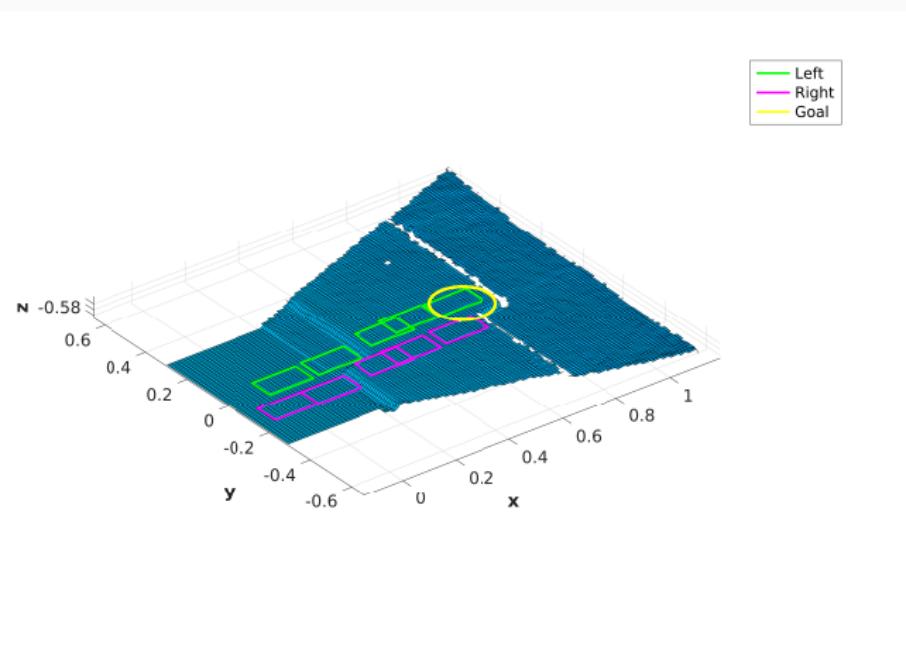


Figure 11: Footstep plan generated for the scenario “Stair Climbing in Unknown Environment”.

Video

Conclusion

Results. Future Works.

Q&A

References

-  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.
-  P. Ferrari, N. Scianca, L. Lanari, and G. Oriolo, “An integrated motion planner/controller for humanoid robots on uneven ground,” in *18th European Control Conference, ECC 2019, Naples, Italy, June 25-28, 2019*, pp. 1598–1603, 2019.
-  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.