SEAN NAV BENCH

Socially Acceptable Bipedal Navigation: A Signal-Temporal-Logic-Driven Approach for Safe Locomotion

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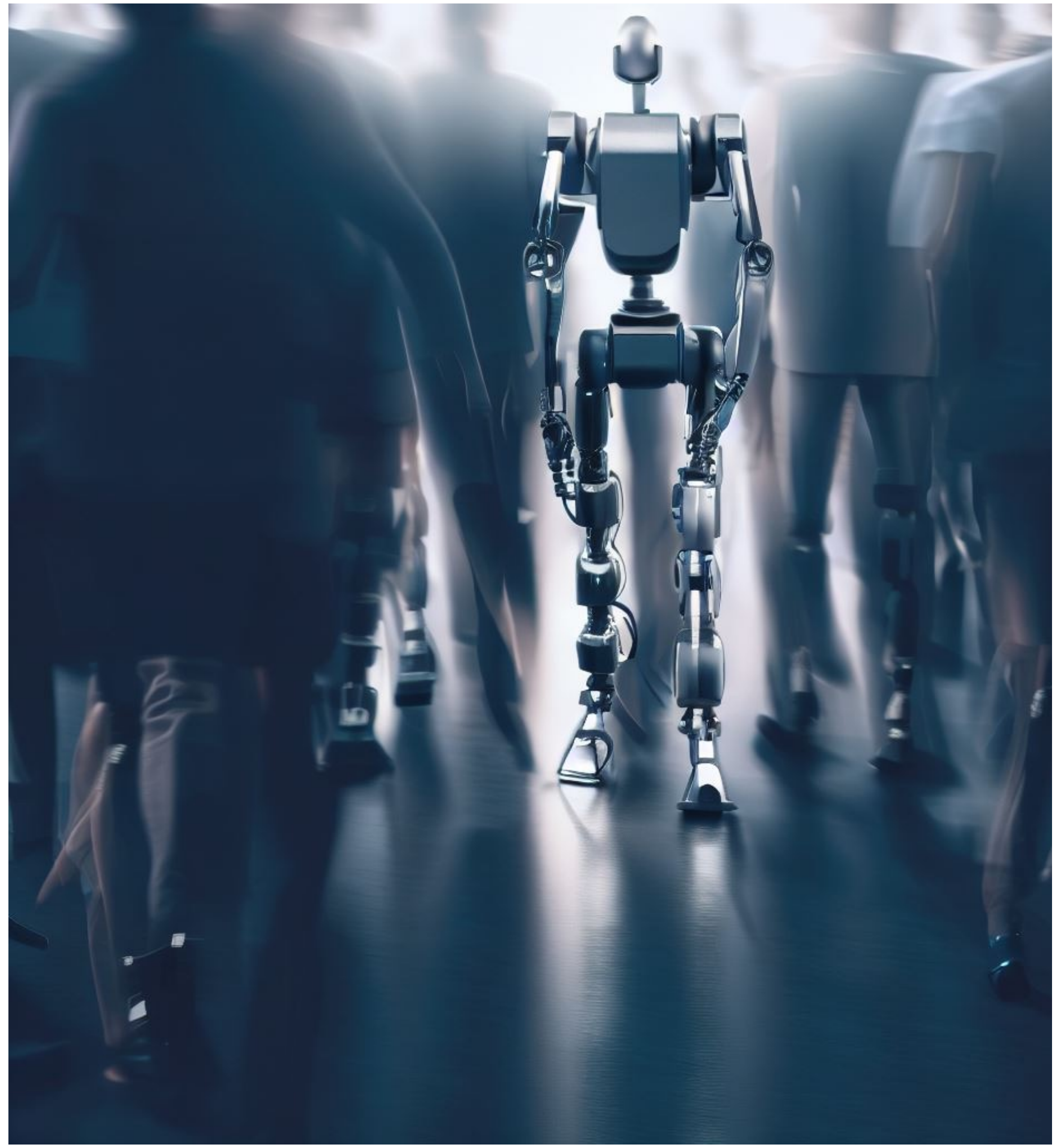
Problem Statement

- How can a **bipedal** robot **navigate** an open, **human-crowded** environment while ensuring:



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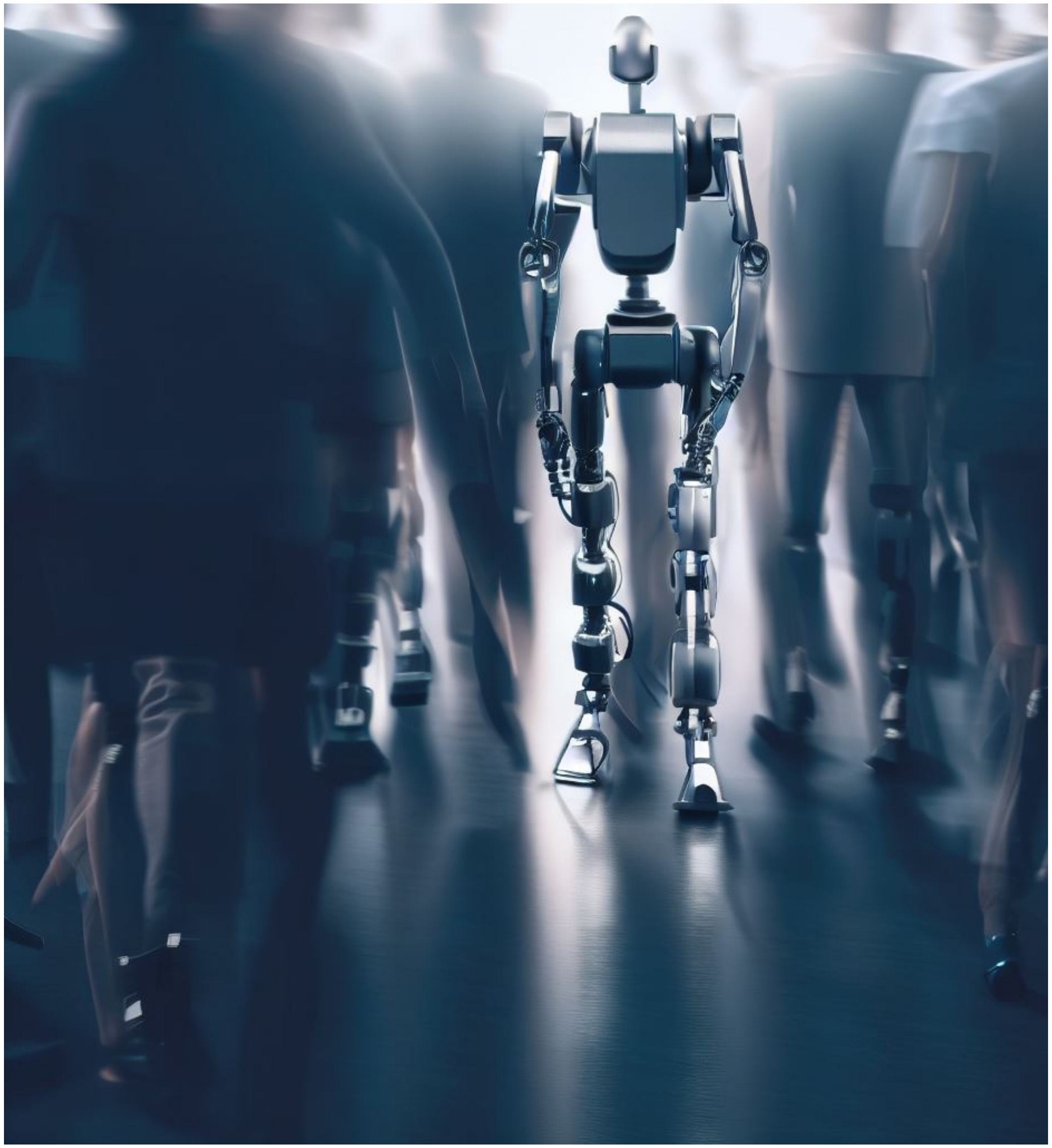
    - Maintain balance



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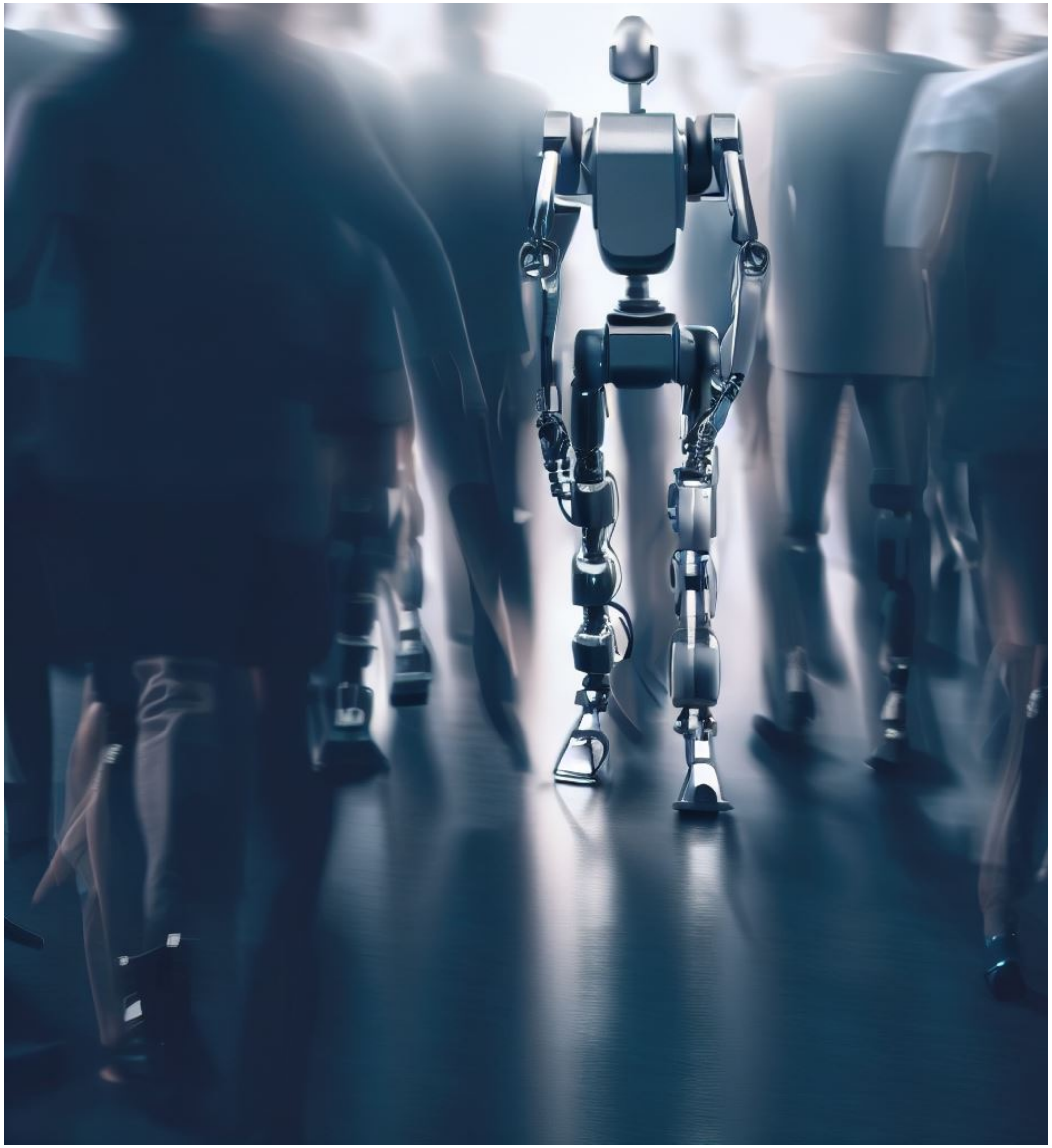
    - Avoid collisions



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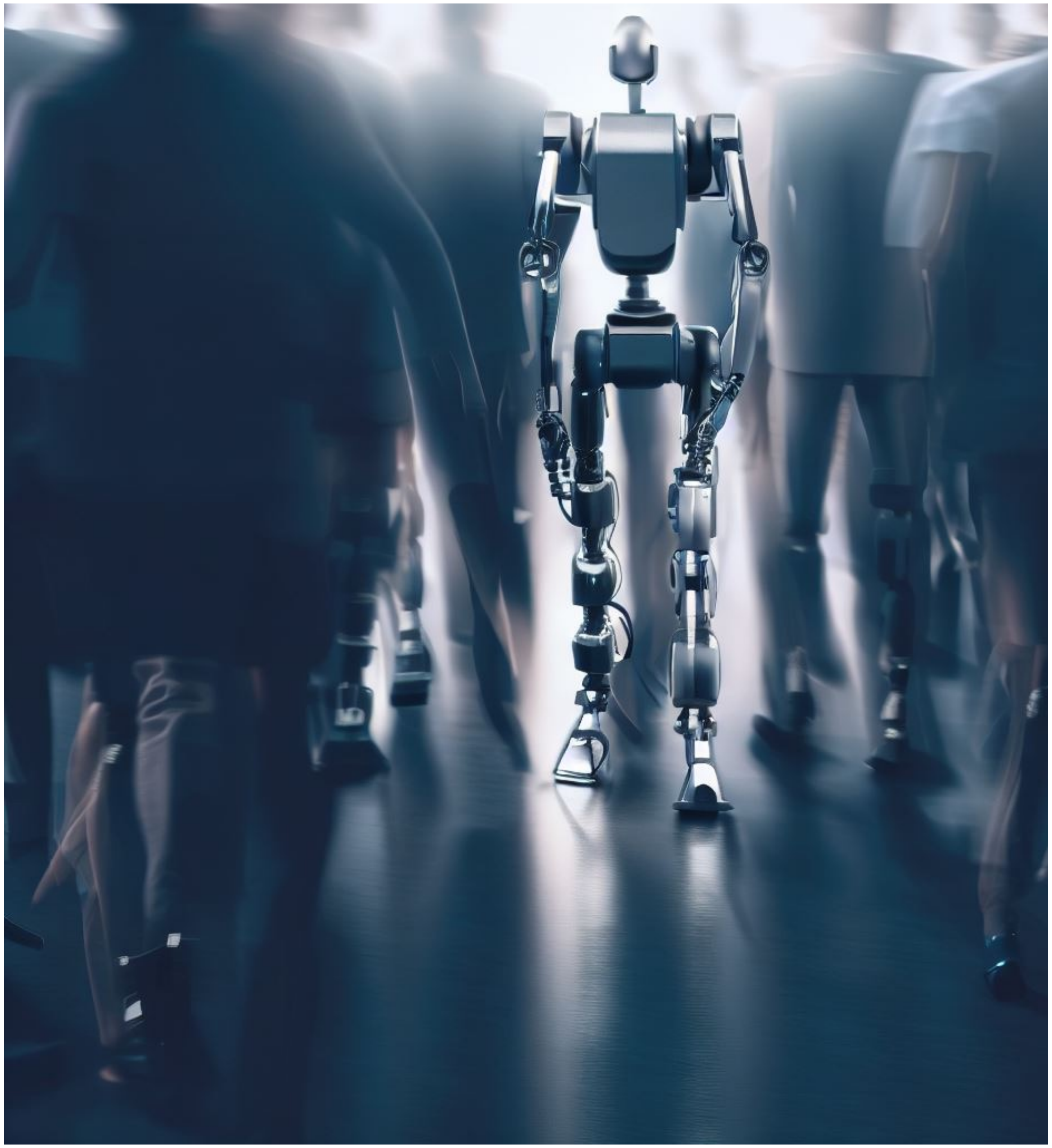

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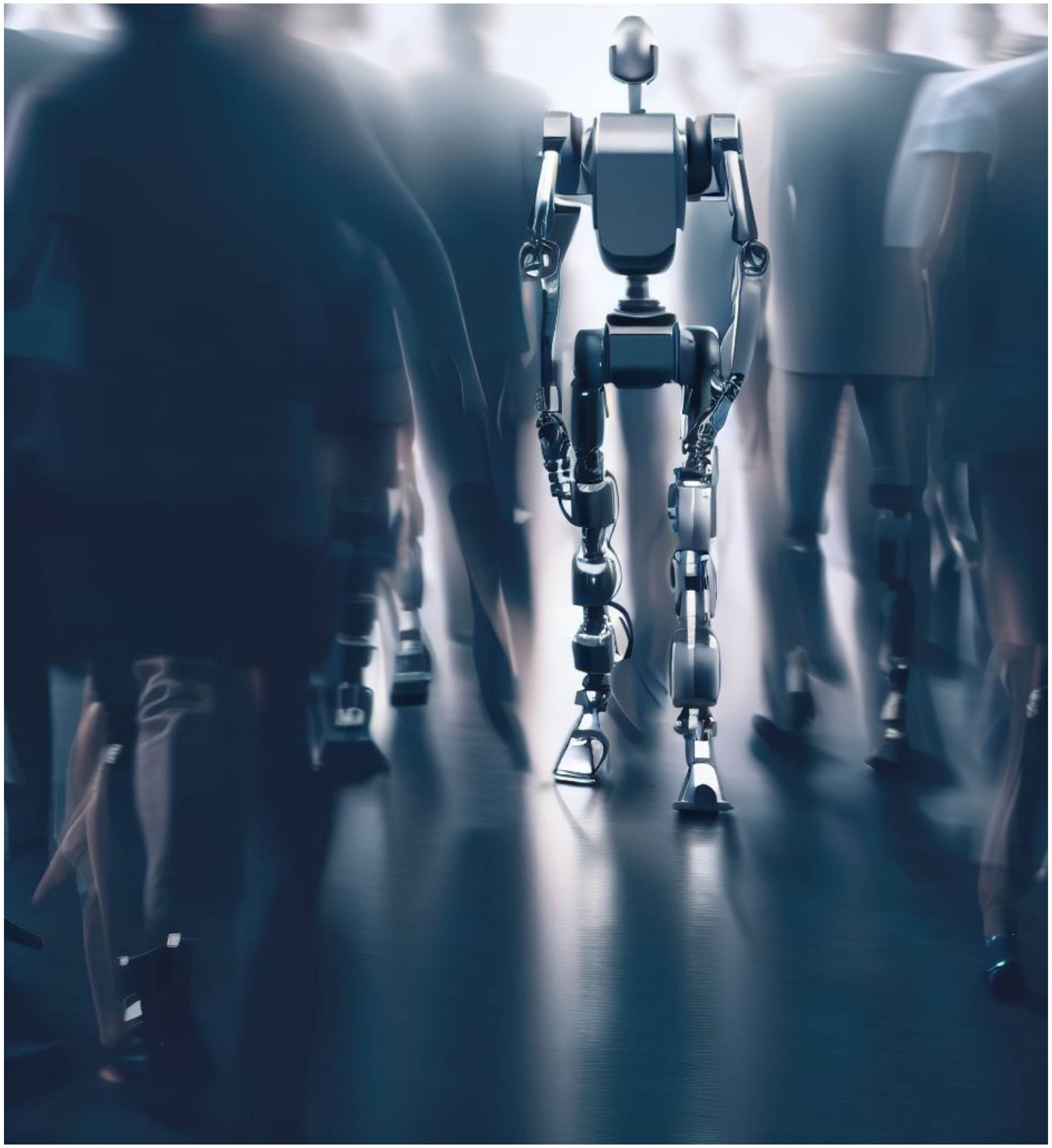

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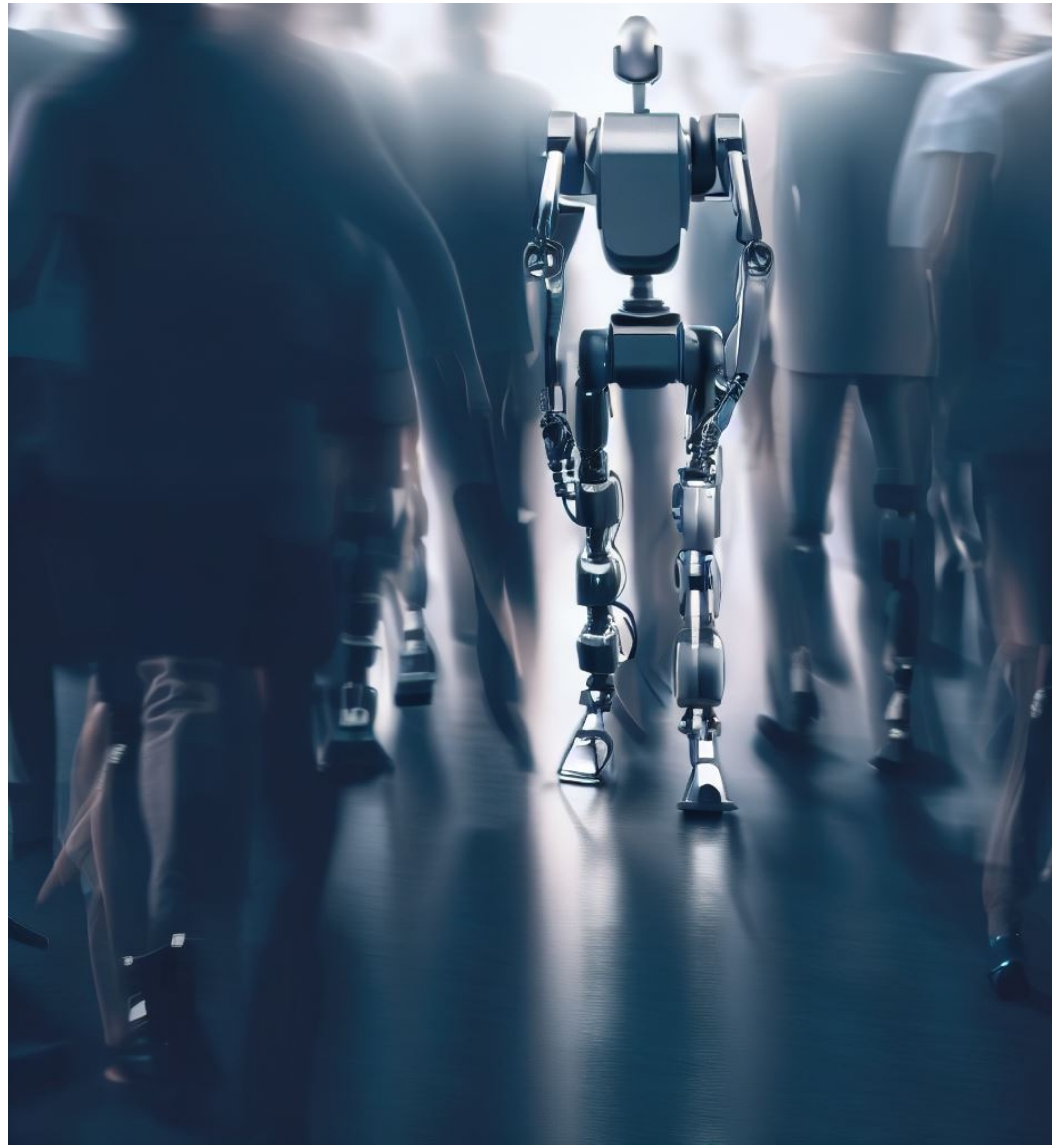
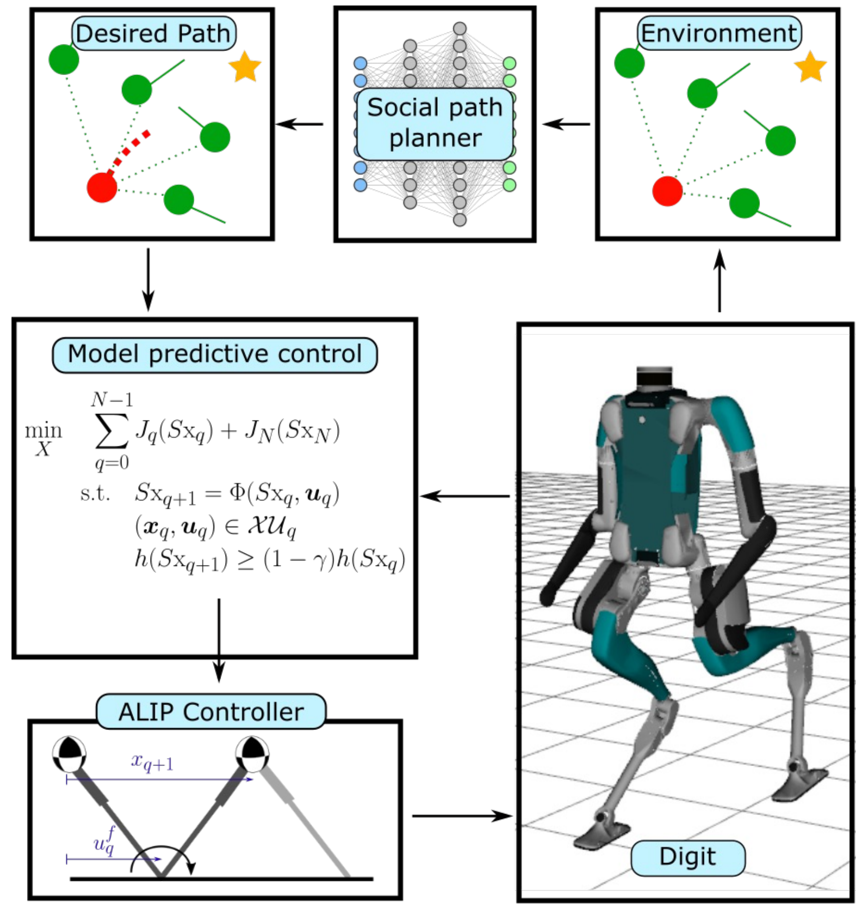
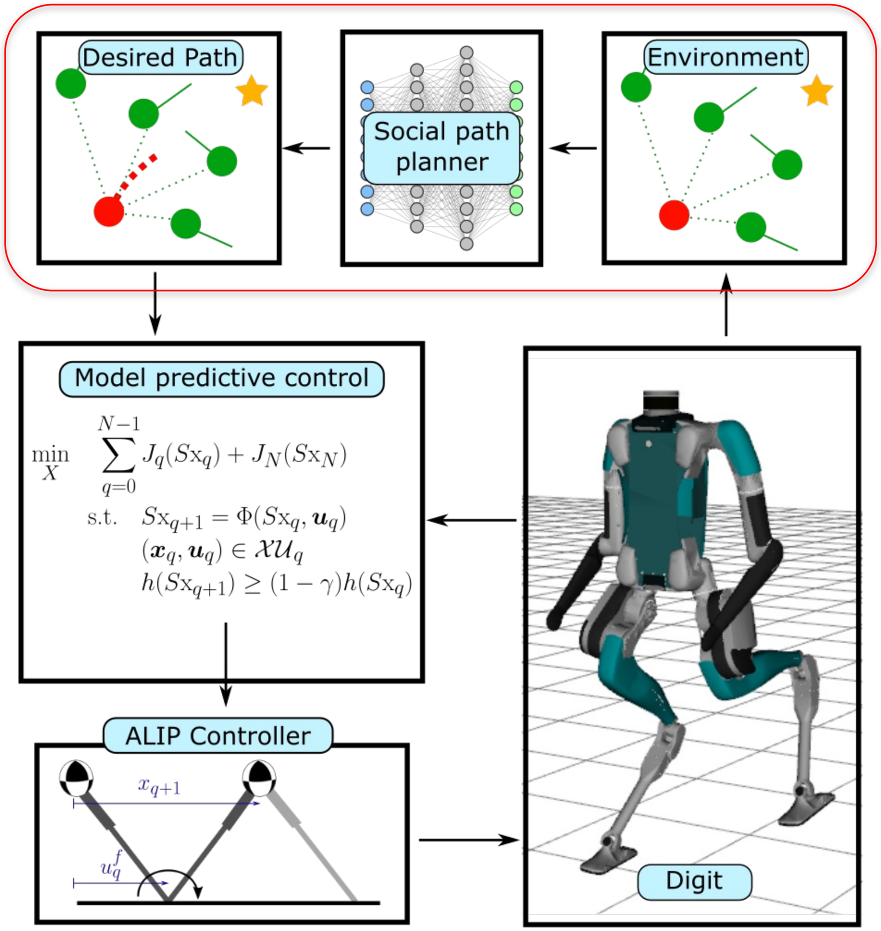


Hierarchical Planning



Hierarchical Planning

- High level: learning-based-social-path planner
  - Generates a **socially acceptable** path and **promotes** locomotion safety



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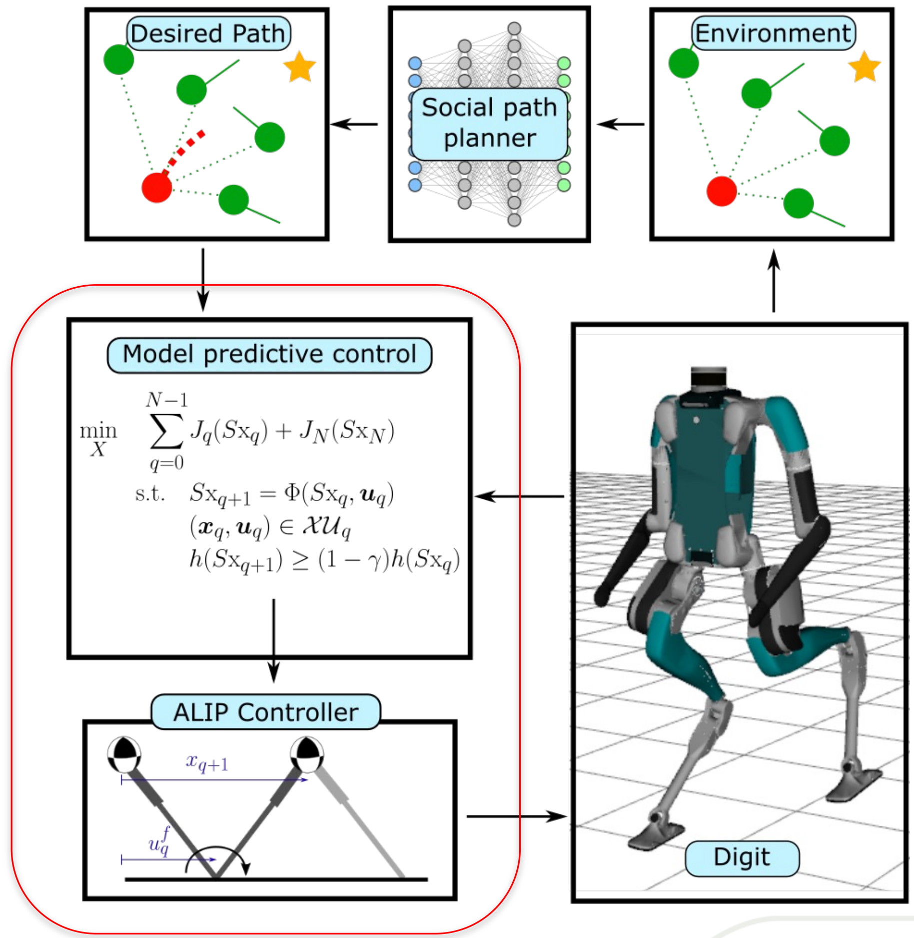
  - **Guarantees** task completion, and navigation and locomotion safety for the reduced order model



$$\min_{X} \sum_{q=0}^{N-1} J_q(Sx_q) + J_N(Sx_N)$$
$$\text{s.t.} \quad Sx_{q+1} = \Phi(Sx_q, \boldsymbol{u}_q)$$
$$(\boldsymbol{x}_q, \boldsymbol{u}_q) \in \mathcal{XU}_q$$
$$h(Sx_{q+1}) \geq (1-\gamma)h(Sx_q)$$

[1] Narkhede, Kunal S., et al. RAL 2022
[2] Y. Gong and J. W. Grizzle, JDSMC 2022

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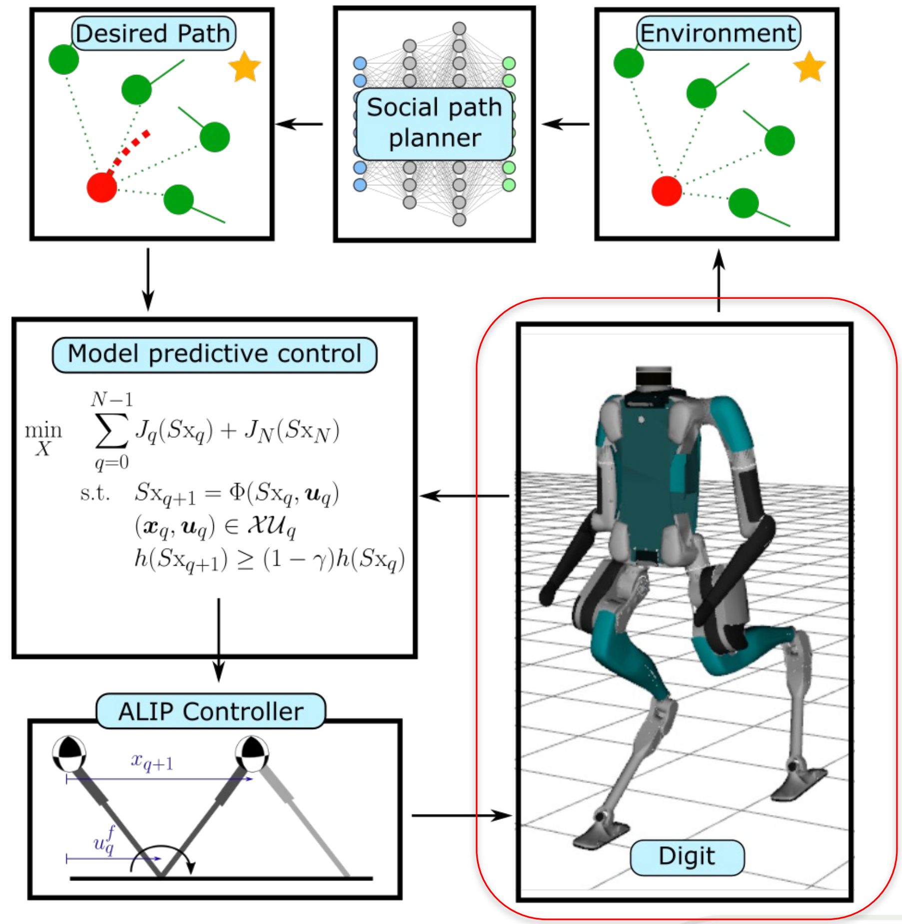
- Low level: passivity-based realtime controller [2, 3]
  - **Tracks** the reduced-order-model trajectory from the middle level



[1] Narkhede, Kunal S., et al. RAL 2022
[2] Y. Gong and J. W. Grizzle, JDSMC 2022
[3] A. Shamsah., et al. TRO 2023

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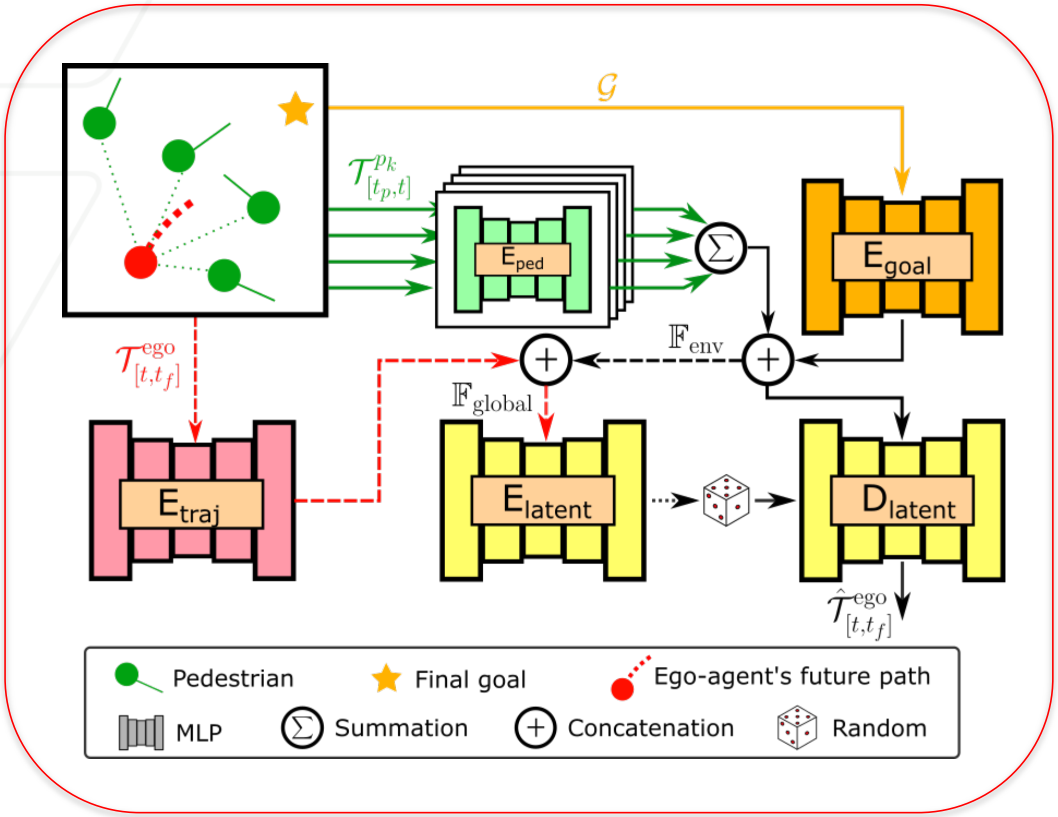
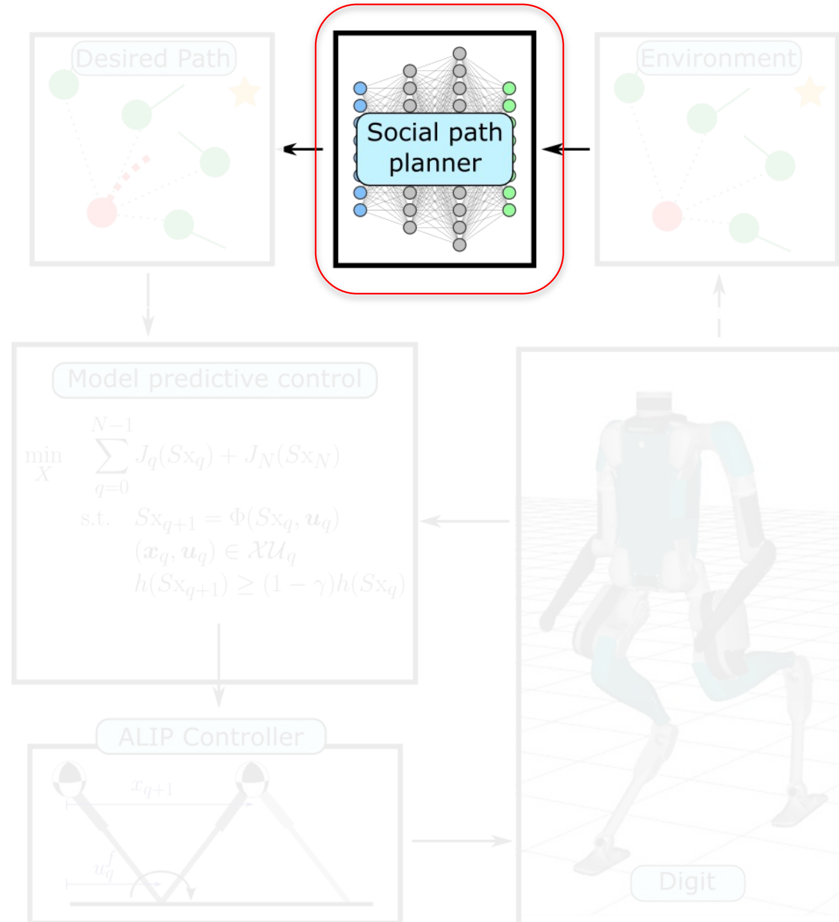
Social Path Planner



Mangalam, Karttikeya, et al. ECCV 2020



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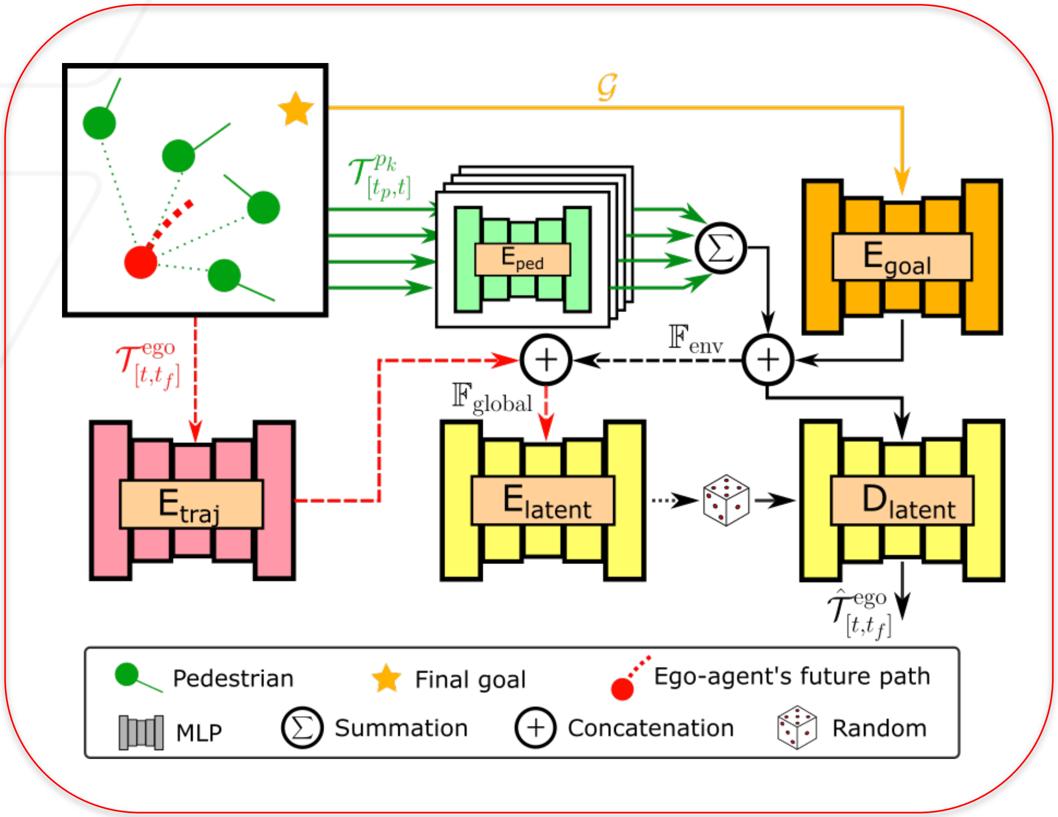
Social Path Planner



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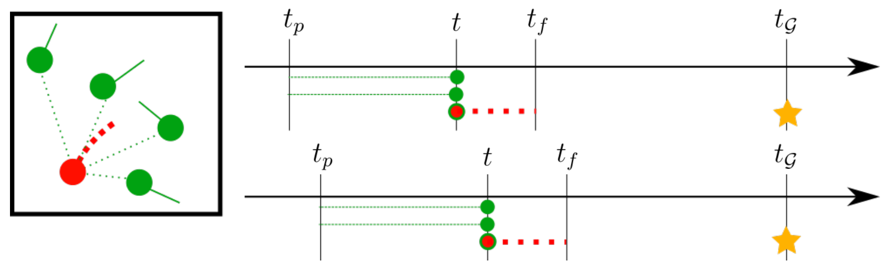
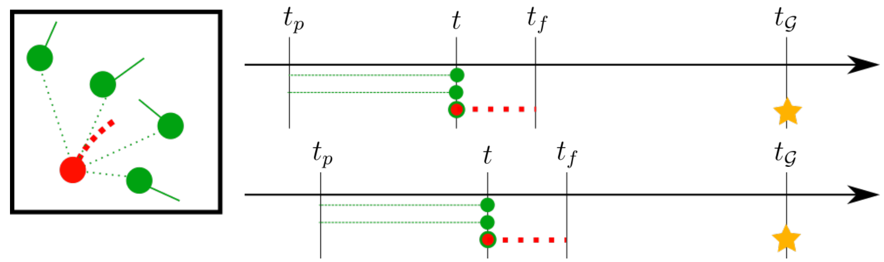


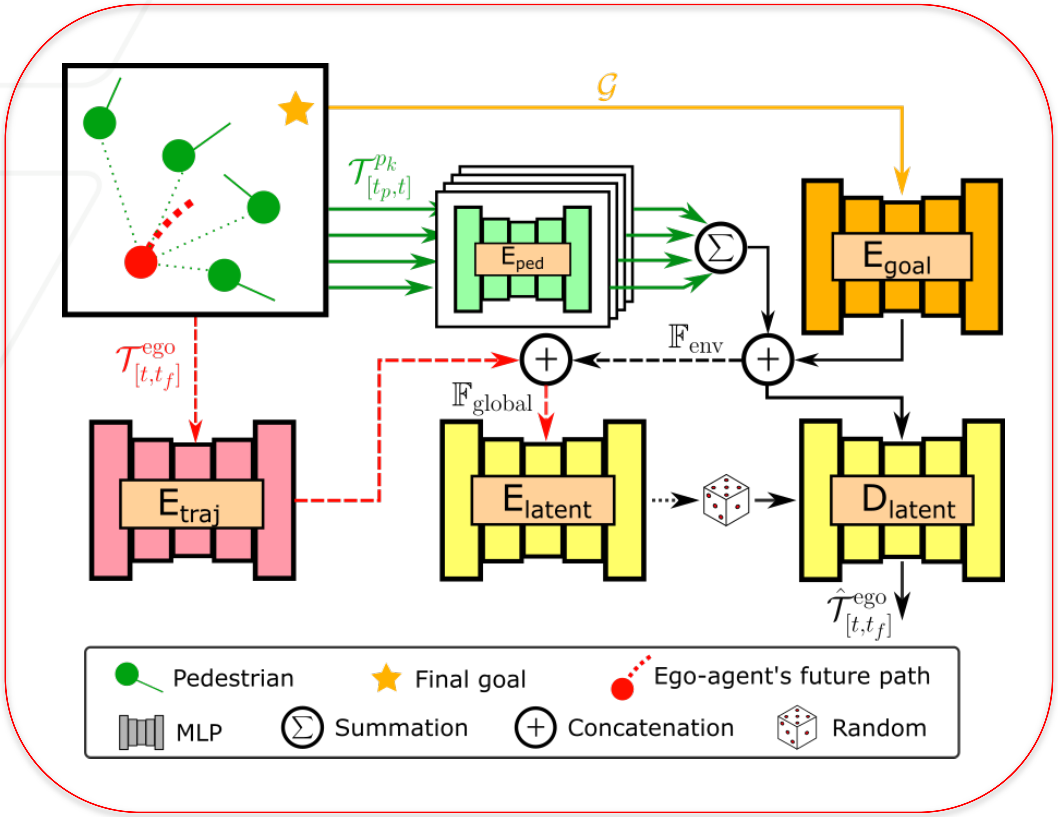
pedestrians' past path $(x^{p_k}_{[t_p,t]}, y^{p_k}_{[t_p,t]}) = \mathcal{T}^{p_k}_{[t_p,t]}$

ego-agent's final destination $(x^{\text{dest}}, y^{\text{dest}}) = \mathcal{G}$

ego-agent's future path $(x^{\text{ego}}_{[t,t_f]}, y^{\text{ego}}_{[t,t_f]}) = \mathcal{T}^{\text{ego}}_{[t,t_f]}$

Social Path Planner





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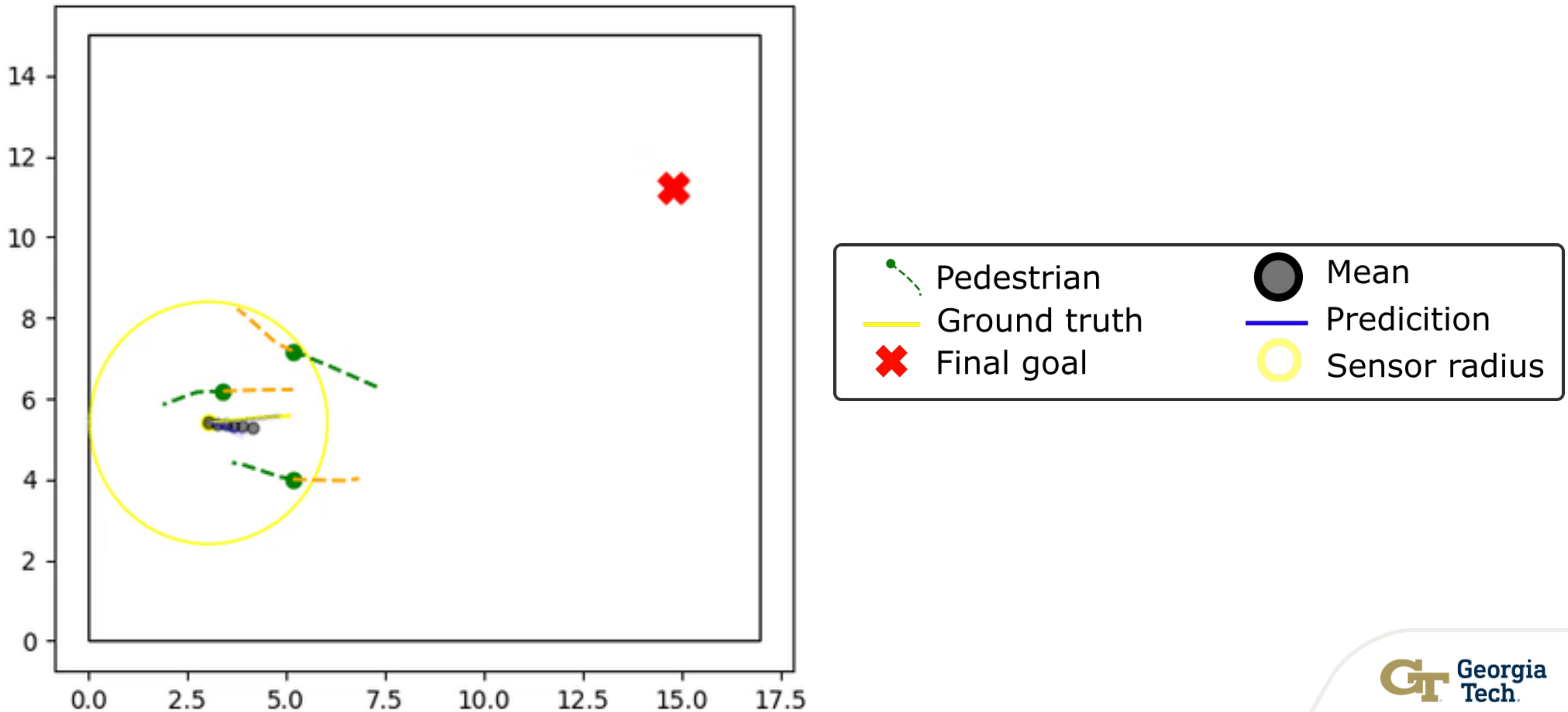
Assumption: A socially-acceptable path for the ego-agent is the path that a human would take in a similar setting

Social Path Planner Results



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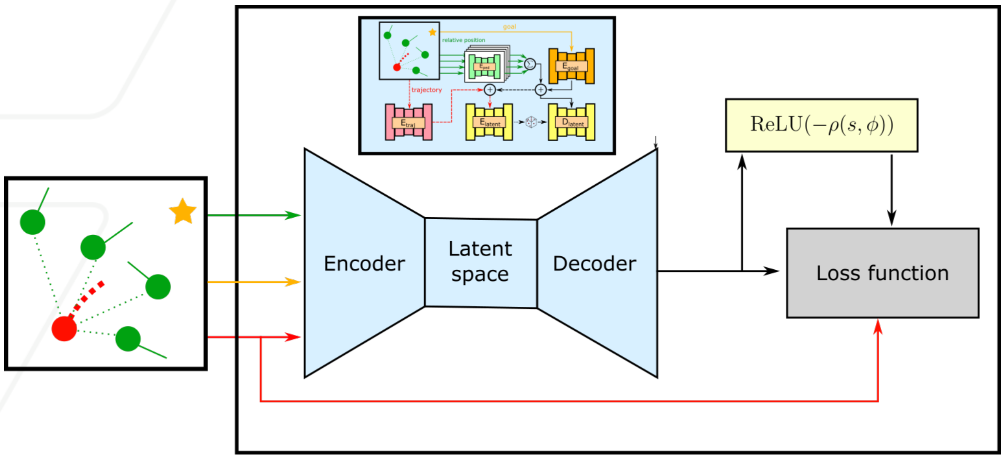
Incorporating Locomotion Safety Specifications



- **Motivation:** regulate the CVAE output to promote **locomotion safety**
- **Methodology:** use the quantitative semantics of Signal-Temporal Logic (STL) as **part of the loss function** [4]

[4] Leung, Karen, et al. IJRR 2023

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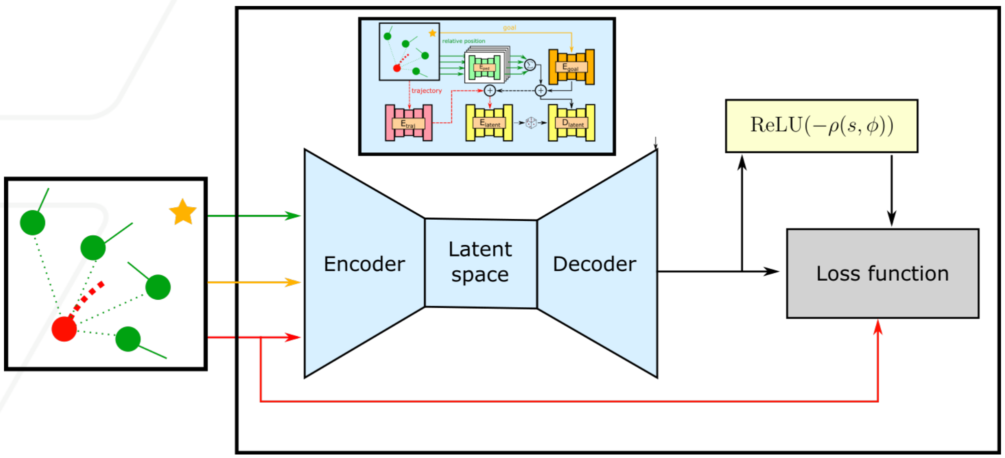

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$\rho(s_t, \phi)$ quantifies **the degree of satisfaction or violation** of the specification ϕ given a specific signal s_t

$$\rho(s_t, \phi) = \begin{cases} \geq 0 & s_t \text{ satisfies } \phi \\ < 0 & s_t \text{ violates } \phi \end{cases}$$

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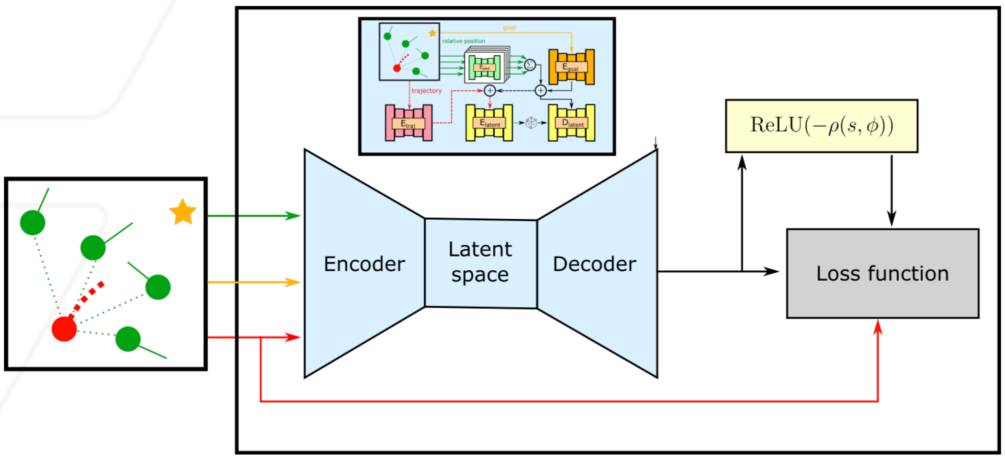

- Locomotion velocity specifications

$$\phi_{\text{sag}} = \square_{[t+1,t_f]}\left(s^{v_{\text{sag}}}_{[t+1,t_f]} \leq v_{\max} \wedge s^{v_{\text{sag}}}_{[t+1,t_f]} \geq v_{\min}\right)$$

$$\phi_{\text{lat}} = \square_{[t+1,t_f]}\left(s^{v_{\text{lat}}}_{[t+1,t_f]} \leq v_{\text{lat}} \wedge s^{v_{\text{lat}}}_{[t+1,t_f]} \geq -v_{\text{lat}}\right)$$

$$\phi_{\text{vel}} = \phi_{\text{sag}} \wedge \phi_{\text{lat}}$$

- Heading change specifications

$$\phi_{\Delta\theta} = \square_{[t+1,t_f]}\left(s^{\Delta\theta}_{[t+1,t_f]} < \Delta\theta_{\max} \wedge s^{\Delta\theta}_{[t+1,t_f]} > -\Delta\theta_{\max}\right)$$

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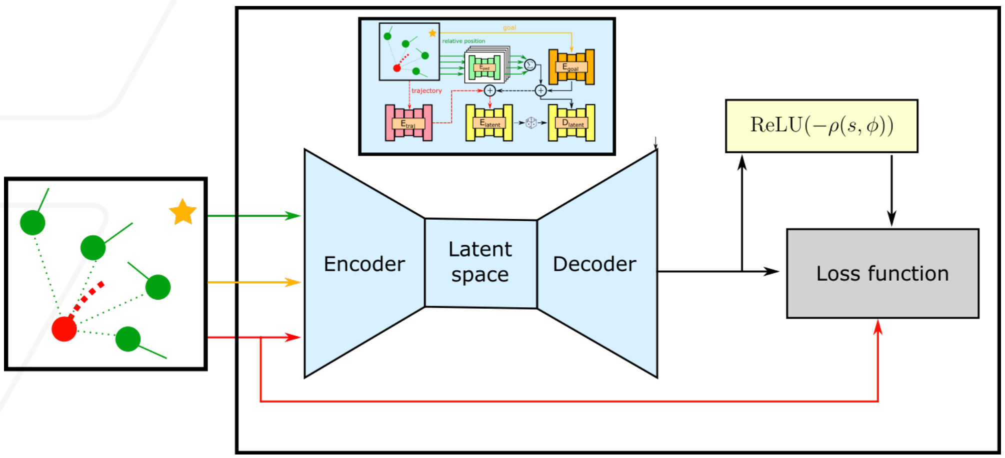

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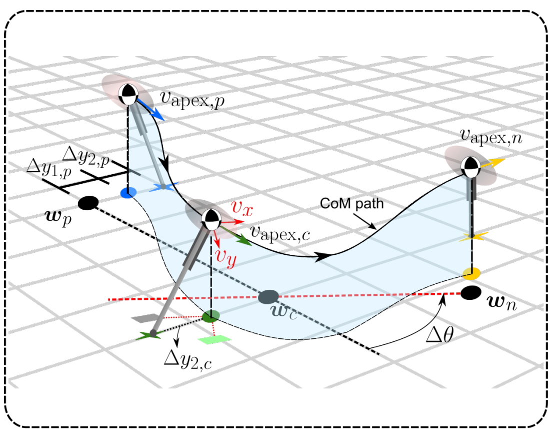

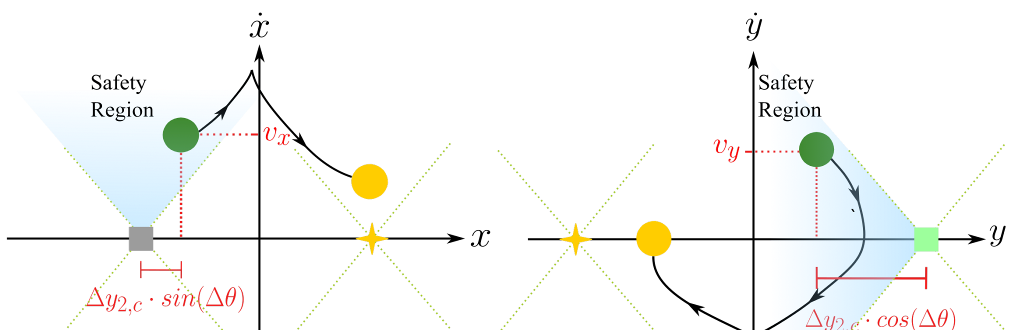

Shamsah, Abdulaziz, et al. TRO 2023

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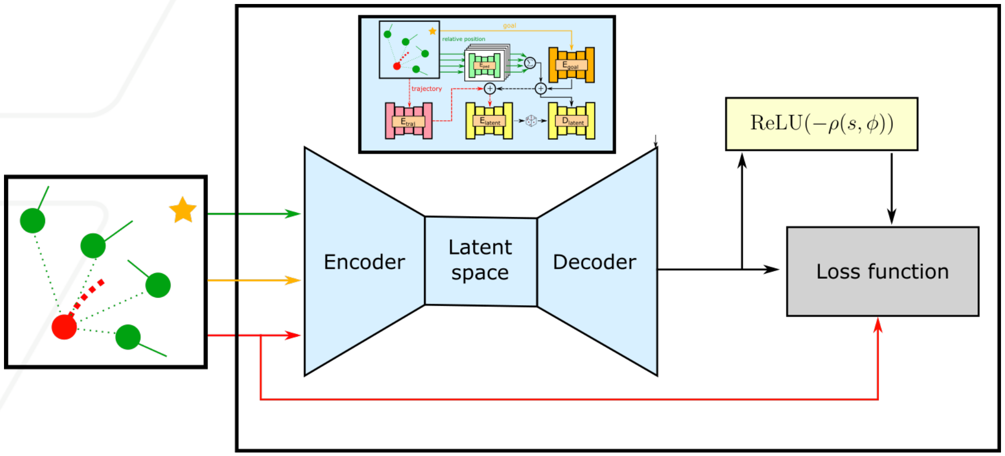

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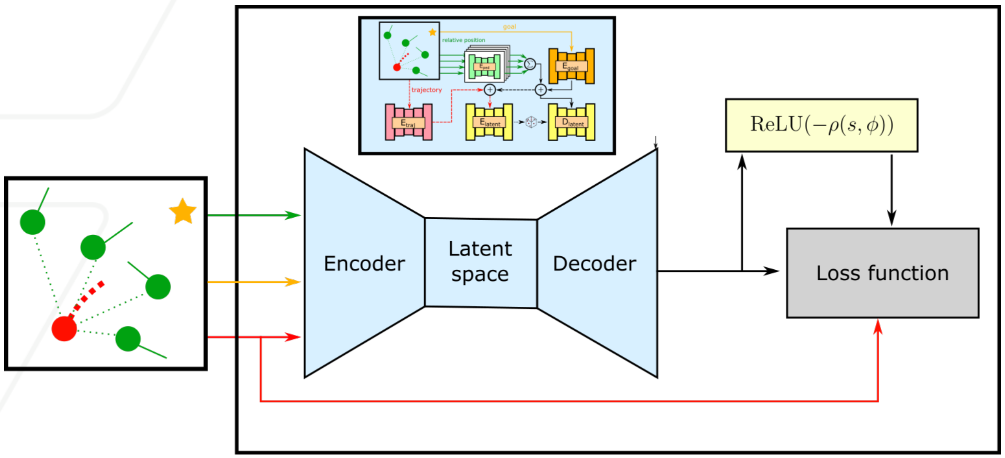
$$\mathcal{L}_{\phi_{\text{vel}}} = \underbrace{\text{ReLU}(-\rho((s^{v_{\text{sag}}}, s^{v_{\text{lat}}}), \phi_{\text{vel}}))}_{\textit{velocity violation}} \qquad \mathcal{L}_{\phi_{\Delta\theta}} = \underbrace{\text{ReLU}(-\rho(s^{\Delta\theta}, \phi_{\Delta\theta}))}_{\textit{heading change violation}}$$

Incorporating Locomotion Safety Specifications



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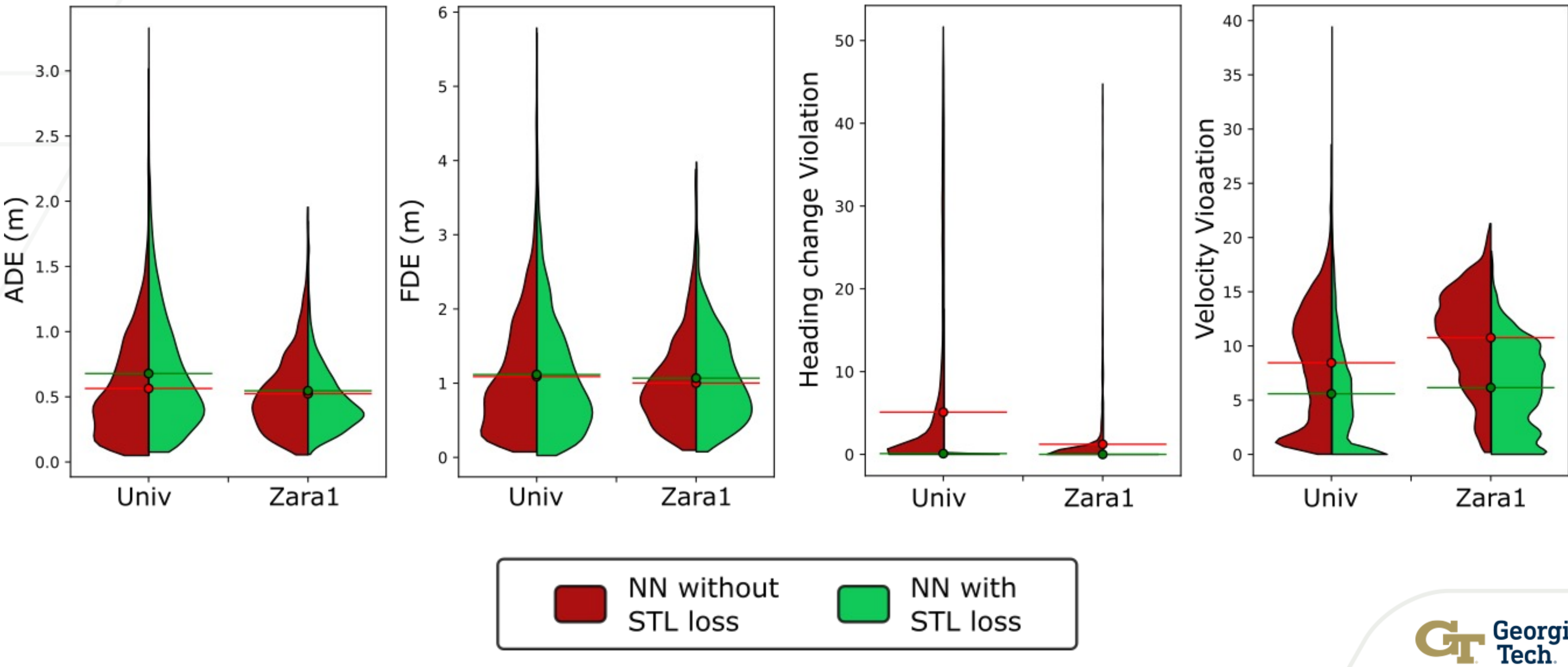
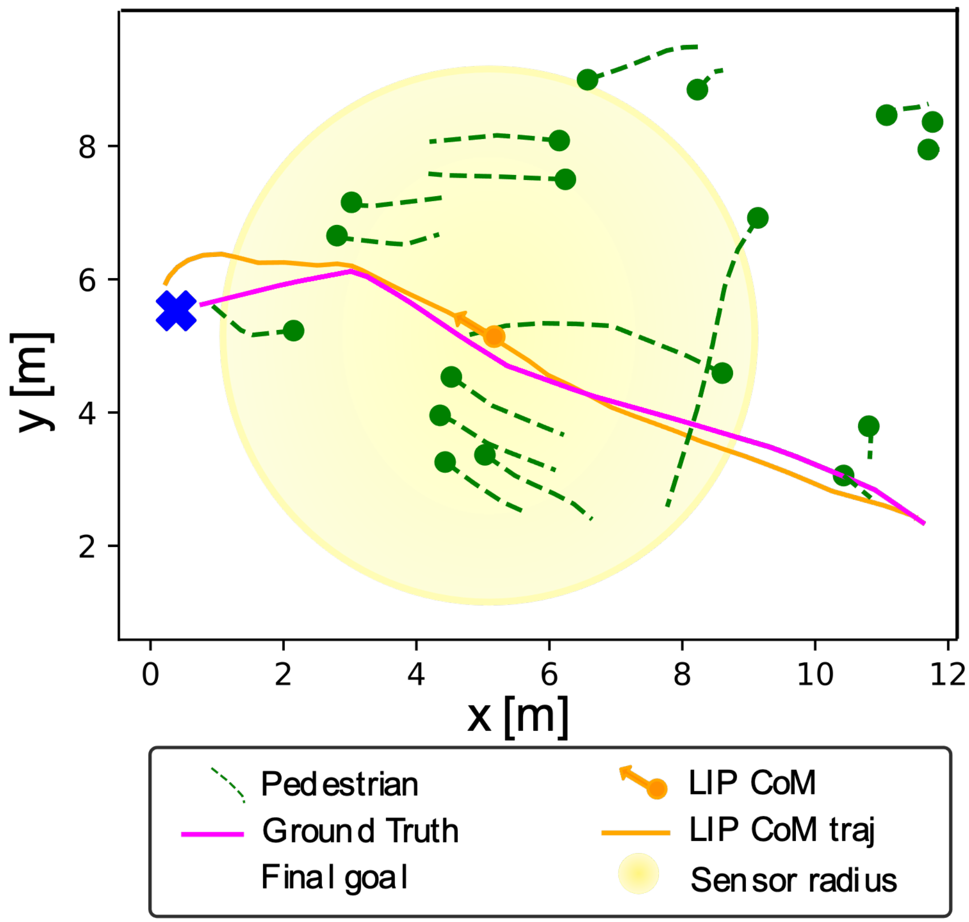
$$\mathcal{L}_{\text{STL}} = \alpha_1 \mathcal{L}_{\phi_{\Delta\theta}} + \alpha_2 \mathcal{L}_{\phi_{\text{vel}}}$$

Social Path Planner with STL results



Bipedal Social Path Planner Results



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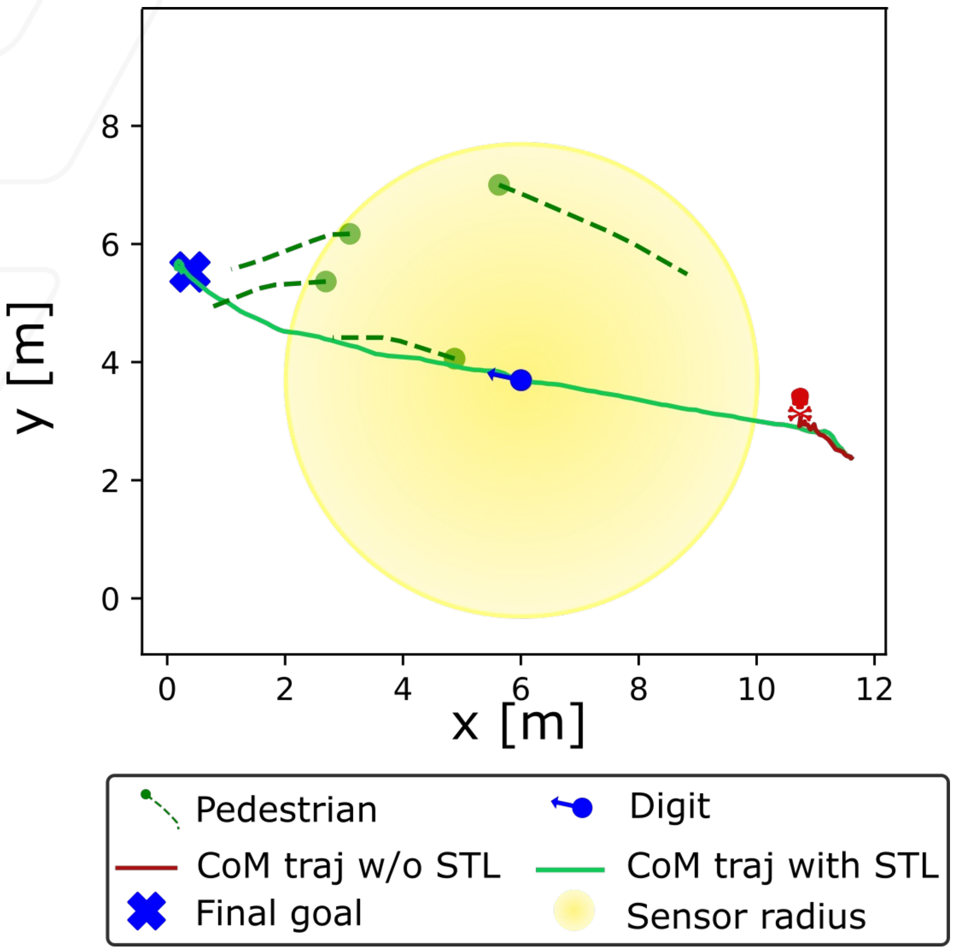

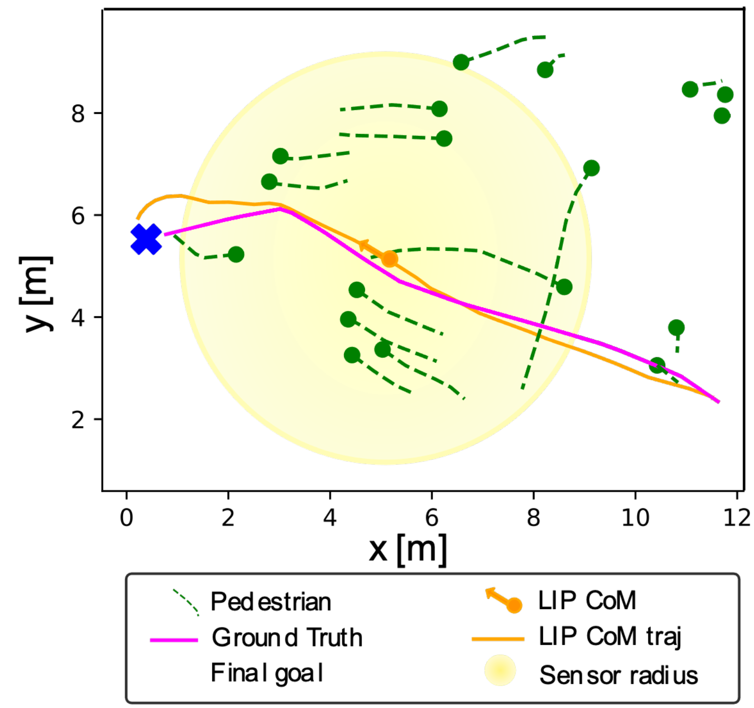

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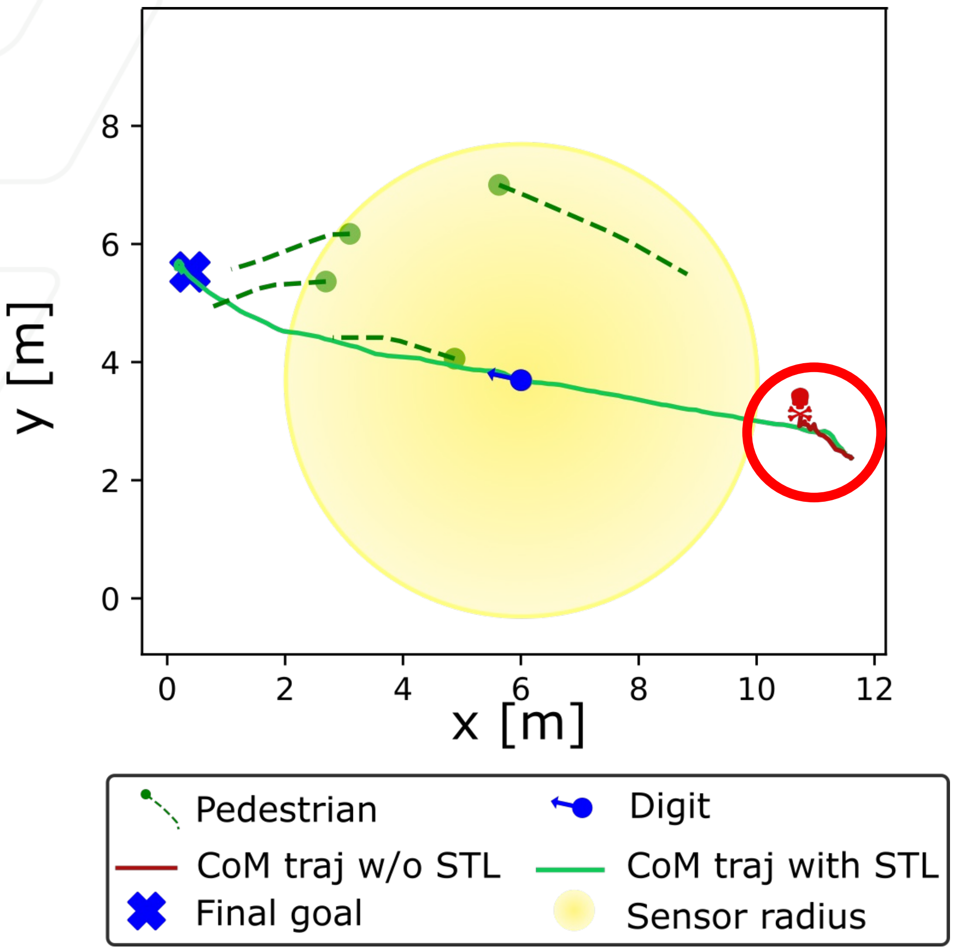
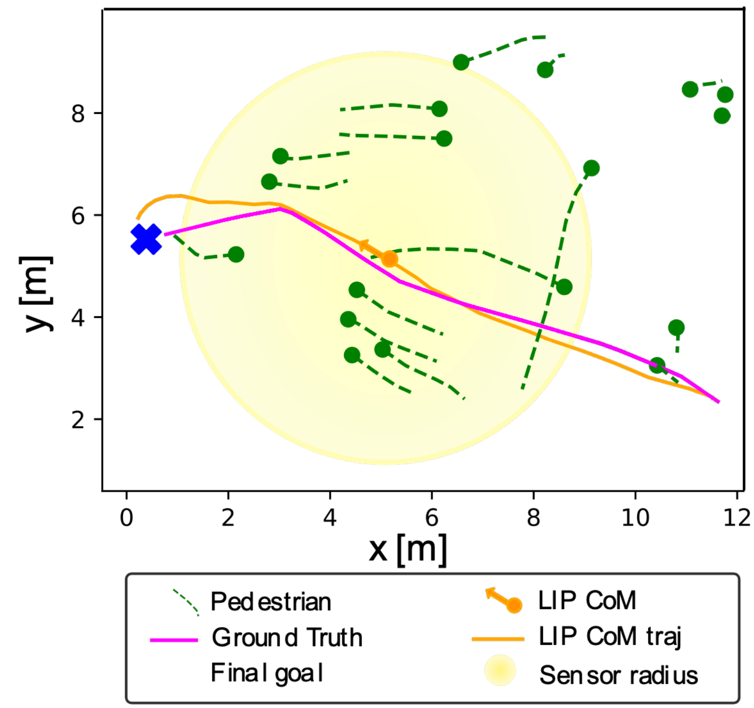
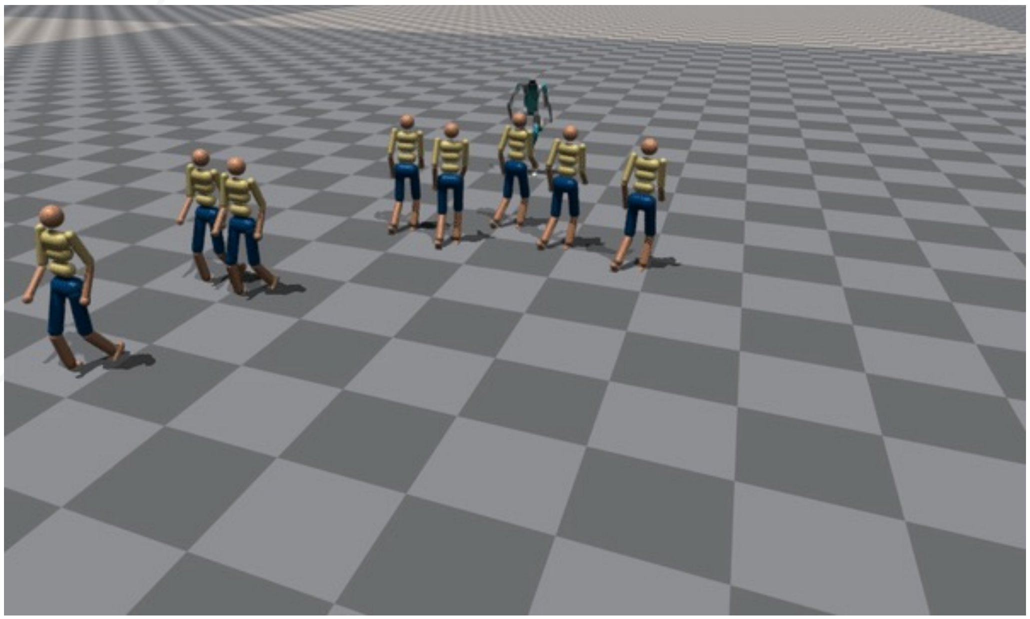




Preliminary Results



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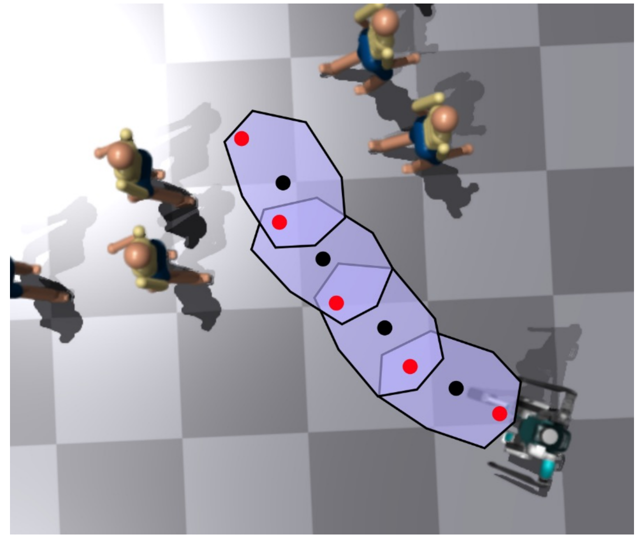
Ongoing work

- Predicting **social reachable corridors** parameterized as zonotopes

$$\mathcal{Z}(c, G) = \{c + G\beta \mid \|\beta\|_\infty \leq 1\}$$

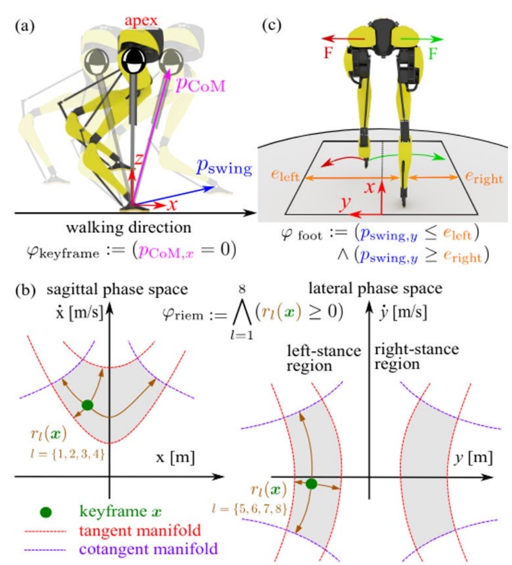
$$\hat{\mathcal{Z}}^{\text{ego}}_{[t, t_{f-1}]} = [c_t, G_t, \ldots, c_{t_{f-1}}, G_{t_{f-1}}]$$

$$\mathcal{L}_{\mathcal{Z}} = f(\mathcal{T}^{\text{ego}}, \hat{\mathcal{Z}}^{\text{ego}}) + \|G\|$$



- Evolved STL specification for **locomotion stability** [5]

$$\phi_{\text{loco}} = \Diamond_{[T^k, T^{k+1}]}(\phi_{\text{keyframe}} \wedge \phi_{\text{riem}}) \wedge (\Box \phi_{\text{foot}})$$



[4] Gu, Zhaoyuan, et al. submitted 2023

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College of Engineering

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