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Legible and Proactive Robot Planning for Prosocial Human-Robot Interactions

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Abstract

Humans have a remarkable ability to fluently engage in joint collision avoidance in crowded navigation tasks despite the complexities and uncertainties inherent in human behavior. Underlying these interactions is a mutual understanding that (i) individuals are prosocial, that is, there is equitable responsibility in avoiding collisions, and (ii) individuals should behave legibly, that is, move in a way that clearly conveys their intent to reduce ambiguity in how they intend to avoid others. Toward building robots that can safely and seamlessly interact with humans, we propose a general robot trajectory planning framework for synthesizing legible and proactive behaviors and demonstrate that our robot planner naturally leads to prosocial interactions. Specifically, we introduce the notion of a markup factor to incentivize legible and proactive behaviors and an inconvenience budget constraint to ensure equitable collision avoidance responsibility.

Background and Motivation

Figure 1: People navigating a complex situation crossing the famous Shibuya crossing.

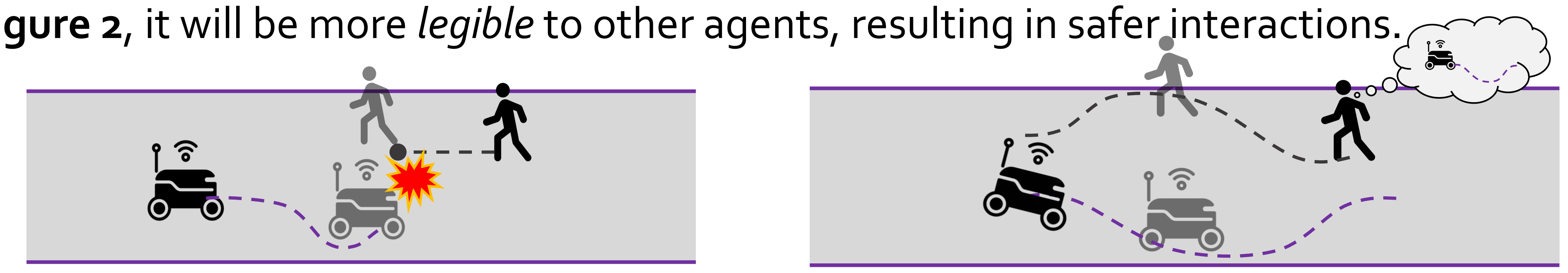
Humans have an incredible ability to successfully navigate complex situations, such as the one shown in **Figure 1**. This led us to ask: what fundamental behaviors enable this ability? It can be boiled down to two simple facts: (1) People are *self-preserving* [1] and (2) engage in *joint* collision avoidance. We can leverage these behaviors through some simple modifications to a general trajectory optimization problem used for social navigation tasks (**Problem 1**).

Problem 1 (Interaction-aware trajectory problem).

$$\min_{\mathbf{u}_{\mathrm{R}}^{0:T}} \sum_{t=0}^{T} J(\mathbf{x}_{\mathrm{HR}}^t, \mathbf{u}_{\mathrm{R}}^t, t) + J_{T+1}(\mathbf{x}_{\mathrm{HR}}^{T+1})$$
$$\text{s.t. } \mathbf{x}_{\mathrm{HR}}^{t+1} = f_{\mathrm{HR}}(\mathbf{x}_{\mathrm{HR}}^t, \mathbf{u}_{\mathrm{R}}^t, \mathbf{u}_{\mathrm{H}}(\mathbf{x}_{\mathrm{HR}}^t)), t = 0, ..., T$$
$$g_i(\mathbf{x}_{\mathrm{HR}}^t, \mathbf{u}_{\mathrm{R}}^t) \leq 0, t = 0, ..., T, i = 0, ..., G$$
$$h_j(\mathbf{x}_{\mathrm{HR}}^t, \mathbf{u}_{\mathrm{R}}^t) = 0, t = 0, ..., T, j = 0, ..., H.$$

Legibility and Proactivity

Accounting for human agents: Accounting for how humans will respond to the robot's decisions is challenging to model and incorporate within an optimization problem. It's believed that if a robot moves out of the way early (i.e. being *proactive*), such as in **Figure 2**, it will be more *legible* to other agents, resulting in safer interactions.



(a) Reactive planning: Illegible robot behaviors leads to collision-prone and inefficient interactions, such as the robot swerving at the last possible moment, leading to collision/near miss.

(b) Proactive planning: Robot executes *legible* plans to convey its intent to the human *early on*, and both agents coordinate to make space to pass by one another smoothly.

Figure 2: Comparing reactive and proactive safety with a motivating narrow corridor example.

Proposed Solution: Incorporating Markup and Inconvenience

Encoding Legibility and Proactivity into a Trajectory Optimization Problem: Legibility and proactivity can be encoded into the trajectory optimization problem by adding a markup term, μ^T into the cost to penalize control actions later in the planning horizon.

To ensure *equitable* interactions between the human(s) and robot (i.e. where both agents engage in collision avoidance), we add an inconvenience budget into the constraints of the optimization problem. Subsequently, the inconvenience budget can cause infeasibilities when paired with the dynamic collision avoidance. To remove the possibility of these infeasibilities occurring, the dynamic collision avoidance is relaxed using a slack variable. The updated formulation is shown in **Problem 2**.

Problem 2 (Follower's trajectory optimization problem).

$$\min_{\substack{\mathbf{x}_{\mathrm{F}}^{0:T+1},\\ \mathbf{u}_{\mathrm{F}}^{0:T},\\ \epsilon_{0:T+1}}} \sum_{t=0}^{T} \mu^t J(\mathbf{u}_{\mathrm{F}}^t, \mathbf{x}_{\mathrm{F}}^t, t) + \gamma_0 \sum_{t=0}^{T+1} \gamma^t {\epsilon_t}^2 + J_{T+1}(\mathbf{x}_{\mathrm{F}}^{T+1}) \tag{2a}$$
$$\text{s.t. } \mathbf{x}_{\mathrm{F}}^{t+1} = f_{\mathrm{F}}(\mathbf{x}_{\mathrm{F}}^t, \mathbf{u}_{\mathrm{F}}^t),\ \mathbf{x}_{\mathrm{F}}^0 = \mathbf{x}_{\mathrm{F}}^{\mathrm{current}} \quad t = 0, ..., T \tag{2b}$$
$$\mathbf{x}_{\mathrm{F}}^t \in \mathcal{X}_{\mathrm{F}}^t \setminus \mathcal{O}_{\mathrm{static}}, \quad t = 0, ..., T+1, \tag{2c}$$
$$\mathbf{u}_{\mathrm{F}}^t \in \mathcal{U}_{\mathrm{F}}(\mathbf{x}_{\mathrm{F}}^t), \quad t = 0, ..., T \tag{2d}$$
$$g(\mathbf{x}_{\mathrm{F}}^t, \mathbf{u}_{\mathrm{F}}^t, \mathbf{x}_{\mathrm{L}}^t, \mathbf{u}_{\mathrm{L}}^t) \geq -\epsilon_t, \quad t = 0, ..., T \tag{2e}$$
$$g(\mathbf{x}_{\mathrm{F}}^{T+1}, \mathbf{x}_{\mathrm{L}}^{T+1}) \geq -\epsilon_{T+1}, \tag{2f}$$
$$J_{\mathrm{incon}}(\mathbf{x}_{\mathrm{F}}^{0:T+1}, \mathbf{u}_{\mathrm{F}}^{0:T}) \leq \beta_{\mathrm{F}}, \tag{2g}$$
$$\epsilon_t \geq 0, \quad t = 0, ..., T+1. \tag{2h}$$

The problem is then solved using iterated best response to account for the response of each agent to the trajectory of the robot agent.

Results and Analysis

We tested our algorithm with random relative starting positions between a robot and human agent. Multiple different planning algorithms were used to represent the human agent throughout experimental trials.

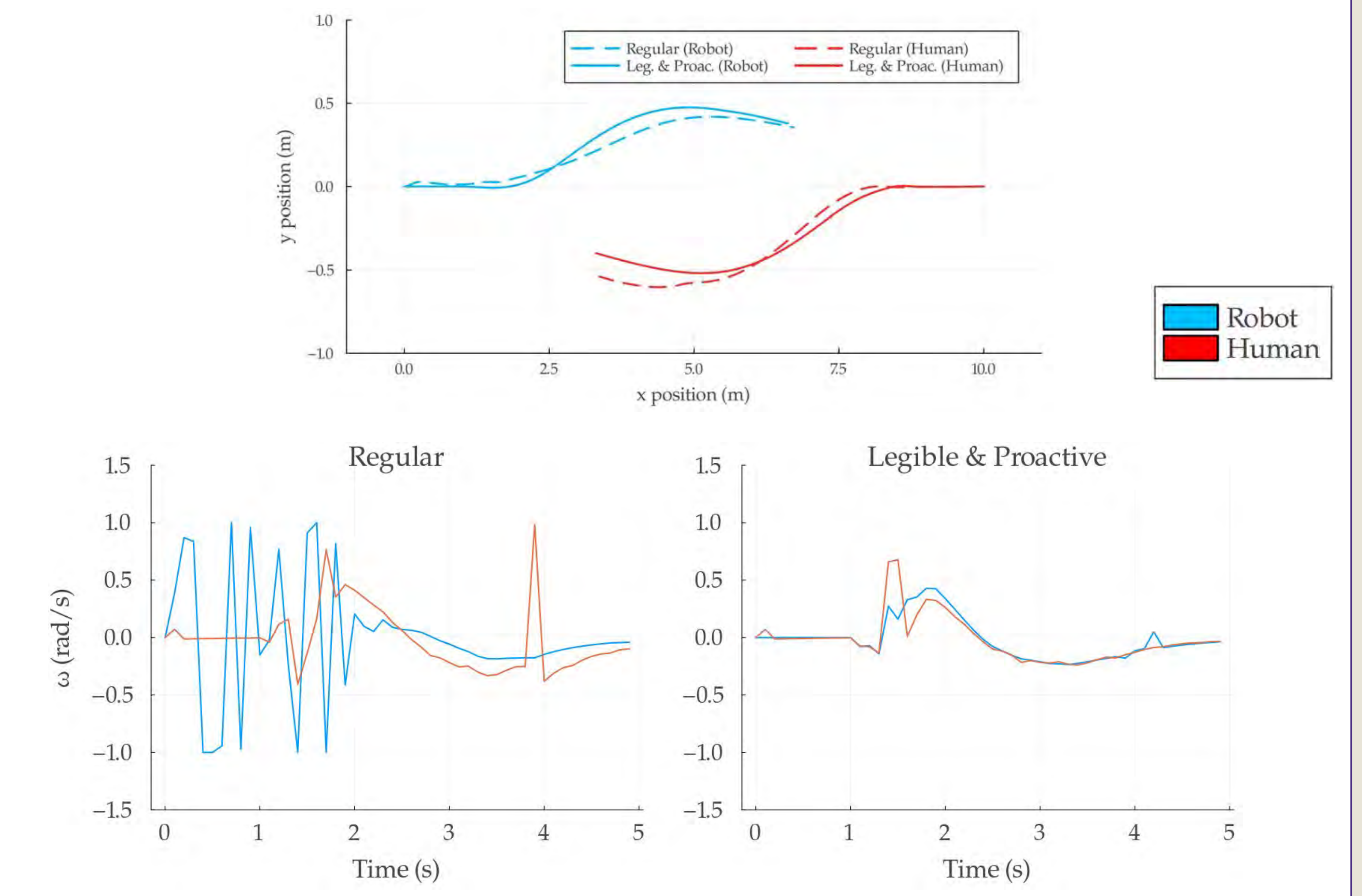


Figure 3: Top: Our method leads to more equitable collision avoidance between a robot and human. **Left:** Using a vanilla optimal controller leads to significant oscillations from the robot, confusing the human agent. **Right:** Our method reduces confusion between the robot and human, leading to efficient and safe collision avoidance.

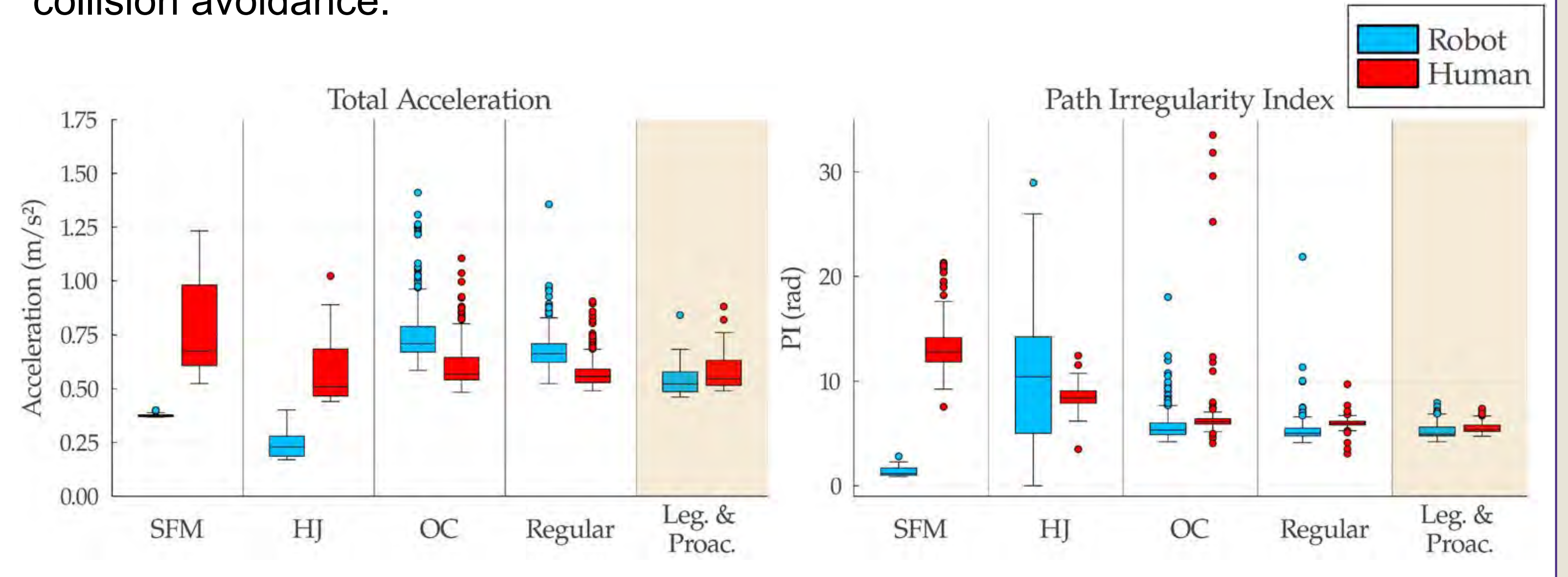


Figure 4: Our method requires less total acceleration and deviation from the ideal trajectory to safely pass by the human agent than other methods

References and Acknowledgements

[1] M. Mayer, R. Bell, and A. Buchner, "Self-protective and self sacrificing preferences of pedestrians and passengers in moral dilemmas involving autonomous vehicles," PLoS ONE, 2021

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