Dynamic Legibility of Robot Passing Side Improves Hallway Navigation

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***Abstract*— Legibility, the property of motion that enables an observer to quickly and confidently infer the robot's goal, is critical for seamless human-robot encounters in pedestrian domains. However, generating legible motion in such dynamic environments remains a challenge. In this work, through a within-subjects user study (N=30) involving a 1-1 hallway passing scenario, we methodically investigate how different goal and dynamics representations underlying the formulation of legibility impact robot performance and human impressions. We find that signaling of the robot's intended passing side (as opposed to its intended goal), and dynamic adaptation to the user's estimated passing side (as opposed to rigidly following the robot's predetermined passing side), were perceived as significantly more competent and required less user effort.**

I. INTRODUCTION

When deployed in pedestrian environments, conventional navigation algorithms may result in robot motion that is hard to read, making it difficult for humans to anticipate robot behavior, and leading to inefficient, uncomfortable, and even unsafe human-robot encounters [15]. Prior work has highlighted the potential of robot intent expressiveness for enabling seamless human-robot interaction (HRI) [5, 6, 13, 16], through the use of modalities like gestures [6, 8], lights [1], and motion [2, 5, 13, 18]. The latter –commonly referred to as legible motion– and defined by Dragan et al. [5] as *motion that enables an observer to quickly and confidently infer the robot's goal* [5], has gained significant attention due to its potential to convey robot intent directly encoded within the robot's otherwise task-oriented motion, without necessarily requiring dedicated signaling components.

While the original legibility formulation [5] assumed static environments and passive observers, enabling a robot to navigate legibly in pedestrian environments requires accounting for the dynamic interactions with incoming pedestrians [2, 13]. Additionally, while legibility has conventionally targeted the communication of the robot's intended goal pose [3, 5, 12], this specification breaks down in social navigation: pedestrians do not need to know each other's goals; they just need to align on a protocol for avoiding each other [13, 23]. Finally, prior studies measuring the effects of legible robot motion for HRI are often not interactive: the user is shown a video and asked to predict the robot's goal [5, 19]. This practice overlooks the user's embodiment and influence on *robot behavior*, which is critical in social navigation scenarios [13, 14, 20]: pedestrians are both observers and actors, actively adapting their behavior in response to each other's movements.

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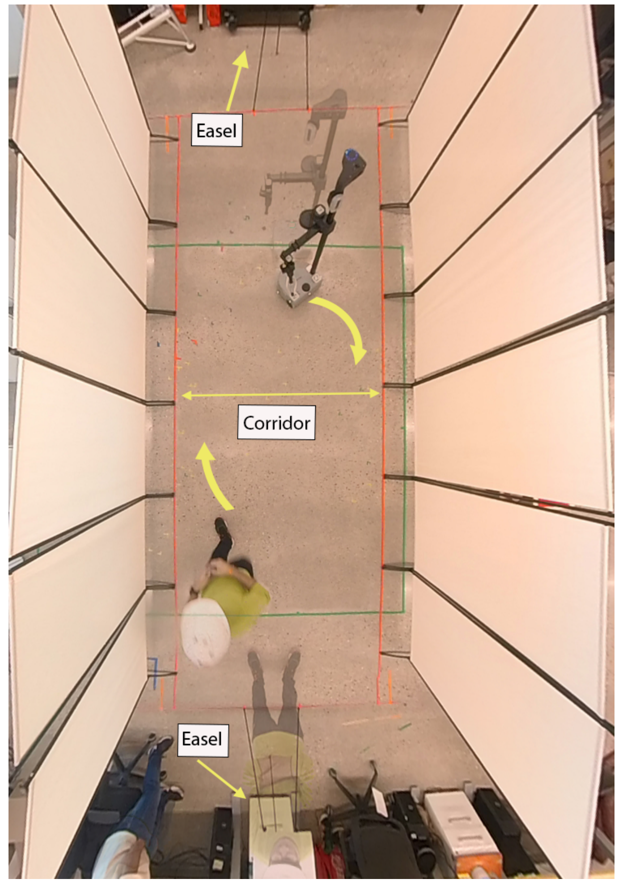


Fig. 1: Instance from our study investigating legible motion generation in hallway scenarios.

Moreover, most prior legibility studies have focused on relatively open, unconstrained spaces where complexity [17] of the scenario play a minimal role in shaping robot behavior [11, 13, 19]. In contrast, constrained scenarios like narrow hallways present unique challenges by forcing tighter negotiations.

Motivated by these observations, we revisit the challenge of generating legible motion in social navigation settings. Based on a general predictive control (MPPI) framework [21], we instantiate a series of navigation algorithms, each implementing legibility in a distinct way, based on prior work [2, 5, 13]. We conduct a within-subjects user study ($N = 30$) involving navigation alongside a robot in a 1-1 hallway scenario (see Fig. 1). We find that signaling of the robot's intended passing side (as opposed to its intended goal), and dynamic adaptation to the user's estimated passing side (as opposed to rigidly following the robot's predetermined passing side), were perceived as significantly more competent and required less user effort.

II. User Study

We present an IRB-approved (HUM00268645) lab study evaluating distinct legible robot navigation strategies in a constrained hallway setting, with a focus on socially compliant behavior.

A. Rationale

Based on the formulation provided by Dragan et al. [5], legibility can be modeled as the ability to confidently infer the correct goal configuration G after observing only a snippet of the trajectory, $\xi_{S\to Q}$, from the start S to the configuration at a time t, where $Q = \xi(t)$:

$$\mathcal{I}_L(\xi_{S\to Q}) = G$$

The quicker this inference occurs (i.e., the smaller t is), the more legible the trajectory becomes.

A score for legibility, therefore, tracks the probability assigned to the actual goal G^* across the trajectory: trajectories are more legible if this probability is higher, with more weight being given to the earlier parts of the trajectory. Using this formulation, a measure of legibility is derived in terms of cost C, where lower costs signify more "efficient" trajectories. This framework provides a generic approach for modeling legible motion, however it leaves two major ambiguities in the context of social robot navigation:

- *Goal Representation*: The *Legibility* framework [5] discusses a global representation of the robot's goal to be inferred. However, the correct representation of goals in social navigation remains unclear. The user might not be aware of or interpret the robot's global goal and may only consider the robot's goal at the local interaction level.
- *Goal Adaptation*: The *Legibility* framework proposes expressing intent towards a fixed robot goal. In socially aware robot navigation, however, methods often replan their paths around the intentions of co-navigating humans. Thus it remains unclear whether the robot should be compliant towards the intentions of co-navigating humans or remain confident in expressing the intent for its goal.

We seek to provide insight into these ambiguities by investigating the empirical effects of distinct goal representation and adaptation strategies. To study this, we evaluate the performance of the different strategies in head-on passing interactions: a common real-world scenario which straightforwardly captures the interactive component of social navigation.

B. Procedure

Each participant completed five trials, repeatedly walking between stations at either end of a $2\,\mathrm{m} \times 5.8\,\mathrm{m}$ corridor while a mobile robot (Hello Robot Stretch 2) moved in the opposite direction. The task was framed by a fictional scenario to motivate repeated navigation. The corridor, built with floor separators in the lab, simulated a constrained hallway. A practice trial with a stationary robot familiarized participants with the task. After each trial, participants completed a questionnaire about their interaction experience, followed by a final survey collecting demographics and prior robotics exposure. Participants were then debriefed and compensated.

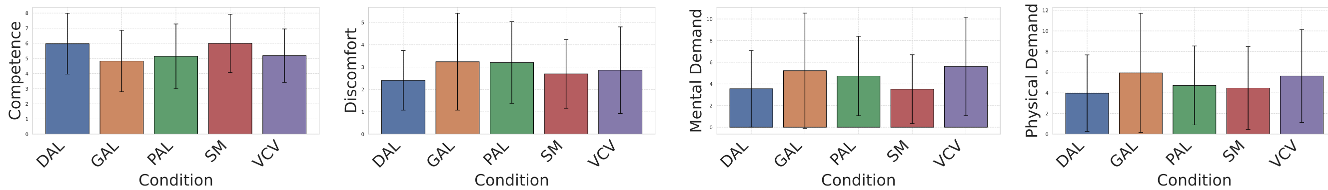
Task Description. Users were asked to assume the role of workers in a factory. The factory corridor has 2 machines represented as easels, one on each end of the corridor. Each participant is given 6 different colored sticker dots. The duty of the participant is to perform inspection of the machines. The inspection is done by sticking a random color sticker on the easel. The participants were told that the robot is monitoring the inspection by keeping a track of colors they stick.

Trial Description. Each trial involved the participant going back and forth between the stations six times, while the robot was navigating in the opposite direction. The participants are instructed to only turn around and move to next station after they hear a gong sound. The gong sound is played when the robot is ready to move for synchronization purposes.

C. Conditions

All participants experienced five navigation conditions in a within-subjects design, with condition order counterbalanced using a Balanced Latin square to mitigate ordering effects. To evaluate the importance of goal representation and adaptation in our experiment, we instantiate five algorithms representing distinct approaches to legibility:

- *Goal-Based Legibility + MPPI* (GAL): MPPI based implementation of framework proposed by Dragan et al. [5]. The legibility was modeled in terms of the global goals at both ends of the corridor.
- *Passing side Legibility + MPPI* (PAL): A modified implementation of the *Legibility* method is proposed to represent goal inference as a passing-side determination. This approach introduces artificial goals positioned on both the left and right of the actual goal, inducing the passing sides. The passing side for each interaction was decided randomly during the trial.
- *Dynamic Passing side Legibility + MPPI* (DAL): Similar to the above mentioned passing side representation of *legibility* framework, but instead of choosing the side randomly it is determined by the probability of human's passing side using constant velocity predictions. The side with lower probability to that of human was chosen for the robot.
- *Social Momentum + MPPI* (SM): MPPI implementation of method proposed by Mavrogiannis et al. [13] which looks at legibility in terms of passing side and used angular momentum to define the interaction between the human and robot and express the passing side intent. The angular momentum is indicative of the tendency of two agents for picking a passing side—the larger the magnitude, the higher the certainty over the passing side given by the sign of the z component of the angular momentum.



(a) RoSAS Competence (b) RoSAS Discomfort (c) NASA-TLX Mental Demand (d) NASA-TLX Physical Demand

Fig. 2: Expected means and confidence intervals for subjective metrics on robot's motion. Quantities represent significantly different distributions based on the results of the Friedman test ($p < 0.05$).

- *Vanilla-MPPI with CV Predictions* (VCV): MPPI with constant velocity predictions for humans and obstacle avoidance cost. This baseline is used to represent non-legible but efficient robot motion for such navigation tasks.

A controlled experimental setup was established by implementing all algorithms within a general model predictive controller [22] framework. This enabled a direct comparison by isolating algorithmic differences to a single legibility cost term, while keeping static and dynamic obstacle avoidance costs consistent across all methods.

D. Metrics

We used the following metrics for performance, colleced from each trial:

Objective Metrics:

- *Path Irregularity* [7]: The amount of unnecessary turning per unit path length, providing insight into the smoothness and efficiency of the robot's trajectory. It is measured in $\frac{\text{rad}}{\text{m}}$, calculated as:

$$\frac{\sum_{\text{Path}}(\text{Rotation} - \text{Min. rotation needed})}{\text{Path length}}$$

- *Acceleration of Human*: Captures sudden changes in human motion as a proxy for how well the robot's actions were understood by nearby agents. Higher accelerations suggest lower legibility and more discomfort. We measure the average acceleration for the human agent throughout the trial.
- *Average Reaction Time*: The average reaction time of the human was measured as the time elapsed from when the participant begins moving from one easel to the point at which their acceleration along the width of the corridor exceeds a specified threshold. Higher reaction time suggests lower legibility.

Subjective Metrics:

- *Robot Social Attributes Scale (RoSAS)*: *Discomfort and Competence* measured using RoSAS [4] scale, with a list of 12 items, presented in a randomized sequence, on a nine-point scale anchored from 1 ("Definitely not associated") to 9 ("Definitely associated").
- *NASA Task Load Index (NASA-TLX)*: To understand the *Mental, Physical, Temporal, Frustration and Effort* load of the user we use the NASA-TLX [9].The original 21-point rating scale format of the scale was utilized.
- *Emotional State Assessment*: Participants' emotional states following the interaction were evaluated using three items rated on a five-point Likert-type scale. These items assessed emotional state along the dimensions of Anxious–Relaxed, Calm–Agitated, and Still–Surprised.
- *Legibility Assessment*: To assess robot's goal perception, participants rated *L1*: "The robot will bump into me in the future" (measuring perceived collision risk, anticipated to be inversely related to legibility) and *L2*: "I was quickly and accurately able to tell where the robot wants to go" (measuring legibility per [5]) on a seven-point Likert scale (1=Strongly Disagree, 7=Strongly Agree).

E. Hypotheses

Our study explores how legible motion, in terms of goal representation and adaptation in human-robot navigation, improves user experience. By varying aspects of legibility, we aim to assess its importance in generating positive user impressions and improving task performance metrics compared to efficient motion alone.

H1: "Legible algorithms will be more positively perceived and enable higher user performance." We hypothesize that legible algorithms (GAL, SM, PAL, DAL) will lead to smoother acceleration and more regular paths for the users, compared to non-legible algorithms (VCV). Additionally, legible algorithms are expected to be perceived as more competent and comfortable by users, as measured by the RoSAS scale. Moreover, we believe legible algorithms will require less effort from users, as measured by the NASA TLX, in contrast to non-legible algorithms.

H2: "Legibility over the robot's passing side will be more positively perceived and enable higher user performance compared to legibility over the robot's goal." We hypothesize that legibility over the robot's passing side (PAL, DAL, SM) will result in faster and more accurate understanding of the robot's intentions compared to legibility over the robot's goal (GAL), as measured by survey responses and reaction times. Additionally, we expect that legibility over the passing side will lead to smoother acceleration and more regular paths compared to legibility over the robot's goal. Furthermore, legibility over the passing side will be perceived as more competent and comfortable for humans, compared to legibility over the robot's goal.

H3: "Dynamically adapting the robot's legibility goal based on user reaction will be more positively perceived

and enable higher user performance compared to legibility over a fixed goal." We hypothesize that dynamically adapting legibility algorithms (SM, DAL) will be perceived as more competent and comfortable by users compared to fixed goal legibility algorithms (PAL). Dynamically adapting legibility algorithms are expected to lead to smoother acceleration and more regular paths compared to fixed goal legibility algorithms. Additionally, we anticipate that dynamically adapting legibility algorithms will require less effort from users, in comparison to fixed goal legibility algorithms.

III. Results

A total of 30 human subjects participated in the study, recruited from university population through relevant mailing groups. The subjects (23 male, 6 female, 1 unidentified) were 22.43 years old (SD = 2.80) on average. They rated their familiarity with robotics technology with an average of 3.56 (SD = 1.04) on a 5-point Likert scale. We used the non-parametric Friedman test followed by a non-parametric paired Wilcoxon signed-rank test with Holm-Bonferroni corrections [10] for post-hoc pairwise comparisons.

A. Analysis

Our analysis did not reveal significant effects for the objective metrics, likely due to their noisy nature which resulted in high variance in our readings. However, we did find that the algorithms significantly impacted user perception regarding *Competence* ($Q = 13.483$, $p = 0.009$) and *Discomfort* ($Q = 12.207$, $p = 0.015$). Similarly, significant effects were observed for user effort, specifically concerning *Mental Demand* ($Q = 17.746$, $p = 0.001$) and *Physical Demand* ($Q = 12.040$, $p = 0.017$). We did not find any significant effects for Temporal Demand, Performance, Effort and Frustration. Additionally, a significant effect was found for *L1* ($Q = 12.619$, $p = 0.013$), whereas no significant effects were detected for *L2*.

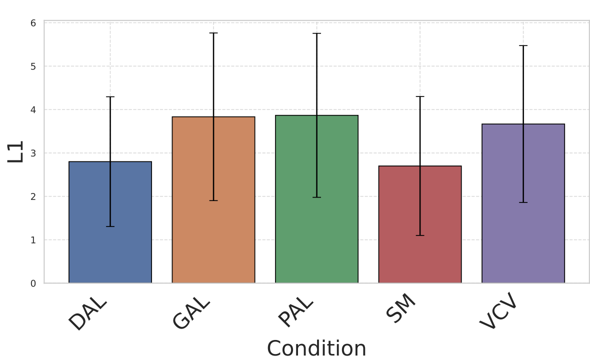


Fig. 3: Robot Bump (future) across all the algorithms. Higher value indicates higher rating for robot will bump into the user in future.

H1. VCV was perceived as significantly less competent compared to SM ($W = 99$, $p = 0.018$) and DAL ($W = 90$, $p = 0.03$). No significant difference was found between VCV and PAL or GAL. No significant result was found for discomfort in pairwise comparisons between these algorithms. VCV was perceived with significantly higher mental demand (MD) and physical demand (PD) compared to SM (MD: $W = 10$, $p = 0.003$; PD: $W = 33$, $p = 0.039$) and DAL (MD: $W = 44$, $p = 0.012$; PD: $W = 37$, $p = 0.019$). These results indicate that the legible formulations with passing side goal representation and dynamic adaptation were considered more competent and required less effort from users than the non-legible algorithm. Thus **H1** is partially supported.

H2. Users found GAL to be significantly more likely to bump (L1) into them in the future compared to SM ($W = 42$, $p = 0.010$) and DAL ($W = 50$, $p = 0.007$). GAL was perceived as significantly less competent compared to SM ($W = 77$, $p = 0.004$) and DAL ($W = 85$, $p = 0.013$). No significant difference was found between GAL and PAL. No significant result was found for discomfort in pairwise comparisons between these algorithms. GAL was perceived with significantly higher mental demand and physical demand compared to SM (MD: $W = 18$, $p = 0.003$; PD: $W = 38$, $p = 0.038$). With respect to DAL, a significant result was found only for physical demand (PD: $W = 21$, $p = 0.005$). These results suggest that the passing side legible formulation with dynamic adaptation was considered more competent and required less user effort compared to the global goal-based legibility. Thus **H2** is partially supported.

H3. PAL was perceived as significantly less competent compared to SM ($W = 102$, $p = 0.022$) and DAL ($W = 101$, $p = 0.0214$). PAL was perceived as more discomforting compared to DAL ($W = 94$, $p = 0.013$). PAL was also perceived with significantly higher mental demand (MD: $W = 26$, $p = 0.018$) compared to DAL. These results indicate that dynamically adapting the legibility to the user's preference was considered more competent than being legible over a fixed goal. We also found significant effects between user's effort for one of the dynamically adaptive algorithms. Thus, **H3** is partially supported.

B. Discussion

Our findings, particularly the partial support for **H1** provide evidence supporting the importance of intention expressivity in human-robot interaction, particularly within the context of shared physical spaces. Notably, the type of legibility matters. Partial support for **H2** and **H3** indicate communicating the immediate avoidance strategy and dynamic adaptation in legible navigation being beneficial for user comfort and trust in close interactions. Overall, algorithms combining dynamic adaptation with passing-side legibility yielded the most positive user ratings for competence, comfort, and reduced mental and physical demand.

These results highlight the importance of shorter-term local interaction intent-expressivity rather than long-horizon goals. Future work should develop algorithms that dynamically adjust legibility strategies in real-time based on the interaction context and co-navigating agents. Investigating these interactions in more varied environments and with diverse user populations would also be valuable extensions of this research.

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