Experimental Evaluation of the Impact of Robot Path Shape and Speed on Human Affective States in a Hallway-Passing Scenario

Benjamin Greenberg, Michael Grossi, Sai Likhith Karri, Jingang Yi, Jacob Feldman, and Karin Stromswold

Abstract— **For robots to be accepted by the public in shared spaces, they must navigate these environments in ways that are not just safe, but are also acceptable for coexisting people. Through a human-subjects experiment ($N = 11$), this research examines the impact of robot path shape and speed on the affective states of people when passing them in a hallway environment. In this study, a custom-built robot followed three unique path plans at two different speeds to navigate around participants in a hallway. The effect of variance of robot motion from the planned path was also studied. Participants reported their affective states through sliders that let them represent their levels of arousal and pleasure during the encounter with the robot. We found that robot speed and path variance have effects on participant arousal. While we did not find a significant effect of curvature on participant affective state. We discuss the emergent trends in the context of a similar study conducted in virtual reality.**

I. Introduction

Mobile robots are becoming more common in daily life [1]. From cleaning floors to making deliveries, in private homes, public spaces, and workplaces, their presence is becoming increasingly normal [2]. As robots navigate through spaces shared with people, it is critical to understand the impact that the introduction of robots has on coexisting people. These consequences can be social, physical, and psychological, and fully characterizing them can lead to improved robot designs [3].

Many factors influence the interaction between people and mobile robots such as robot appearance, communication, and safety [4], this work focuses on robot navigation. In particular, it aims to make path planning more socially acceptable by empirically characterizing how the shape of a robot's path impacts the affective states of coexisting people.

This research builds on our prior work in which we conducted an experiment in a virtual reality (VR) hallway environment where a robot would pass human subjects following a series of cubic Bezier curve-shaped trajectories [5]. The results from that study showed that the distance at which a robot begins its avoidance motion (its signaling distance) impacts the affective state reported by participants. Additionally, the experiment suggested that the sharpness of curvature of the robot's passing motion has an impact on the induced affective state of the participant. While that study provided new insight into how robot trajectory shape effects the affective states of people encountered by the robot, it also raised several questions that we sought to answer with this study.

Specifically, we wanted to understand how people respond in real encounters with robots. To attain a higher degree of realism, we made two important changes from the prior study. First, the experiment was conducted in a physical environment with participant encountering a real robot in a mock-up hallway environment, not in VR. This is a significant change because experiences in VR, though highly immersive, are inherently different from real world experiences. For example, the robot motion in VR follows the prescribed trajectory perfectly smoothly, whereas with a real robot there are physical constraints on the motion due to the mechanics and dynamics of the system. The second major difference from the prior study is that the robot trajectories being tested were produced by a realistic path planner instead of being cubic Bezier curves which are not typically the trajectory shapes that robots follow.

II. Related Work

Proxemics is the field of research that studies how the distance between two agents in an environment impacts their perception of each other [6]. Pacciarotti et al empirically determined proximal rules for human-robot interactions [7]. Bera et al. modeled proxemic zones around people as circularly shaped [8], while others used proxemic rules as low-level safety constraints in social navigation systems [9]. Neggers et al. performed experiments to determine the precise shape of a person's personal space during interactions with robots [10]. These efforts have expanded what is known about human perception of robots, and how it can be used in a robotic navigation system. However, proximal spaces are only one dimension through which to consider spatial relationships between people and robots. Khambhaita et al. expanded on this to consider the projected time to a future collision as a constraint for socially aware robot path planners [9]. The present research evaluates other dimensions such as path curvature and path variance to lend finer resolution to the time-integrated view to these interactions.

III. Methodology

We made several methodological decisions to achieve our goals of evaluating differently shaped robot trajectories in

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a more realistic way than the prior VR experiments. However, several parallels between the experimental setups were deliberately maintained to enable some broad comparison between them.

A. Robot Platform

The robot used for this experiment was a custom-built omnidirectional mobile robot with a height of 1.37 meters. This height is one of the reasons that this platform was chosen, since it provides more of an obstructing presence than a smaller robot and is comparable to the height of social mobile robots currently on the market [11]. This is the same robot that was modeled in VR for the prior experiment. 1.

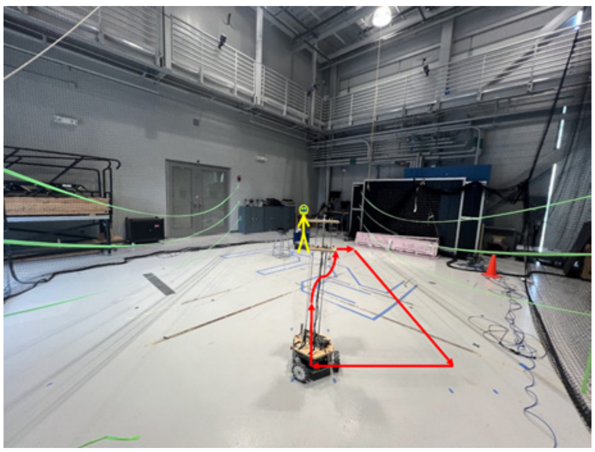

Fig. 1. Experiment environment with robot in foreground, approximate trajectory for one trial (including loop back to start position) shown with red arrows, and position of participant represented with the yellow figure.

The robot is controlled via a remote LabView program. This program streams the robot's position via the Vicon DataStream SDK MatLAB DotNet interface and provides control signals to the robot's motors via the onboard MyRIO microcontroller.

B. Environment Design

Due to the necessity of using a Vicon camera-based motion capture system as part of the robot's motion control pipeline, the experiment was conducted in the largest Vicon-equipped lab available. The usable workspace for the Vicon system in this lab is a 4 meter by 6 meter rectangle. To maximize the space available for the robot's approach and passing motion, the main axis of the robot's motion was along a diagonal of this workspace. To give the environment a shape more similar to the narrow hallway tested in VR, we draped three layers of high-visibility tape where the walls of the hallway would be. These barriers were approximately two meters tall, and enclosed an experimental area that was approximately four meters wide. The environment can be seen in the background of Figure 1. Had a larger space been available, we could have more closely replicated the dimensions of the VR environment, however, practical constraints precluded this.

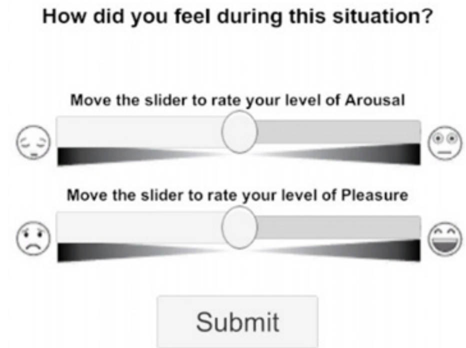

Fig. 2. Affective Slider interface used by participants to self report their affective states

C. Data Acquisition

The primary dependent measures in this experiment were the affective states of participants which they reported after each trial using an Affective Slider interface set up on a laptop that was within their reach during the experiment. This interface is shown in Figure 2. After each trial, participants were instructed to report their level of arousal and pleasure during the preceding encounter. Slider values were converted to whole numbers in the range of 1-100. In addition to the self-reported affective states collected via the Affective Slider interface, participants also provided answers to pre- and post-participation questionnaires, and had their heart rate and galvanic skin response measured during the experiment. Only the self-reported affective states will be analyzed in this paper.

D. Conditions Tested

Three robot trajectories were tested and each trajectory was tested at two speeds, for a total of six unique combinations of trajectories and speeds. Each condition was repeated four times for a total of 24 trials per participant. All participants encountered all of the trials, however, the order of the trials was randomized for each participant. In keeping with the goal of testing realistic robot motions, the robot trajectories were generated using the ROS Navigation stack [12] in conjunction with the social costmap layer [13]. The hallway was represented in the planning environment, with a 'person' object located where the participants in the experiment would be located. Although the participants in our study stood still, the 'person' object in the planning environment was assigned a velocity towards the robot in order to produce an elongated gaussian cost layer around the person. The robot was always given the same starting position, three meters ahead of the person, and the same goal position, 0.8 meters to the left hand side of the person. The default Navfn planner was used with Dijkstra's expansion. The only parameter varied to produce unique paths was the cost_scaling_factor. Setting this parameter to 0.10, 0.15, and 0.20 allowed us to generate robot paths with varied sharpness of curvature, shown in Figure 3.

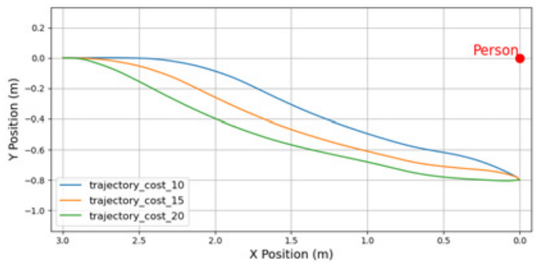

Fig. 3. ROS-generated trajectories for each of the three cost_scaling_factors

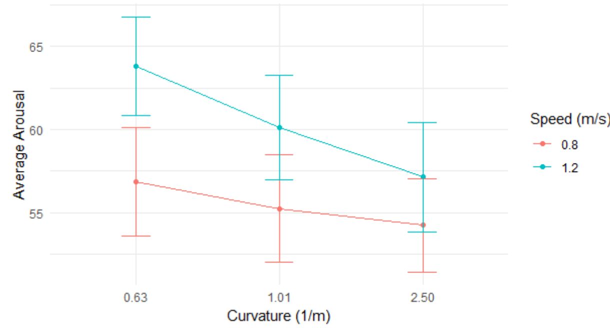

Fig. 4. Plot of participant arousal versus robot path curvature

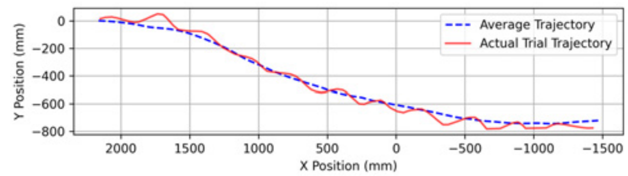

Fig. 5. Sample robot trajectory illustrating a high path variance (in this case, variance = 3363)

E. Participants

This study was conducted in accordance with Rutgers University IRB-approved protocol Pro2023002444. Our participant pool was drawn from the university population. Our test subjects included 11 participants (four females and seven males) with an average age of 19.4 years ($\sigma = 1.2$ years).

F. Procedure

When participants arrived at the testing location they were given a safety briefing and overview of the experiment which included a brief demonstration of the robot's motion and how to use the Affective Slider interface. After this, they read and signed the informed consent documentation and filled out the pre-participation questionnaire. Next, the participants were led to their mark in the lab, which they were instructed to stand on during the experiment. Their mark was located in the center of the width of the hallway at one end. The Affective Slider laptop and sensors were set up, then the participants were informed that the experiment would begin momentarily.

For each of the trials, the robot began at a position opposite the person at the other end of the hallway, four meters away. The robot then moved straight towards the person at one of the two experimental speeds for one meter, then it began one of the three passing motions once it reached a signaling distance of three meters from the participant. After the robot passed by the side of the participant, the robot followed a rectangular path back to its starting position for the next trial. Participants reported their affective state using the Affective Slider interface on the nearby laptop after each trial.

IV. RESULTS

A necessary first step in analyzing the results of this experiment is to quantify how the variation of the path planning parameters (i.e. the cost_scaling_factor) altered the trajectory of the robot. There are many ways to look at the differences between these trajectories, but since this experiment was motivated by prior work focused on the sharpness of curvature of the robot path, we will focus on this aspect.

The curvature for each of the three trajectories was defined using the mathematical definition of curvature (κ) in Equation 1.

$$\kappa = \frac{1}{R} \tag{1}$$

Where R is the radius of the smallest circle that can be inscribed within the trajectory.

We excluded from all analyses 14 trials (5.6%) in which path variance was more than three times as great as the variance in the next highest trial. We analyzed participants' arousal and pleasure levels using 2 (speed) x 3 (curvature) Bayesian ANOVAs in which participant was a random factor. For arousal, the best fitting model ($BF_{10} = 18.9$) included only speed ($BF_{incl} = 13.2$), with participants' reporting higher arousal levels when the robot moved at the higher speed (see Figure 4). For pleasure, the best fitting model was the null model, indicating that neither speed nor curvature, nor their interaction affected participants' reported pleasure level.

During the review of the robot trajectory data gathered during the experiment, we found that although the average trajectories for each condition were consistent across participants, there was substantial variance in several individual trials caused by inconsistencies in the Vicon system used for controlling the robot's position. This variance was manifested in the robot not following the trajectory in a smooth way. Instead, the robot would follow a zig-zagging path centered on the trajectory. An example of a high-variance path is shown in Figure 5.

We systematically analyzed the effect of this path variance. We truncated the trajectory data to focus on the portion during which the robot was moving to avoid the person. Both the average and trial trajectories were resampled to contain the same number of points. Path variance for each trial was then calculated as shown in Equation 2.

$$V = \frac{1}{N} \sum_{i=1}^{N} \left((x_i - \bar{x}_i)^2 + (y_i - \bar{y}_i)^2 \right) \tag{2}$$

We investigated the impact of path variance on arousal and pleasure via Bayesian multiple regression models with path variance, speed and curvature as factors. For arousal, the best fitting model ($BF_{10} = 11.4$) included path variance and speed, with participants reporting higher arousal levels for trials with greater path variance ($BF_{incl} = 6.8$) and speed ($BF_{incl} = 2.1$). For pleasure, the best fitting model ($BF_{10} = 3.8$) included only path variance, with participants reporting lower pleasure levels for trials with greater path variance ($BF_{incl} = 2.1$).

V. Discussion

Our finding that higher robot speeds lead to greater arousal in a person being passed builds on previous results that show that greater robot speeds are less comfortable for people [14]. Additionally, our finding that higher path variance results in higher arousal and lower pleasure provides empirical psychological evidence to support the goal of reducing jerk in robot motion, which supplements the typical motivation of easing the electromechanical control problem [15], [16].

While numerous aspects of this experiment differed from the VR experiment that served as inspiration for it, we find it worthwhile to discuss the curvature results in that context. Our prior work found that there is a significant effect of curvature on participant affective state, while this experiment demonstrated no such effect. To more accurately compare the experiments, we recalculate the curvature values from the prior experiment in a similar manner as we did for this experiment. Figure 6 shows the average arousal data with these recalculated curvature values from the VR experiment with the most similar signaling distance (four meters) along with the data from this experiment.

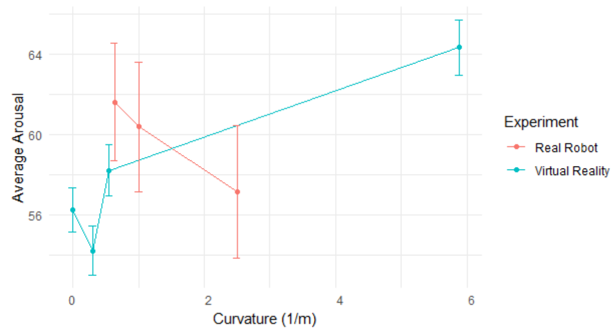

Fig. 6. Participant arousal versus curvature for the two most comparable conditions between the real robot and the VR experiments

The disparities between these results, though somewhat surprising, should be taken in the context of the significant differences between the experimental conditions. During this experiment, the robot began its avoidance motion when it was three meters away from the person, instead of four meters, as was the case in the VR data plotted. This smaller signaling distance could contribute to the higher arousal in response to the real robot at lower curvature, however it does not explain why the arousal curve for the real robot drops below the curve for the VR robot at higher curvature values. Similarly, the use of a real robot over a simulated one could have contributed to higher arousal for lower curvature conditions, however it does not explain the change in the trend of arousal as curvature is varied.

One possible cause for this is that the shape of the robot trajectory is not fully encapsulated by the curvature measure. This measure does not account for variation in apparent signaling distance. Although the robots all begin their avoidance motion at the same point in each experiment (three meters from the person with the real robot, and four meters from the person with the VR robot), the shapes of the avoidance motions vary such that it may be perceived as beginning the avoidance motion later than it actually is. In other words, when executing a lower-curvature condition, the robot may appear to be getting closer to the person before moving to avoid them.

VI. Limitations

One of the major limitations to this study is the cultural homogeneity of the population of participants. All were university students in the United States. Further studies are needed to determine how well these results translate to other age, social, and cultural contexts.

The narrow range of robot trajectories tested is another limitation. We evaluated three trajectories and two robot speeds. The role of other robot motion parameters and environmental factors need to be studied further.

VII. Conclusions and Future Work

Our statistical analysis found that robot speed and path variance had significant effects on participant arousal. Additionally, while we did not find a statistically significant effect of curvature on the affective states of participants, we observe that the trends in the data do not align with previous studies of robot path curvature. We speculate that there are several causes for this divergence, including experimental setup, overall path shape, and apparent signaling distance differences.

Future work will continue to explore the role that robot path shape has on the affective states of coexisting people. In particular, we will explore a wider range of curvatures, and investigate more complex multi-robot and multi-human scenarios. Another area of future work is to apply the findings of this study to improve robot path planners. Approaches for doing this include guiding the tuning of path planning parameters, supplementing costmap layers, and developing novel post-processors to achieve desired affective responses from people. Additionally, the trajectory and affective state data collected in these experiments can be used to train a machine learning model to achieve the same goal.

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