A kinematic model generates non-circular human proxemics zones

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***Abstract*— Hall's theory of proxemics established distinct spatial zones around humans where they experience comfort or discomfort when interacting with others. Our previous work proposed a new model of proxemics and trust and it showed how to generate proxemics zone sizes using simple equations from human kinematic behaviour. But like most work, this assumed that the zones are circular. In the present paper, we refine this model to take the initial heading of the agent into account, and find that this results in a non-circular outer boundary of the social zone. These new analytical results from a generative model form a step towards more advanced quantitative proxemics in dual agents' interaction modelling.**

***Index Terms*— proxemics zone shapes, trust, dual agents' behaviour, human-robot interaction.**

I. INTRODUCTION

The increasing prevalence of autonomous robots that operate in human environments has created new challenges in human-robot interaction (HRI). One of the key questions in HRI is how autonomous robots can share and negotiate space with humans, especially in densely populated areas. While robots are typically programmed to be safe and always yield to humans to avoid collisions, this can lead to the Freezing robot problem [13], where the robot may yield indefinitely to a stream of humans, never making progress to its destination.

This problem has motivated the development of game-theoretic models, such as the sequential chicken model [3], which allow for frequent successful interactions by planning for a small but nonzero probability of collision based on the agents' estimates of the probability and utility of a collision versus the value of time lost by yielding. Collisions are not usually actualised, but their possibility creates a 'credible threat' which affects the behavior of the agents during interactions, encouraging them to negotiate and succeed in these interactions most of the time. Deliberately engineering collision events with a small probability is clearly undesirable. But the sequential chicken model goes on to show that rare severe collisions could be replaced by more frequent but lower severity penalties, if suitable forms of penalty could be found.

Humans are known to have personal spaces [4], and to feel uncomfortable if certain of these spaces are occupied without their consent. It has been proposed in [1] that invasion of this personal space can be used as a penalty for autonomous robots in the sequential chicken model to avoid collisions. The invasion of personal space can be quantitatively modeled using proxemics, which studies the empirical results on zone sizes and utilities. By combining the chicken model and proxemics, the robot can plan its movements to avoid collisions but occasionally causing them mild discomfort by invading their space. This would enable successful interactions without the risk of physical harm.

The *Personal zone* is the region surrounding a human to a radius of 1.2m. Humans generally reserve this zone for friends and acquaintances with whom they have some degree of familiarity and trust. The *Social zone* is the region surrounding the Personal zone, extending from approximately 1.2 to 3.6m. This zone is typically used for more formal interactions, such as job interviews, and is generally considered an appropriate distance for strangers to interact. The *Public zone* is the region beyond the Social zone, extending beyond 3.6m. This zone is used for public speaking and other formal interactions.

Early proxemics studies reported empirical results on zone sizes and utilities, but to use them for active interaction control in HRI, a generative, quantitative theory is needed. In the comprehensive review of proxemics for human-robot interactions proposed by Rios-martinez et al. [12], it was suggested that "quantitative models for shape, location and dynamics of personal space are interesting opportunities for collaborative research."

A. The PTR Model

In [1], we proposed a generative, quantitative model of the Hall proxemics zones, called Physical Trust Requirement (PTR). From the perspective of some Agent_1, such as a pedestrian, vehicle or robot, states of the world including kinematics (position and velocity) of another Agent_2 can be classified as possessing PTR or not. PTR is present when Agent_1's future utility may be affected by an immediate decision to be made by Agent_2. Fig. 1 shows the direct mapping between the PTR model and Hall's proxemics zones established in [1], [2]. The set of locations of Agent_2 which give rise to PTR for some choice of other parameters including both agents' sizes and speeds – was identified with Hall's social zone. The inner boundary of the social zone is called d_{crash} as if Agent_2 is within this boundary then a collision is certain to occur and neither agent can prevent it – even if they try to decelerate there is not enough time. The outer boundary is called d_{escape} because if Agent_2 is outside it then Agent_1 can always escape from a collision without depending on Agent_2. The social zone is the most interesting because here, Agent_1 has to rely on Agent_2. Agent_1 has no power to cause or prevent collision, but Agent_2 does have

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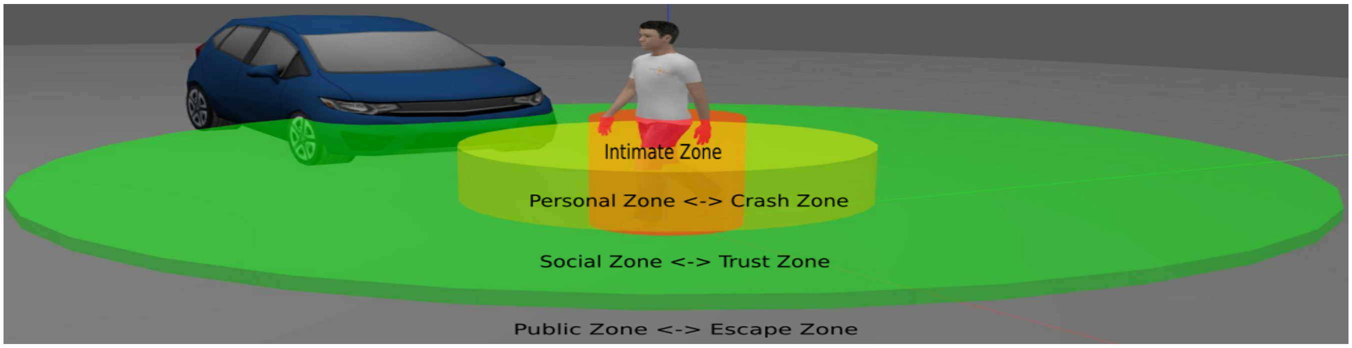
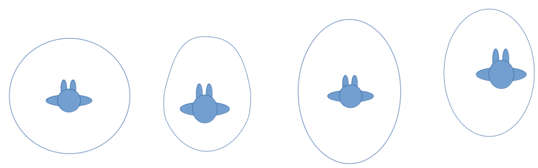


Fig. 1. Vehicle entering pedestrian's social zone, which has been identified with the trust zone generated by the PTR model [1], [2].



(a) Circular (b) Egg shape (c) Elliptical (d) Dominant side

Fig. 2. Types of proxemics zones shapes as reported by [12].

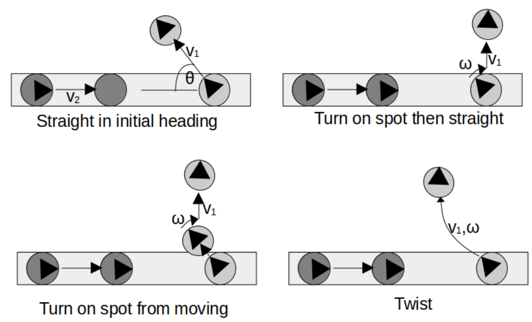


Fig. 3. Geometries of the different strategies tested. In each strategy, Agent_2 is the darker circle, moving horizontally from left to right. Agent_1 is the lighter circle.

this power over Agent_1. This is an unpleasant situation for $Agent_1$, a negative utility.

B. Contributions

To our knowledge, this is the first kind of work deriving non-circular proxemics zone shapes and sizes from human kinematics. The results imply that robots interacting with humans should use non-circular proxemics zones to plan their interactions, and precise numerical sizes can be generated for use, which may vary between interactions depending on properties of the two agents. Such systems could be applied in robots including pavement delivery vehicles, self-driving cars, and humanoid assistive robots.

II. Empirical evidence for proxemics zone shapes

This section reviews recent relevant empirical findings in the area of proxemics zones shapes. Hall's theory defined the four proxemics zones as concentric circles, and several empirical research works have used these commonly used circular proxemics zone shapes, cf. Fig. 2a.

Several recent studies have shown that proxemics zones are of non-circular shapes. For instance, Hayduk [5] investigated the 2D shape of personal space and found that egg-shaped zones describe best human proxemics zones, with a larger frontal space and smaller in the rear, and no difference found in preference in genders. Neggers et al. [10] showed that "experimental research on how robots can avoid a person in a comfortable way is largely missing ". Their empirical findings suggest that the outer proxemics zone shape is not circular and that passing at the back of a person is more uncomfortable compared to passing at the front. Their results showed an empirical 'comfort' zone, probably inverse of hall zones, which match the elliptical shapes expected.

The proxemics zone shapes shown in Fig. 2 summarize these findings which support the idea of non-circular zones to best describe human proxemics.

III. Methods

A. Assumptions

We here derive analytical equations and their visual shapes for the outer boundary of the social zone (d_{escape}) for a human Agent_1 being approached by another human or robot, Agent_2, using the PTR model [1], [2]. We assume that Agent_2 travels in a straight line towards Agent_1 and does not turn or brake to avoid collision.

Both agents are assumed to be circular with width (diameter) w. The agents could be humans, humanoid robots, or vehicles. The strategies examined are chosen to be amenable to exact or approximate analytic solutions while representing plausible though simplified kinematics of both human and wheeled agents. To simplify the equations, we approximate all models by assuming that the minimal collision occurs exactly when Agent1 has left the collision corridor. We assume the same values for the kinematic parameters across the strategies.

Unlike previous work, we will now take account of the initial heading of Agent_1 relative to the direction of approach by Agent_2, and of various possible strategies that Agent_1

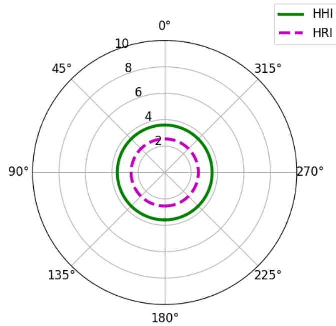


Fig. 4. Instant turn on spot

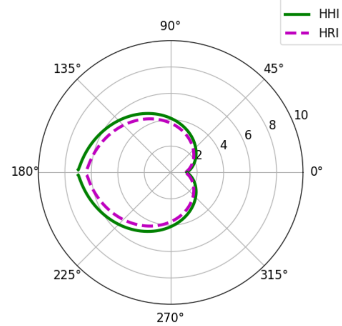


Fig. 5. Straight in initial heading

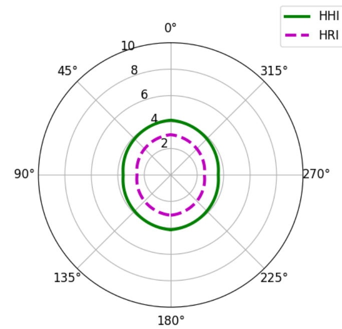


Fig. 6. Turn on the spot then straight

could use to optimise their escape distance in order to reduce the zone sizes.

As in [2], we provide numerical results for two cases: human-human interaction (HHI) and human-robot interaction (HRI) where we assume that a human walker is interacting with a humanoid robot such as PR2. These values for human pedestrians were obtained from the empirical literature and used in our previous study [2] and are: speed $v = 1.1$m/s, width $w = 1.19$m, thinking or reaction time $t = 1.1s$, turning speed $\omega = 1.0$rad/s. The values for HRI were similarly obtained from realistic robot estimates in the previous paper [2] and are: $t_1 = 1.1$s, $t_2 = 0.5$s, $v_1 = 1.1$m/s, $v_2 = 1.0$m/s, $w_1 = 1.19, w_2 = 0.4$m with index 1 for the human and 2 for the robot.

B. Strategies

The strategies are illustrated in Fig. 3. Agent_1 begins the scenario oriented at angle θ from the approach of Agent_2. Agent_1 then attempts to avoid collision by escaping from the collision corridor formed by Agent_2's path, using its maximum linear speed v_1 and maximum angular velocity ω in different ways as explained and solved in the following subsections.

1) Baseline strategy: instant turn on spot: As a baseline, the first experiment reproduces previous results of Option 1 in [2], but presenting them in a new polar form. This strategy assumes that Agent_1 may turn on the spot to any heading instantaneously, then move forwards in a straight line. Regardless of initial heading, the optimal strategy is thus always to rotate to face orthogonally to Agent_2, then walk straight forwards to escape.

The analytic solution was found in [2] to be,

$$d_{escape} = v_2 t_1 + (w_1 + w_2)\,\frac{v_2}{v_1}, \tag{1}$$

where $w_1 + w_2$ is the total distance that Agent_1 must travel in front of Agent_2 in order to avoid contact with Agent_2. The resulting zone shape is a perfect circle, as shown in Fig. 4 because the initial turn on the spot takes no time, and escapes from all initial headings then follows the same straight trajectory.

2) Strategy: Straight in initial heading: In this strategy, Agent_1 tries to escape by moving forward in a straight line in the direction of their initial heading, they do not rotate at all. The analytical solution [2], was previously found to be,

$$d_{escape} = v_2 t_1 + (w_1 + w_2)\frac{v_2}{v_1|\sin(\theta)|}. \tag{2}$$

It was plotted there as a U-shaped Cartesian graph. To enable comparison with the other new strategies, it is now plotted in polar coordinates because this shows the actual physical shape of the zones. The resulting zone is shown in Fig. 5.

3) Strategy: Turn on spot then straight: This strategy was previously suggested as future work in [2] and is tested here for the first time analytically. In this option, Agent_1 begins standing stationary at angle θ to Agent_2's heading. Agent_1 first turns on the spot at angular velocity ω, until they are orthogonal to the other's approach, and then moves forward at speed v_1. The rotation direction is chosen to be the shortest to reach the orthogonal direction, so that,

$$d_{escape} = v_2 t_1 + (w_1 + w_2)\,\frac{v_2}{v_1} + v_2(|\pi/2 - |\theta||)/\omega. \tag{3}$$

Here we are assuming that it is always best to take time to rotate to 90 degrees first. This seems sensible for normal humans. but we could imagine mathematical cases where the rotate speed is very slow relative to forward speed, where it might be more optimal to rotate to some smaller angle. We

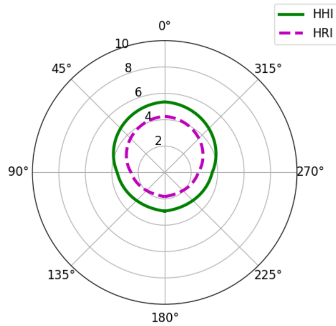


Fig. 7. Turn on the spot from moving

are assuming that turning on the spot is 'fast' compared to walking forwards. The analytical solution is shown in Fig. 6.

4) Strategy: Turn on spot from moving: This strategy was also suggested as future work [2] and is tested for the first time here. In this model, Agent_1 begins moving in their heading direction, and continues to do so during their thinking time, as in Straight In Initial Heading. Then Agent_1 stops instantly, and behaves as in Turn on the Spot then Straight.

During their thinking time, Agent_1 travels $v_1 t_1 \sin(\theta)$ vertically and $d_1 = v_1 t_1 \cos(\theta)$ horizontally (which may be positive or negative). This vertical distance traveled reduces the remaining vertical distance needed to escape the collision corridor to $w_1/2 + w_2 - v_1 t_1 \sin(\theta)$. The turning time is the same as in the turn then straight strategy, $(|\pi/2 - |\theta||)/\omega$.

The total escape time is thus,

$$\tau = t_1 + (|\pi/2 - |\theta||)/\omega + (w_1/2 + w_2/2 - v_1 t_1 \sin(\theta).)/v_1 \tag{4}$$

Agent_2 will travel at v_2 during this time, giving escape distance,

$$d_{escape} = v_2(t_1 + (|\pi/2 - |\theta||)/\omega + (w_1/2 + w_2/2 - v_1 t_1 \sin(\theta))/v_1). \tag{5}$$

The resulting zone boundary is shown in Fig. 7.

IV. Discussion

The results show that the human proxemics zones generated by kinematics under the PTR model become non-circular due to changes in the time required for the human to escape from impending collisions. The outer boundary of the social zone retains its usual assumed value of 3.6m when two human agents begin at right angles, but becomes larger towards the front of the person and smaller behind them. The precise shape depends on details of what strategy model is assumed for the pedestrian kinematics.

This is the first time that non-circular proxemics has been generatively and quantitatively modelled from human kinematic behaviour in order to explain the deformation of Hall's zones as a function of rotation and motion of the agents. Non-circular zones have previously been observed empirically, as shown in Fig. 2 but not explained. For example, Kirby's model [6] and some others assumed quantitative non-circular zones to fit these empirical results, but did not derive them from generative kinematics. The HRI zone boundaries are generally smaller than the HHI ones, this is consistent with previous empirical studies. This is because the robot is smaller and slower than a human, so poses less of a threat to the human whom it is approaching. The human is therefore willing for it to come closer than another human.

Future work should also extend the model to derive the inner boundary of the social zone, formed when Agent_2 acts to try to prevent the collision by braking. There have been recent empirical observations [9], [11], which suggest that zone boundaries stretch as functions of both agents initial speeds, including to long (tens of meters) ranges when dealing with high-speed vehicles – which may be related to the stopping distances taught to and used by human drivers. The current model could be used to explore these effects to see if they match with these stopping distances. The resulting zone shapes could be compared with and calibrated to a more detailed review of known empirical zones in different settings.

The model proposed in this work is based only on kinematics so is not able to explain the adaptive proxemics zones shapes of [7], [8] reviewed above. These changes are hypothesized to be caused by additional social factors such as attention and perceived control. Our current model assumes that the agents have perfect information and computation resources. Real humans are constrained by noisy, uncertain information and, restricted computation, and various utilities and biases which might be added to the model in the future to capture these social effects.

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