

A Hybrid Control Framework for Navigating Pedestrian Interaction at Mid-Block Intersections

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Abstract—As autonomous vehicles (AVs) inch closer to reality, a central requirement for acceptance will be earning the trust of humans in everyday driving situations. In particular, the interaction between AVs and pedestrians is of high importance, as every human is a pedestrian at some point of the day. This paper considers the interaction of a pedestrian and an autonomous vehicle at a mid-block, unsignalized intersection where there is ambiguity over when the pedestrian should cross and when and how the vehicle should yield. By modeling pedestrian behavior through the concept of gap acceptance, the authors show that a hybrid controller with just four states allows an autonomous vehicle to successfully interact with a pedestrian across a continuous spectrum of possible crosswalk-entry behaviors. The controller is validated in simulation through comparison with a previously published control policy obtained through solution of a POMDP, and experimental results are provided on a Hyundai Genesis vehicle for a virtual pedestrian.

I. INTRODUCTION

A. Motivation

While autonomous vehicles have the potential to save thousands of lives every year and create tremendous societal benefits [1], widespread adoption is unlikely until AVs gain the broad trust of society. Given that every human is a pedestrian at some point during the day, one of the central ways that autonomous vehicles will be evaluated is through their interactions with pedestrians. In fact, recent events with industry leader Waymo highlight that AV-pedestrian interaction has still not been perfected[2]. In general, interactions with pedestrians are complex, even for experienced human drivers. Issues such as lack of visibility, improper communication, poorly marked roads, and distraction on both the driver or pedestrian side can lead to accidents and fatalities. From 2015-2016, pedestrian fatalities increased by 9% to 5987, representing the highest number since 1990, and also representing 16% of all automotive fatalities [3]. As autonomous vehicles inch closer to widespread adoption, they must have a clear control strategy for pedestrian interaction that can handle a wide variety of pedestrian behaviors while maintaining a reasonable flow of traffic.

B. Prior Art

The need to further understand pedestrian behavior for autonomous driving has created growing body of interdisciplinary research. One branch of research has focused around modeling pedestrian behavior given various sensor inputs.

Keller et al [4] presented a study on pedestrian path prediction and action classification (e.g. crossing vs. waiting) using Gaussian process dynamical models and trajectory matching from optical data. Several other techniques for pedestrian trajectory prediction have been proposed, including LQR [5], set-based reachability analysis [6], and Markov processes [7]

Another branch of literature is focused on developing binary predictive models for pedestrian crossing. While typically studied for purposes of road design, this body of literature holds promising insights for AV designers. For example, Schroeder and Roupail [8] explored factors associated with driver yielding behavior at unsignalized pedestrian crossings. Using logistic regression, the authors found that drivers are more likely to yield to assertive pedestrians who walk briskly in their approach to a crosswalk. Kadali and Perumal [9] studied the “gap acceptance” behavior of pedestrians at mid-block crosswalks through a video graphic survey, and found that the gap accepted for crossing was explained by factors such as crossing direction, vehicle speed, and pedestrian age. Yannis et al. [10] and [11] also found that gap acceptance was influenced by the size of the oncoming vehicle and the presence of other pedestrians. Lee and Aty [12] studied interactions in the form of crashes, and found crashes were linked with higher daily traffic.

Finally, a small but rapidly growing body of literature specifically studies the interaction between pedestrians and autonomous vehicles at crosswalks. An excellent review of these studies was conducted by [13]. As an example, Rothenbuecher et al. [14] studied the interaction between pedestrians and driverless vehicles by constructing a car seat costume to disguise a driver. The authors noted that pedestrians overall managed interactions at crosswalks effectively, but later mentioned increased uncertainty about the autonomous vehicles behavior. To improve the issue of trust, several researchers have developed external interfaces to more clearly broadcast the intent of the autonomous vehicle [15], [16].

Several real-world studies of AV-pedestrian interaction note that once a local population learned a vehicle was programmed to be perfectly safe, pedestrians would regularly take advantage of the AV and walk in front of it. [?]. This illustrates an issue with automated driving in that an overly conservative crossing algorithm will often be taken advantage of or cause confusion among pedestrians. Camara et al [17] attempted to model the natural negotiation for priority between a pedestrian and an AV at an intersection using the framework of “sequential chicken” adopted from game theory. Chen et al. [18] notes the need for a tradeoff between passive and aggressive driving behavior, and devel-

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oped a stochastic model of pedestrian behavior to evaluate proposed AV control policies. Control policies for pedestrian interaction are also developed by [19], who proposes a Mixed-observable Markov Decision Process (MOMDP) to incorporate the intention uncertainty of a pedestrian. A POMDP formulation is also proposed by Thornton [20], who proposes navigation of the pedestrian uncertainty through value-sensitive design.

C. Statement of Contributions

While there exists a wide body of research on the distinct subjects of pedestrian modeling and AV control, there is a lack of research that combines the two. In other words, significant research has been conducted to understand the likelihood of pedestrian crossing given certain traffic conditions and pedestrian demographics [8]–[12], and a small but growing body of literature develops control strategies for pedestrian avoidance [19]–[20]. However, what is missing is a contribution that explicitly considers tests whether a proposed control strategy is robust to the variety of pedestrian behaviors that have been observed from experimental studies on real roads. What is also missing is analysis of how this controller should behave across multiple traffic scenarios – for example, the navigation problem is different for the pedestrian crossing on the opposing side of traffic, and also depends on which particular lane the vehicle is in.

This paper aims to address this gap by developing a state-machine based control architecture that accounts for several distinct pedestrian modes of behavior at an unsignalized crosswalk. An unsignalized crosswalk is chosen as it is the trickiest crosswalk for a pedestrian and vehicle to navigate, as there is no explicit declaration of whose turn it is cross. Simulations show that the state machine controller is able to handle a continuous spectrum of pedestrian *gap acceptance* behavior, tolerating a range of highly conservative to highly aggressive pedestrians. Moreover, this is possible with just four distinct states. Simulations are also used to compare the closed-loop controller with the controller developed by [20]. Finally, experimental results are shown on a real vehicle to demonstrate the feasibility of the proposed state machine controller.

II. PROBLEM DESCRIPTION AND SYSTEM REQUIREMENTS

A. Unsignalized Intersections

In general, pedestrian crosswalks may be controlled or uncontrolled. In the case of the former, control devices such as stop signs or walk signals guide the interaction of vehicles and pedestrians explicitly. Fig. 1 shows the latter example, in which a pedestrian must select a gap in traffic flow and cross.

In general, right-of-way for uncontrolled intersections is complex. For example, nine states and the District of Columbia require motorists to stop when approaching a pedestrian in an uncontrolled crosswalk. Six states require a motorist to stop when a pedestrian is upon the same half of the roadway or within one lane of the lane that the

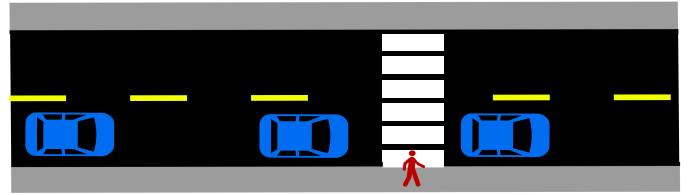


Fig. 1. Schematic of pedestrian approaching a stream of traffic at a mid-block intersection.

motorist is traveling upon. Another nineteen states require a motorist to yield when a pedestrian is upon any portion of the roadway, and another 20 states mandate that motorists yield when a pedestrian is upon the same half of the roadway or approaching closely from the opposite side of the roadway [?].

B. Pedestrian Gap Acceptance

One of the major factors that determines pedestrian crossing behavior is *gap acceptance*, defined in this paper as:

$$\text{gap} = \text{vehicle speed} \times \frac{\text{distance to crosswalk}}{\text{distance to crosswalk}}$$

III. PROPOSED CONTROL ARCHITECTURE

IV. EVALUATION METHODOLOGY AND SIMULATION RESULTS

V. EXPERIMENTAL RESULTS

VI. CONCLUSIONS

APPENDIX

Appendixes should appear before the acknowledgment.

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