INTENT COMMUNICATION BETWEEN AUTONOMOUS VEHICLES AND HUMANS

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INTENT COMMUNICATION BETWEEN AUTONOMOUS VEHICLES AND HUMANS

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Abstract: When pedestrians encounter vehicles, they typically stop and wait for a signal from the driver to either cross or wait. What happens when the car is autonomous and there isn't a human driver to signal them? This paper seeks to address this issue with an intent communication system (ICS) that acts in place of a human driver. This intent system has been developed to take into account the psychology behind what pedestrians are familiar with and expect from machines and integrate those expectations into the design. The goal of the system is to ensure that communication is simple, yet effective without leaving pedestrians with a sense of distrust in autonomous vehicles. To validate the ICS, two types of experiments have been run: simulations to account for multiple behaviors and field tests to determine how humans actually interact with the ICS. The results from both experiments show that humans react positively and more predictably when the intent of the vehicle is communicated compared to when the intent of the vehicle is unknown.

Contents

Chapter Page

1 Introduction **1**

1.1 Introduction 1

2 Related Works **4**

2.1 Related Work 4

3 Preliminaries **7**

3.1 Preliminaries 7

3.1.1 Initial Problem Formulation 7

3.1.1.1 Belief-State Markov Decision Process 7

3.1.1.2 Partially Observable Markov Decision Process 9

3.1.2 Initial Methodology 9

3.1.3 Initial Results 10

3.1.3.1 Description of the Experiment 10

3.1.4 Initial Conclusions 11

4 Problem Definition **15**

4.1 Problem Formulation 15

4.1.1 Pedestrian Surveys 15

4.1.2 Dec-MDP Definition 16

4.1.3 Intent Communication Psychology 23

5 Solution Methods **24**

5.1 Methodology 24

5.1.1 Intent Communication System Description 24

5.1.2 Real World Experiments 29

5.1.3 Simulation Setup 30

6 Results **32**

6.1 Results . . . 32

6.1.1 Real World Results . . . 32

6.1.1.1 Group 1: With ICS and Prior Knowledge of Golf Car . . . 32

6.1.1.2 Group 2: With ICS and no Prior Knowledge of Golf Car . . . 33

6.1.1.3 Group 3: Without ICS and Prior Knowledge of Golf Car . . . 33

6.1.1.4 Group 4: Without ICS and no Prior Knowledge of Golf Car . . . 33

6.1.2 Simulation Results . . . 35

6.1.2.1 With ICS and Prior Knowledge . . . 36

6.1.2.2 With ICS and No Prior Knowledge . . . 36

6.1.2.3 Without ICS and Prior Knowledge . . . 36

6.1.2.4 Without ICS and No Prior Knowledge . . . 36

7 Conclusions and Future Work **41**

7.1 Conclusion . . . 41

7.1.1 Future Work . . . 42

Bibliography **44**

A Acronyms **49**

A.1 Pedestrian Surveys . . . 50

A.2 Passenger Surveys . . . 77

List of Tables

Table Page

6.1 Pedestrian Trust Results 34
6.2 Passenger Trust Results 35

List of Figures

Figure Page

1.1 Example of how pedestrians interact with cars 2

3.1 Navigation with Intent Communication Diagram. The intent is shown to be communicated when the golf cart anticipates a pedestrian action and displays a message accordingly. 12

3.2 Navigation with Intent Communication Results. Shows how intent communication causes the POMDP to converge to a reward value based on the given inputs. 12

3.3 Navigation without Intent Communication Diagram. When intent commuication isn't taken into consideration, the golf cart can identify the pedestrian, but it shows no interest in changing its path with respect to what the pedestrian could do. 12

3.4 Navigation without Intent Communication Results. Shows how the POMDP responds when intent communication is removed. The reward value is lower and it has yet to converge. 13

3.5 Picture of experimental setup. 13

4.1 Visualization of how the Dec-MDP model works within the simulation 17

5.1 Intent Communication System Block Diagram 24

5.2 Intent Communication System on Autonomous Golf Car 25

5.3 Example of passenger HUD 26

5.4 Passenger ICS Testing 27

5.5 Example Visual message displayed by the Intent Communication System 27

5.6 Example of golf car in testing environment 28

6.1 Group 1: With intent communication system and prior knowledge of golf car, Group 2: With intent communication system and no prior knowledge of golf car, Group 3: Without intent communication system and prior knowledge of golf car, Group 4: Without intent communication system and no prior knowledge of golf car 34

6.2 The results from the passenger surveys are based on the maximum number of trust points which is 75. Each question has a trust value assigned to it based on the survey responses. 35
6.3 Trust quantification plot comparing all four scenarios discussed above 37
6.4 20 Percent Confidence Level 38
6.5 40 Percent Confidence Level 38
6.6 60 Percent Confidence Level 39
6.7 80 Percent Confidence Level 39
6.8 99 Percent Confidence Level 40

Chapter 1

Introduction

1.1 Introduction

Autonomous vehicles need to interact with pedestrians whenever they encounter them at crosswalks, intersections, or anytime they wander into the vehicle's path. When a human driver has this type of encounter with pedestrians, they usually provide some kind of signal, such as waving their hand, looking in to the pedestrian's eyes, or simply a smile, to let the pedestrian know they have been acknowledged. This bi-modal communication is a critical component that autonomous vehicles lack. How do they get the same point across to pedestrians without getting into a deadlock situation where neither the pedestrian nor the vehicle moves?

Another human-vehicle interaction is how the vehicle interfaces with the passenger. It is essential to ensure that the person inside feels comfortable with the vehicle's decision making. Usually, a person has complete control over the car so they have little doubt about any errors that could be made without them giving some for of agreement. This control is completely taken away from a driver when the car is autonomous. How do we ensure that the passengers don't have a high level of fear or mistrust in the autonomous vehicle?

Figure 1.1: Example of how pedestrians interact with cars

There are many researchers currently working on autonomous vehicles, along with major robotics companies, such as Google, Tesla, and other auto manufacturers. Yet, vehicle to pedestrian communication is still an area that is being developed; some examples of ongoing research will be discussed in the next section. The authors are not aware of any quantitative experiments that analyze the utility of an intent communication system (ICS) with real vehicle-human interactions. This research seeks to address this gap in the literature. One of the biggest questions within the vehicle-pedestrian interaction problem is how to successfully communicate the intent of the vehicle with the surrounding pedestrians in a way that is efficient, comfortable, and easy to understand. In this case, the ability to communicate intent means that the vehicle is able to make a decision about what the pedestrian will do and then send a message to the pedestrian to try and guide their behavior as to avoid a deadlock situation. A deadlock situation is where neither the pedestrian nor the vehicle will move due to uncertainty in the others' next action. The research also addresses the interior communication problem with the passengers in a similar manner as the pedestrians.

This research seeks to address the vehicle-human intent communication issue by examining psychological aspects of this type of communication and designing a physical and mathematical system around them. As such, our main contribution is in the design of software and hardware for an ICS and its evaluation in realistic vehicle-human encounters. The developed systems are assessed through two types of experiments: real world testing and simulations. To conduct the real world experiments, a golf car has been outfitted with sensors that give it autonomous capabilities as well as the ability to communicate with pedestrians and passengers through an ICS to help form trust between the vehicle and the humans that have to interact with it. The development of this system took careful design consideration based on user-interaction surveys to take into consideration the environment it would operate in. It had to be simple and yet effective, reliable in dusty, water, and debris prone road situations, and not overly costly. The development of the system will be discussed further in Section 3. The simulations are an extension to the real world testing in that they allow for more scenarios to be performed that would be potentially unsafe for our participants. The simulation development will be discussed in detail in the latter Section 4.

Along with testing the ICS for communication efficiency, the research also explores some of the psychology that is behind the perception of autonomous vehicles, what people's expectations are, and how they believe that autonomy is being integrated into society. The psychological underlyings are just as important as the physical and mathematical systems because understanding people's preferences and aversions can guide the development of more dependable and socially acceptable autonomous vehicles, and in general other robots that work with humans.

Summarizing, the key contributions of this research are: a robotic Intent Communication System to diffuse a deadlock situation between an autonomous vehicle and pedestrian, which could prevent the pedestrian and vehicle from getting to their desired locations, develop a mathematical model that shows how trust can be quantitatively defined in context of the ICS, and report detailed evaluation through experiments.

The remainder of the thesis will be laid out as follows: Section 2 will discuss the related works in the state of the art on autonomous vehicles, human-machine interaction, and simulated systems. Section 3 will outline the preliminary research that went into the current development. Section 4 will discuss the problem formulation for both the real world experiments and the simulations. Section 5 provide a more in depth look at how the ICS was developed and how the simulation parameters were chosen. Section 6 will address the results that were gathered from both the real world and simulation experiments. Section 7 will discuss the conclusions and future work of the paper.

Chapter 2

Related Works

2.1 Related Work

The intent communication problem has been gaining more attention in the past year with Google, Tesla, and other automotive manufactures dedicating more resources to their autonomous vehicle development. Last year, we began development of our ICS [35] months before Google made public a patent for their ICS [49]. Google's interest in this patent shows that the pedestrian intent communication problem is one that will need to be further researched and addressed to be able to handle the changing expectations people have of how interactions with autonomous vehicles should be. Yet, technology and fancy computer displays are not the bane of this problem, it is the careful evaluation using human feedback that is most important in designing usable ICS. As more effort is focused on this area, more of the psychological aspects of pedestrians will have to be taken into account such as, how people feel about autonomous vehicles in general, how open people are to listen to these vehicles, and what can be done to ensure that a relationship of trust and safety can be built between humans and autonomous vehicles. Some of the issues with Google's idea is that they haven't revealed if they've done testing to determine the best way to communicate with people, how robust their system is, or how cost effective their solution is.

There are numerous researchers who are currently learning more about the psychology behind human-machine interactions (HMI). Such as in [45], [19], [17], [21], [48], [46], [12], [40], [44], [32] which addresses the issues of how humans and machines interact with each other when compared to how humans interact with other humans. By building off of human-human interactions, autonomous systems in industrial areas like manufacturing plants or space applications are evolving to the point where they can be relied on as teammates instead of replacements. With this approach to integrating autonomy, humans have been shown to be more receptive to robotic instructions when their is some dialogue taking place between human and machine [4], [20], [5]. The ICS in this paper is expanding this idea to include a mathematical way of quantitatively measuring how much of a difference is seen when dialogue is present compared to when it isn't. Another factor that the previous papers haven't focused on as heavily is how well these systems are at creating trust between humans and machines. In our real world testing, we get a measurement of how trust is built between pedestrians and autonomous vehicles by conducting a post-survey that specifically asks for feedback on how trust was perceived to be affected.

Most of the research that has been conducted on quantifying trust are in the e-commerce field [33], [13], [27]. These papers provide a foundation on how to develop a model for trust when people aren't sure if they are working with a human or a machine. Some other work that has been done on modeling trust as variations of Markov Decision Processes (MDPs) [18], [37], [7], [14], [15]. These papers look into how variations of MDPs such as partially observable Markov Decision Processes (POMDPs), decentralized POMDPs (Dec-POMDPs), multi-agent MDPs (MMDPs), and decentralized MDPs (Dec-MDPs) can be used to quantify trust in a way that accounts for the stochasticity of a human's potential actions [2], [39], [3], [22], [24]. This paper's work focuses on the use of the Dec-MDP framework for the simulations and will be discussed in Section 4. By having a framework to quantify trust, the development of the physical system can be driven by the findings from the simulation results to improve upon the state of the art in this research area of trust.

There is also a psychological aspect that happens when a human encounters an autonomous machine. The work in this area was used as a way to understand what to look for in the pedestrian encounters with the autonomous car. In [28], [25], [31], [29], [6], [42], [16], [38], [9] the problems of human emotion factoring into decision making, shared intention, and individual differences are addressed. This work provides insight into how people's internal states affect their external reactions.

Various approaches have been studied to find the most reliable and natural way to communicate from machine to human; they include: gesture identification, audio feedback, haptic feedback, which is not applicable here, and other types of human-machine interfaces. Some of the most prominent work relies on gesture identification [30], [10], [50]. The problem with gesture identification in the context of autonomous vehicles is that human gestures are not easily understood by machines and gestures require a large library to have an accuracy that makes them meaningful. There have also been other approaches to the communication problem as seen in [41], [26], [51], [47]. With audio feedback, [23], [8] accounts for the way that people perceive sounds coming from a machine, but a problem with this is that the sounds have to be taken in a specific context. The difficulty that these methods have shown include the need for the human to have previous knowledge of the machine or training with the machine, the option of explicit or implicit communication, and the notion of trust. The current paper has found a method that is able to intertwine the notion of trust with both implicit and explicit communication in a way that people with no previous interactions with the machine will understand.

Chapter 3

Preliminaries

3.1 Preliminaries

3.1.1 Initial Problem Formulation

The goal of this research is to accurately predict the intent of pedestrians as the golf cart approaches them and have the golf cart adjust its speed and direction accordingly. The golf cart will relay information about its intent via an LED word display and LED light strips to indicate the desired pedestrian action. There will also be a heads-up display (HUD) system inside of the golf cart to show passengers that the cart is aware of the obstacles around it and that it knows how to avoid them. The hypothesis is that since people associate certain colors to certain feelings, they will be able to better understand the golf cart's intent. The lights are also used to catch people's attention to make sure they see the cart approaching them. The LED word display will be able to explicitly communication the golf cart's intent using pictures, words, or a combination of the two. To accomplish this, an algorithm will be created that models the intent of both the pedestrian and the golf cart.

3.1.1.1 Belief-State Markov Decision Process

The intent of pedestrians has uncertainty associated with it due to the unpredictability of humans. Due to this uncertainty, a POMDP-based model would be appropriate. Because of the time constraint imposed by real-time calculations of POMDPs, this model, like others, will be based on a belief-state MDP. This simplification can be done because of the fact that there are a limited number of actions the golf cart can take and there are also a limited number of actions pedestrians will take.

The model of the intent communication between the golf cart and pedestrians will be based on the following belief-state MDP tuple:

$$\langle B, A, \tau, r, \gamma \rangle \tag{3.1}$$

where:

- B: the set of belief states over the POMDP states
- A: the same finite set of actions as the POMDP
- τ: the belief state transition function
- r $\in$ BxA $\Rightarrow$ R: the reward function on belief states
- $\gamma \in$ [0,1] : the discount factor
- τ (b,a,b') = $\sum$Pr (b'| b,a,o) $\cdot$ Pr (o| a,b) where:

$$Pr\,(o \mid a, b) \tag{3.2}$$

is provided from the POMDP:

$$\sum \text{Pr}(b' \,|\text{b,a,o}= \begin{cases} 1 & b' \\ 0 & otherwise \end{cases} \quad (3.3)$$

To construct a realistic belief-state to be used, a survey was conducted to determine the potential actions pedestrians might take during an encounter with an autonomous golf cart and the probabilities of those actions. Based on the survey of 50 people with no affiliation to the research, potential pedestrian actions were gathered and their probabilities were calculated. The goal of the survey was to narrow down the number of actions pedestrians might take when they encounter a golf cart that may or may not have a person operating it and to use their responses to determine what kind of communication system would perform the task well and help people to feel more receptive of autonomous vehicles so that they will be more likely to perform what the vehicle asks of them. Some of the questions asked include:

- What would you do if you saw a car approaching you without a driver?
- How would this make you feel?
- What would make you feel more comfortable around this type of vehicle?

The demographic of the survey included students on campus between the ages of 18-22, faculty on the Oklahoma State University campus between the ages of 30-70, and people with no affiliation to the university between the ages of 14-65. There were five pedestrian actions identified: stop, wait, cross, get in the car, and don't notice the car. With this information, the belief-state of the MDP, **B**, was composed. Based on the typical operations of a golf cart, the action space, **A**, has also been determined. The transition function, τ, will be calculated based on the reward function, **r**, to determine the appropriate action for the golf cart to take.

3.1.1.2 Partially Observable Markov Decision Process

Due to time limitations, the belief-state MDP was not used for this portion of the research. It was going to be utilized in the future work of the project, but a better model was found that will be discussed in the Methodology section. To begin the preliminary simulation experiment, a POMDP model was be used. The SARSOP algorithm created in [24] was used to execute the modeled POMDP. In this portion of the research, the POMDP model is completely define by the following tuple:

$$\langle S, A, O, T, Z, R, \gamma \rangle \tag{3.4}$$

which includes the possible states, actions, and observations defined based on the world that the golf cart will be tested in. The POMDP will be used to show the difference in pedestrian trust based on the condition of if the ICS is enabled or if the ICS is disabled. These results will be contrasted directly with each other to show any improvements in trust between the two situations.

3.1.2 Initial Methodology

Before the intent communication algorithm was implemented on the real golf cart, it was first tested in a gridworld simulation. The simulation was based on the data collected from the survey and knowledge about the operational environment. While the simulations are being conducted, psychologists were consulted to determine the best colors to use in the LED light strip to convey the intent of the golf cart as well as what words, phrases, or pictures should be streamed across the LED word display. The color red was chosen for the word display and alternating colors were chosen for the light strip. At the time, the word display showed the simple messages of either STOP or PLEASE CROSS. The HUD system was also tested to see how accurately it could highlight pedestrians and show the cart's intended action to the passenger.

The SARSOP program required all of the transition probabilities, observation probabilities, and rewards for each agent (both car and pedestrian) to be manually entered into a file that would be used to solve the POMDP. The transition probabilities were calculated based on the surveys by dividing the number of responses for a single action by the total number of participants. The observation probabilities were calculated based on the proximity of the car to the pedestrian.

After the simulations were completed using SARSOP, the algorithm was optimized based on the results. The simulations were based on the vehicle determining the intent of the human based on a probabilistic model created from the survey discussed earlier. Once the simulations and optimizations were completed, the algorithm was implemented on-board the golf cart and the LED light strip, word display, and HUD system was interfaced with the correct computer. The algorithm was then be tested in a more structured environment to see how accurately it will be able to predict the intent of pedestrians and how well it will be able to relay its intent. The main focus of this updated algorithm was in its ability to be able to quantify how the pedestrian's trust level fluctuated over the duration of an autonomous vehicle encounter. After several trials were conducted, the algorithm was further optimized. Once the final optimization was completed, the golf cart will be used in a real world environment.

3.1.3 Initial Results

3.1.3.1 Description of the Experiment

The algorithm for intent communication was been designed based on a POMDP given the reward and transitions models:

$$R\left(a,b\right)=\sum_{s\in S}r\left(a,s\right)\cdot b\left(s\right) \tag{3.5}$$

$$p\left(s'\mid a,b\right)=\sum_{s\in S}p\left(s'\mid a,s\right)\cdot b\left(s\right) \tag{3.6}$$

$$b\left(s\right)=p\left(s\right) \tag{3.7}$$

In these equations, R(a,b) represents the reward given an action, a, in the belief-state, b, r(a,s) is the reward associated with the action in the current state, s, p(s' |a,b) defines the probability that we will transition to the next state, s', given the action and the belief-state, p(s'| a, s) defines the probability we will transition to the next state given the action and current state, and b(s) represents the probability distribution over the world states. For this algorithm, the belief-state was constrained based on the responses from the survey and knowledge about the environment the golf cart will be operating in.

In addition, based on the probabilities of potential actions a pedestrian might take, one obstacle was added that can move like a pedestrian. For example, in the gridworld, it would be the equivalent of a block possibly moving in front of our car or deciding to remain in its current position. This obstacle will move different ways each time the simulation is run. To determine how well the algorithm is able to detect and successfully react to a pedestrian, the simulation will perform 2000 Monte Carlo runs. Each time the golf cart moves through the gridworld, it has a reward of -5 if it gets within one grid-space of a pedestrian and a reward of 1 for each transition it doesn't hit a pedestrian. The SARSOP algorithm used in the Approximate POMDP Planning Toolkit (APPL) [24] was the testing ground for this simulation. The algorithm was run to test how well it would perform with and without the intent communication between the golf cart and pedestrian and with the pedestrian moving according to the given probabilities. There was one obstacle placed in the simulation. The obstacle had a probability of either moving in front of the car, moving into the same grid-space as the car, or not moving at all. The following plots show how well the golf cart was able to relay its intent to the pedestrian.

In the simulations, the intent of the golf cart was provided to the pedestrian based on the observation of the pedestrian's motion. With intent communication, the pedestrian reacted to the golf cart's intent, i.e. either stopped or crossed. Without intent communication, the pedestrian continued on the path they were taking without accounting for the golf cart's approach. The plots show that with or without the intent communication, convergence takes about the same number of iterations or approximately 100 seconds. The pedestrian movement probabilities remained the same throughout both simulations.

When intent communication was included, the reward converged to a higher value than when intent wasn't included. When the intent wasn't communicated between the golf cart and the pedestrian, the reward was noticeably lower and it didn't appear to reach a convergence point. The reason the simulations stop at 2000 iterations is in part due to the intractability of a POMDP and due to the computational speed of the computer. When the simulations were allowed to run over 2000 iterations, the program crashed the computer and all work was lost. The results were also deterministic as the probability distributions remained unchanged. The problem with the slower convergence speed without the ICS is that the golf cart may not have an adequate amount of time to react to pedestrians or it might not react appropriately to pedestrians. It is possible that the navigation without intent communication could converge to a potentially higher value, but given the time constraint in a real world environment, navigation with intent communication has an advantage.

3.1.4 Initial Conclusions

The key findings from these preliminary results include: the development and implementation of the ICS, the algorithm used to simulate car-pedestrian interactions in a trust quantification aspect,

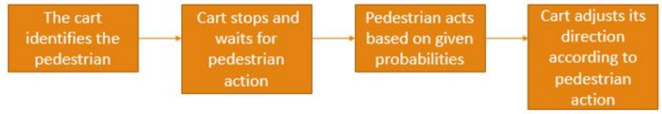

Figure 3.1: Navigation with Intent Communication Diagram. The intent is shown to be communicated when the golf cart anticipates a pedestrian action and displays a message accordingly.

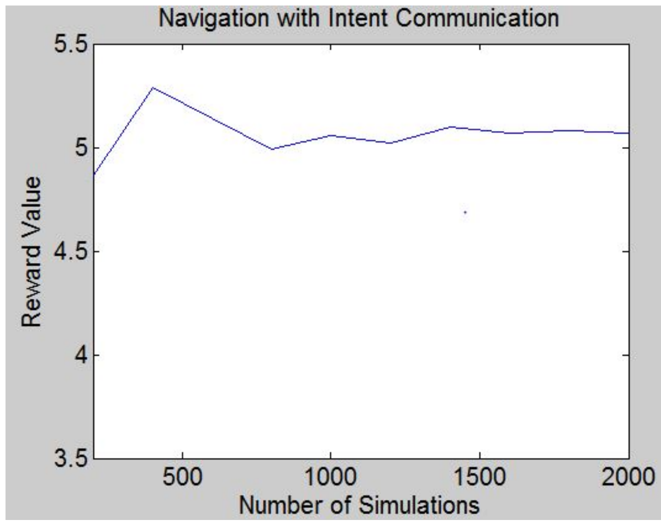

Figure 3.2: Navigation with Intent Communication Results. Shows how intent communication causes the POMDP to converge to a reward value based on the given inputs.

Figure 3.3: Navigation without Intent Communication Diagram. When intent commuication isn't taken into consideration, the golf cart can identify the pedestrian, but it shows no interest in changing its path with respect to what the pedestrian could do.

and a guide on how to proceed to the next phase.

Based on the literature this is the first attempt at solving this problem in this manner. In previous works, there haven't been many clear attempts at creating a feedback loop between autonomous vehicle and pedestrian. They have mostly been based on experiments with the humans and machines interacting directly. The papers that had more of a mathematical foundation were limited in the number of actions a person could take [18], [19] or the MDP was idealistic and had no POMDP backing [16]. The benefit of the proposed algorithm is that it will take into account a given belief-state drawn from the original POMDP instead of directly solving a POMDP or creating too idealistic of a model based on an MDP. The simulation run allowed for 9 states to be recorded with the potential for more. The approach seen in [25] and [26] has similar elements, but is currently missing the ability for the vehicle to communicate with pedestrians in an easy to understand manner.

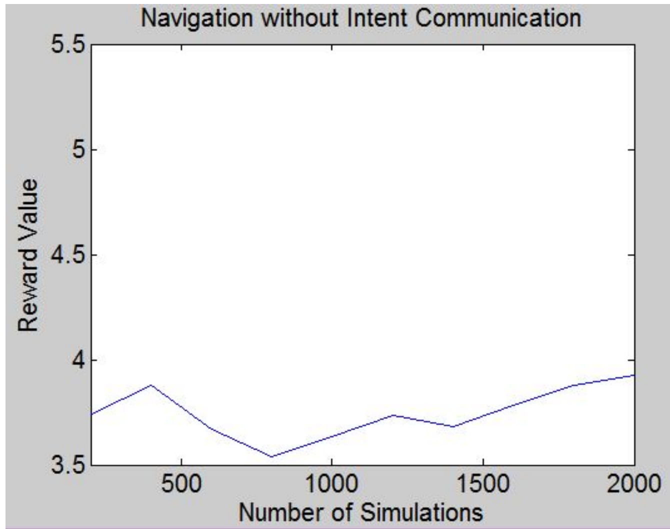

Figure 3.4: Navigation without Intent Communication Results. Shows how the POMDP responds when intent communication is removed. The reward value is lower and it has yet to converge.

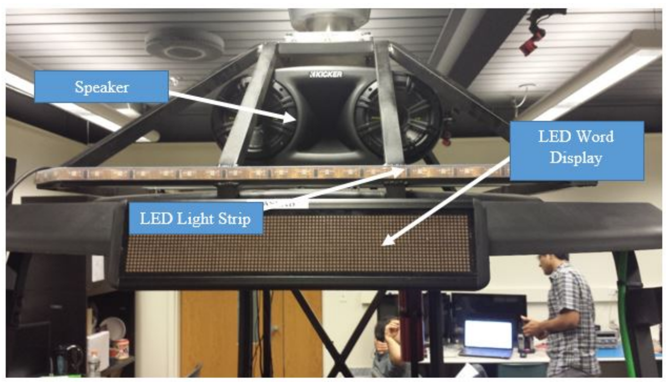

Figure 3.5: Picture of experimental setup.

There were some shortcomings noted in this preliminary phase. The LED light strips and word display were not bright enough to be seen in direct daylight. The color red is hard to view in daylight unless the brightness is within a certain lumens range. A suggested solution was to replace these components with laser lights to create a lane around the golf cart and to project symbols in front of the golf cart. The problem with this suggestion was that there are not any components available to produce the brightness required without consuming more power than available on the golf cart. The current solution is to mount the LED word display onto the front of the cart to signal what the cart intends for pedestrians to do and strobe lights to indicate the cart is trying to get the attention of pedestrians. The difference between these components and the initial components will be outlined in the Methodology section.

Because there are a limited number of actions the golf cart will ask of the human, there are few opportunities for a miscommunication to take place. Based on this assumption, the belief-state

MDP model was replaced by the decentralized MDP (Dec-MDP) model which will be explained in the Problem Formulation section. To further decrease the opportunities for miscommunication, a HUD system has been included to communicate the cart's intent to passengers which helps to establish trust in the vehicle. The idea is that if the people inside the vehicle appear confident, the pedestrians will be more likely to pay attention the cart's indicators.

There are a few factors that could account for the behavior of the trust quantification seen in the POMDP simulation results. Since the probabilities had to be input manually for each agent at each state, the results could reflect an underlying issue with values at different states.

Chapter 4

Problem Definition

4.1 Problem Formulation

The goal of this research was to be able to effectively communicate with the pedestrian based on observed actions, in both the real world experiment and the simulations, and develop a mathematical model for the quantification of trust in this situation. To do this successfully, a model had to be created that incorporated the stochasticity of a pedestrian's actions, a way to measure how trust changes over time between the autonomous car and the pedestrian, and a method for being able to show how effective the communication of the car to the pedestrian was. The other goal of the research was to effectively communicate with passengers to ensure that they were not tempted to override the autonomous features of the golf car in an attempt to avoid hitting pedestrians. It is important that the passengers don't override autonomous mode because they are unaware of the next action of the car and this could lead to a situation where the car actuators could be damaged causing the car's actions to be negatively affected. To measure the comfort level of the passengers, real world experiments were conducted to get feedback on what made them feel more comfortable.

4.1.1 Pedestrian Surveys

To construct a realistic pedestrian model, a survey of human participants was conducted to determine the potential actions pedestrians might take when faced with an autonomous car and the probabilities of those actions. The survey method was chosen over observing people's reactions by driving the autonomous vehicle around due to safety precautions. Details of the survey are presented below. The full survey can be found in the Appendix.

Based on the survey of 50 people with no affiliation to the research, potential pedestrian actions were gathered and their probabilities were calculated. The goal of the survey was to narrow down the number of actions pedestrians might take when they encounter a golf car that might not have a person operating it and to use their responses to determine what kind of communication system would perform the task well and help people to feel more receptive of autonomous vehicles so that they will be more likely to perform what the vehicle asks of them. Here is an idea of the type of questions asked:

- What would you do if you saw a car approaching you without a driver?
- How would this make you feel?
- What would make you feel more comfortable around this type of vehicle?

The goal of the questions was to get a general idea of people's perceptions and expectations of autonomous vehicles. The demographic of the survey included students between the ages of 18-22, faculty and staff between the ages of 30-70, and people with no affiliation to the university between the ages of 14-65. There were five pedestrian actions identified: move, stop, wait, get in the car, and do not notice the car. Using these actions, the Dec-MDP model was built [1].

4.1.2 Dec-MDP Definition

The intent of pedestrians has uncertainty associated with it due to the unpredictability of human actions. Several models were compared for their applicability to this issue. The partially observable Markov Decision Process (POMDP) was the initial choice based on the fact that the autonomous vehicle-pedestrian interaction is unknown. In [24], [34], the authors discuss the limitations of using a POMDP model due to its intractability. The decentralized POMDP can be NEXP-Complete, hence suffering from computational limitations onboard the vehicle. On the other hand, Markov Decision Processes (MDP) themselves are P-complete, however the main objection to using MDPs has been that the MDP model would not be able to account for the fact that both the car and pedestrian were unaware of the other's current and future states. In particular, the internal *intent* state of both the pedestrian and the vehicle are not fully known to both of the agents. The model had to be updated to include observability of at least the current state for intent to be effective. Note here that the observation of the current *physical* state of both the agents is on the other hand a reasonable assumption due to the fact that in a real environment, a car and pedestrian would be able to sense each other and see where they are with respect to one another.

To overcome this issue of unobservability, we build on the hypothesis that if the vehicle can communicate its intent to the pedestrian, the pedestrian's actions can be reasonably well predicted. This is a key insight to making the solution implementable on real-world robots, because it means that if the ICS is active, we can effectively treat the partially observable problem as a fully observable Dec-MDP. In other words, we use the ICS as a method to make it easier to communicate the current internal state of the vehicle to the pedestrian, and as a result, narrow the number of potential actions of the pedestrian. The situation is rather akin to what would happen if a human driver motioned for a person to cross the street. In that case, the pedestrian being aware of the driver's mind state is highly likely to cross the street. This allows us to use the Dec-MDP as a model for the vehicle-pedestrian encounter by allowing each agent to move freely, only consider each other when they intersect, and include the observability, like in the real world. The Dec-MDP model was appropriate for this scenario because in reality we have complete control over the car, but not the pedestrian and the model easily allows for stochasticity in one agent, while reducing the complexity by leveraging the deterministic predictability in the other, and allowing both to interact in stochastic ways that can be quantitatively measured. In [36], [37], [1], [22], the decentralized MDP (Dec-MDP) is used in a way that accounts for stochastic behavior in an agent while showing that the need for observability can be handled.

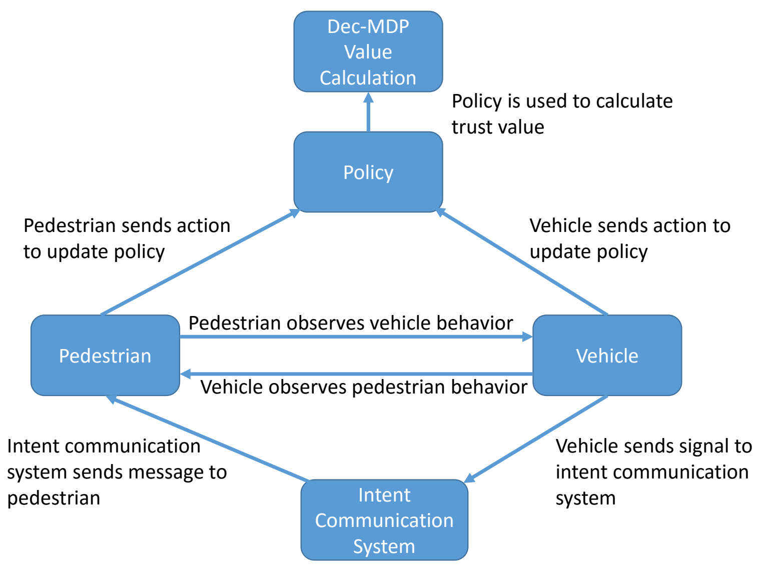

Figure 4.1: Visualization of how the Dec-MDP model works within the simulation

The Dec-MDP can be defined by the tuple $\langle S, A, P, R, O, \Omega \rangle$ where:

- S is a finite set of world states both agents (car and pedestrian) share.
- A = $A_1 \times A_2$ is a finite joint set of actions where A_i indicates the set of actions taken by agent i.

- P is the transition function. P(s'|s, a_1, a_2) is the probability of the outcome state s' when the actions a_1, a_2 are taken in state s.

- R is the reward function. R(s, a_1, a_2, s') is the reward obtained from taking actions a_1, a_2 in state s and transitioning to state s'.

- O is the observation function. O(s, a_1, a_2, s', o_1, o_2) is the probability of agents 1 and 2 seeing observations o_1, o_2 respectively after the sequence s, a_1, a_2, s' occurs.

- Ω is the set of all observations for each of the agents.

We formalize the intent communication problem as follows:

$$\begin{gathered} \gamma \in [0,1],\ \phi \in [0,1] \\ r_1(s,a_1),\ r_2(s,a_2),\ d(s_1,s_2) \in [0,6] \end{gathered} \tag{4.1}$$

In Eq.(1), γ is the discount factor on the transitions that each agent will experience, ϕ is the discount factor on the trust quantification which is a combination of both agents states and actions respectively, r_1 is the reward that the vehicle receives depending on its state and action, and r_2 is the reward that the pedestrian receives depending on its state and action. The rewards, r_1 and r_2, are independent of each other. The proximity function, $d(s_1, s_2)$, ranges between [0,6] based on the size of the simulation environment, the scenario being tested by both agents, and the distance between agents. The proximity function can be updated to accommodate larger or smaller environments or different test scenarios. The transition dependence of when the agents interact is accounted for in the trust quantification reward function. This trust quantification is the main focus of the simulation. Although the biggest changes were seen when the two agents interacted, the trust level later in the simulation was dependent on how well those interacts went for both agents. If the interactions should influence the states and actions each agent selects, the transition reward function will have either a positive or negative gain to account for the interaction. Again, the focus isn't on how well the agents are able to navigate in the environment, but how well they can communicate with and understand each other.

We also include the notion of joint full observability, meaning that the pair of observations made by both the agents (pedestrian and autonomous vehicle) together fully determine the current state. Mathematically, this can be represented as: If O(s,a_1, a_2,s',o_1, o_2) $>$ 0 then P(s' $\mid$ o_1, o_2). The notion of joint full observability can be extended to multiple pedestrians by using observations from interacting agents to determine the current state of each agent. In the case of more than two agents, the mathematical representation can be expanded to include situations where the two agents might be interacting while another agent is at a distance. The joint full observability assumption for this problem is only critical when two or more agents are going to interact with each other. If the agents aren't interacting, their current state isn't taken into account for the trust portion which is the primary focus.

Using the variables from Eq.(1), the reward functions can be represented as follows:

$$R(s_1, s_2) = \sum_{i=1}^{n_{g_1}} \gamma_i r_1(s, a_1) + \sum_{i=1}^{n_{g_2}} \gamma_i r_2(s, a_2) \tag{4.2}$$

$$R(s_1, s_2, a_1, a_2) = \sum_{j=1}^{n_{g_{1,2}}} \phi_j r_{1,2}(s_1, a_1, s_2, a_2) \tag{4.3}$$

$$\begin{aligned} r_{1,2}(s_1, s_2, a_1, a_2) &= \sum_{i=1}^{n_{g_1}} \theta_i r_{1_i}(s_1, a_1) + \sum_{j=1}^{n_{g_2}} \theta_j r_{2_j}(s_2, a_2) \\ \theta_i &= P(s_1{}' \mid s_1, a_1) O(s, a_1, a_2, s', o_1, o_2) d(s_1, s_2) \\ \theta_j &= P(s_2{}' \mid s_2, a_2) O(s, a_1, a_2, s', o_1, o_2) d(s_1, s_2) \end{aligned} \tag{4.4}$$

Eq.(2) corresponds to the transition reward function and Eq.(3) corresponds to the trust quantification reward function. Because the goal of this research is to show how intent communication affects trust between an autonomous vehicle and a pedestrian, Eq.(3) will be the focus of further discussion of the problem, but Eq.(2) has been included for completeness in the description of the Dec-MDP framework. In Eq.(3), $r_{1,2}(s_1, a_1, s_2, a_2)$ takes into account the interaction of the agents. The values of $P(s_1{}' \mid s_1, a_1)$ are based on the probability that the vehicle will take a certain action based on its current state. The values of $P(s_2{}' \mid s_2, a_2)$ are based on the probabilities that were calculated from the pre-survey and the current state of the pedestrian. These calculations were made by taking the number of actions that were collected and dividing the number of people who selected an action by the total number of people that participated in the survey. This reward is dependent on how the pedestrian agent views the vehicle agent. When the pedestrian has a stronger trust in the vehicle, the reward is higher and the reward is lower when the opposite is true. The reward varies based on the proximity of the agents with respect to each other. Typically, if the vehicle is closer to the pedestrian, the trust the pedestrian has in the vehicle is lower. This proximity value is updated depending on which scenario is being tested. This change in the proximity value based on the scenario is due to the different confidence levels seen in the pedestrians depending on the scenario they are in. The pedestrians that have more knowledge about the vehicle are typically more confident in the vehicle's ability to make sound decisions compared to someone who has never seen the vehicle.

To determine the action probabilities of the car, $P(s_1{'} \mid s_1, a_1)$, we use the current state of both the car and pedestrian. The probability is updated based on the distance the car is away from the pedestrian which is varied by scenario. For example, if the scenario being tested is with ICS enabled and no prior knowledge, the car will have a 70 percent probability of stopping when it is within a distance factor, $d(s_1, s_2)$, of 3 grid-spaces of the pedestrian. Another example would be in the scenario without ICS enabled and prior knowledge where the car would have at least a 30 percent probability of stopping when it is within 3 grid-spaces of the pedestrian. In essence, the transition probability is updated based on the distance that the car is away from the pedestrian, depending on the scenario. Typically, the shorter the distance, the higher probability there is for the car to stop. The grid-space unit is used because the simulations are run in a grid-world, but this unit can be changed to consider real world distances in feet or meters. For clarification, prior knowledge means that the pedestrian has been introduced to the intent communication system before testing. They have seen how the exterior system activates and have some knowledge of the underlying software.

To calculate the action probabilities of the pedestrian for each scenario, $P(s_2{'} \mid s_2, a_2)$, the results of the post-surveys were used. The most important factor for the transition probabilities was the scenario being tested. After the scenario was determined, then the answers were looked at for weighting. The probability on the actions were dependent on how much confidence was seen in the survey results. For example, in the scenario with ICS enabled and prior knowledge, the results showed a high pedestrian confidence in both their behavior and the car's behavior. These results will be discussed further in the Results section. The way confidence was interpreted numerically was from the value assigned to the questions. The yes or no questions were assigned values of one for yes and zero for no and the other questions were ranked on a scale of 1 - 5. To determine what the probabilities on each action would be, the numbers from the surveys and the subtleties seen in the video were used to estimate how likely a pedestrian would be to take an action. In the with ICS enabled and prior knowledge example, they had a high confidence value. Considering that the confidence was high and what a rational human would do when they have high confidence, the risker actions such as get in the car or not notice the car were given higher probabilities at closer distances when compared to the scenarios that had lower confidence.

To determine what parameters would be best suited for the simulations, the pre- and post-survey responses were used. Based on the pre-survey, an action set was obtained. To get the probability of a pedestrian taking a certain action, the number of responses given for a particular action was divided by the total number of responses which was 50. In order to decide how likely a pedestrian would be to take one of these actions in a given scenario, the post-surveys were consulted. Based on the trust levels calculated from the responses, another probability distribution was calculated by assigning a higher value to the actions that already had a high probability of occurring based on the pre-survey. So basically the post-surveys were used to put a weight on the overall probability distribution. When the post-survey results were compared with one another, there was a strong pattern noticed being that the more information a person had about the vehicle, the higher their trust was in the decisions it made. By taking the scores from the 1-5 scaling category, the action probabilities were updated. For example in the ICS enabled and prior knowledge scenario, there is an overall trust rating of 27. Since the maximum is 30, 27 was divided by 30 (90 percent) to see how closely the pedestrians would follow the baseline probability distribution. The pre-survey created this baseline where the actions had the following probabilities: stop (23 percent), wait (22 percent), cross (25 percent), don't notice the car (17 percent), get in the car (13 percent). Once the trust value was known for a given scenario, the probability distribution was updated to show how the actions would be weighted. So in the case of ICS enabled and prior knowledge, the trust level is at 90 percent. Therefore the new probability distribution would assign higher values to the actions that have a lower probability because these actions are typically not taken by pedestrians who don't know anything about the car. For example, there is a 90 percent chance the pedestrian will trust the car's ability to make decisions. That means the actions can be weighted at a value of 0.9 more than what they previously were starting with the lower probability actions. These actions are weighted first and their "extra" probability is taken from the higher valued actions and the higher valued probabilities share an equal probability after the lower probability actions have been adjusted. The probability distribution of actions in all of the scenarios would look like the following: With ICS enabled and prior knowledge: Get in the car ((13*0.9) +12) (24), don't notice the car ((17*.9) + 17) (32), wait (14), stop (14), cross (14)

For the interaction problem, several assumptions have been made. It is assumed that the car's behavior is fully known, observable, and controllable. This assumption stems from the fact that the car has been programmed to behave in the safest manner possible meaning there is always full control of the car in either autonomous or manual mode. In other words, it is assumed that the vehicle is a deterministic system, and there is no stochasticity in the car. The action set of the car is limited to: forward, left, right, stop as these are the actions seen in normal driving operations. Another assumption is that the car and the pedestrian are only interested in each other when they have an encounter, otherwise they act independently. The reward function contains the concept of trust as seen in Eq.(4), which is an expansion of Eq.(3). Both the car and the pedestrian have individual trust rewards depending on their proximity to one another and the observations they have based on the probability of the actions the other may take. Also, the Dec-MDP is considered over a finite-horizon because after the agents encounter each other, they no longer consider each other in their future actions unless they have another encounter which would be considered independently of the previous encounter.

Algorithm 1 describes how the Dec-MDP was used in the simulations, the Dec-MDP solutions are based on [1]:

Algorithm 1 Intent Communication Algorithm

```
procedure DEC-MDP(S, A, P, R, O, Ω)
    A ← A_1 × A_2
    s_1, s_2 ← S
    a_1, a_2 ← A
    R(s_i, a_i) = 0, i = 0, j = 0
    repeat
        i ← i + 1, j ← j + 1
        for o_1, o_2 do
            Determine scenario ∈ [1, 4]
            p_1, p_2 ← P(s' | s, a_1, a_2)
            a_1, a_2 ← A
            max_{a_1,a_2} r_{1,2}(s_1, s_2, a_1, a_2)
            for s_1, s_2 do check
                if d(s_1, s_2) ≤ scenario threshold then
                    Update θ_i, θ_j using d(s_1, s_2)
                end if
                π[s_1, s_2] = arg max_{a_1,a_2} r_{1,2}
            end for
        end for
    until s_1 = s_{g_1} or s_2 = s_{g_2}
    return π, R(s_i, a_i)
end procedure
```

The purpose of the algorithm is to illustrate the development of an algorithm that is better than a reactive strategy. Because the Dec-MDP framework predicts over a finite interval, the vehicle can change its actions to accommodate the oncoming pedestrian before there is a chance for a collision. A reactive strategy would only inform the vehicle of a change in the environment when a pedestrian is already in range of the sensors and by then it may be too late for the vehicle to maneuver accordingly. The goal with the Dec-MDP model is to keep the vehicle and pedestrian as safe as possible without incurring a large amount of computational overhead. The model also allows for the vehicle to update its actions when the pedestrian acts in an unexpected manner by having the observation ability. This is significantly more robust than a rule-based technique because there are a finite number of pedestrian actions that can be thought of in advance and these can change drastically when the pedestrian is actually in front of the vehicle. The proximity measure $d(s_1, s_2)$ also gives more flexibility in the area of safety and trust as there is an established and adaptable distance away from the pedestrian that the vehicle starts changing its actions to accommodate pedestrian behavior.

4.1.3 Intent Communication Psychology

The effectiveness of the ICS has less to do with the technological sophistication of the communication than with how people perceive the communication. If the ICS is advanced, fancy, or complicated to the point no one understands what it is trying to do, it is useless. We found this during the initial development of the ICS when people were brought in to provide feedback on what was effective and what could be improved upon. Moving forward from this point, the biggest consideration of how to design the system was based around what humans are used to seeing on the roads. In the transition time that will follow from when autonomous cars are introduced on roads, this is a reasonable assumption. This includes things like words (including their fonts and colors), flashing lights, and sounds.

To determine what communication would be most effective, learning how humans talk to each other was crucial. In [4], [43] relational trust was discussed. The dialogue that takes place between humans is an enormous source of trust building. The previously mentioned papers show how in depth conversation is not necessary to give a command and have others follow it. For example, in an emergency situation, humans are trying to get to safety and if a robot is able to lead them to safety, they won't need in depth conversation but simple statements. Using this insight, the messages that are displayed on the ICS are as simple as saying please cross. By keeping the message short, there is little room for misinterpretation of the meaning.

Understanding what people expect to see is also important for getting passengers to be comfortable trusting the car. Even though they don't have control over what is happening, it is important that they are able to understand what is happening. To account for this, the interior ICS was developed in tandem with the exterior ICS that communicates with the pedestrians. The passenger system is different from the pedestrian system as they are looking for completely different types of communication from the car.

Chapter 5

Solution Methods

5.1 Methodology

5.1.1 Intent Communication System Description

The intent communication is a fusion of hardware and software. The following diagrams describe how the system is interfaced on the autonomous golf car.

Figure 5.1: Intent Communication System Block Diagram

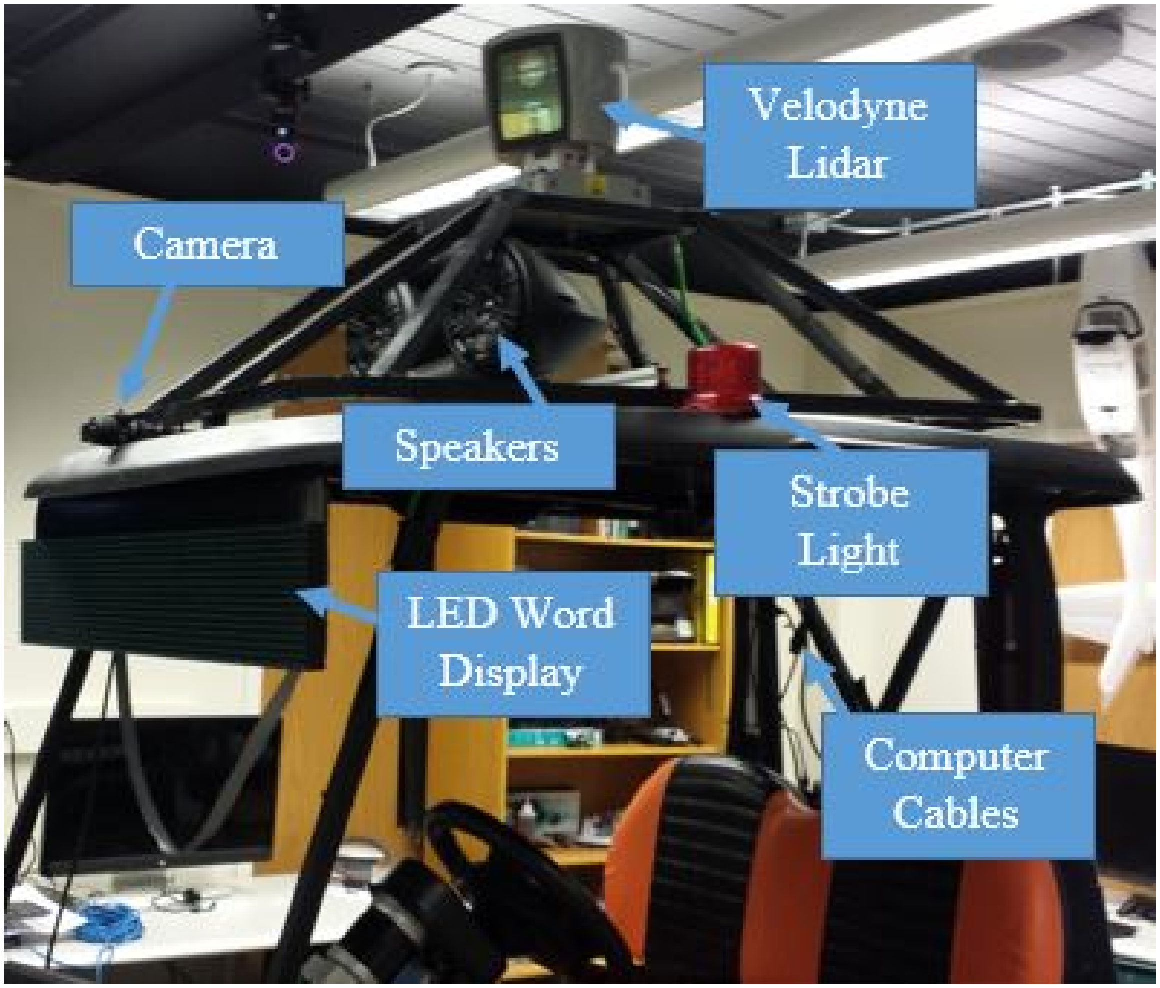

Figure 5.2: Intent Communication System on Autonomous Golf Car

One of the goals with the exterior ICS was to keep it simple, make it communicate effectively, and have the ability to operate in diverse environments. There are two strobe lights on-board the golf car, one on each side, used to get the attention of the pedestrians. The LED word display along with the speakers provide a message as to what the golf car would like for the pedestrian to do. Because the computers are mounted in a way where they are not seen, the cables were pointed out to show where all of the hardware is routed to. The computer contains the software used to detect pedestrians via the front-mounted camera and send a signal to the microcontroller mounted on the LED word display to tell it what message to show, how long to show it for, and when to activate the speakers and strobe lights.

The goal with the interior ICS was to show enough information to the passenger that they trusted the car's decisions and saw reasoning for those decisions, but not show too much information which could potentially confuse the passenger and make them have less trust in the car. To do this, a heads-up display (HUD) was developed. The biggest concern people showed in the development of this system was if the pedestrian would be hit or not. The HUD was designed around this concern. Software on-board the golf car already allowed for the detection of pedestrians via the front facing camera. This software was based on the HOG algorithm developed in [11]. The HOG algorithm was tested in real world environments so objects in urban environments are not detected by the software. It also works on a per-frame evaluation of the video feed to accurately determine if a pedestrian is truly in the path of the vehicle. What the passenger sees is the HOG algorithm working by highlighting any people in the view of the camera. By highlighting the pedestrians, the passenger will know that the car has seen them and will most likely avoid hitting them.

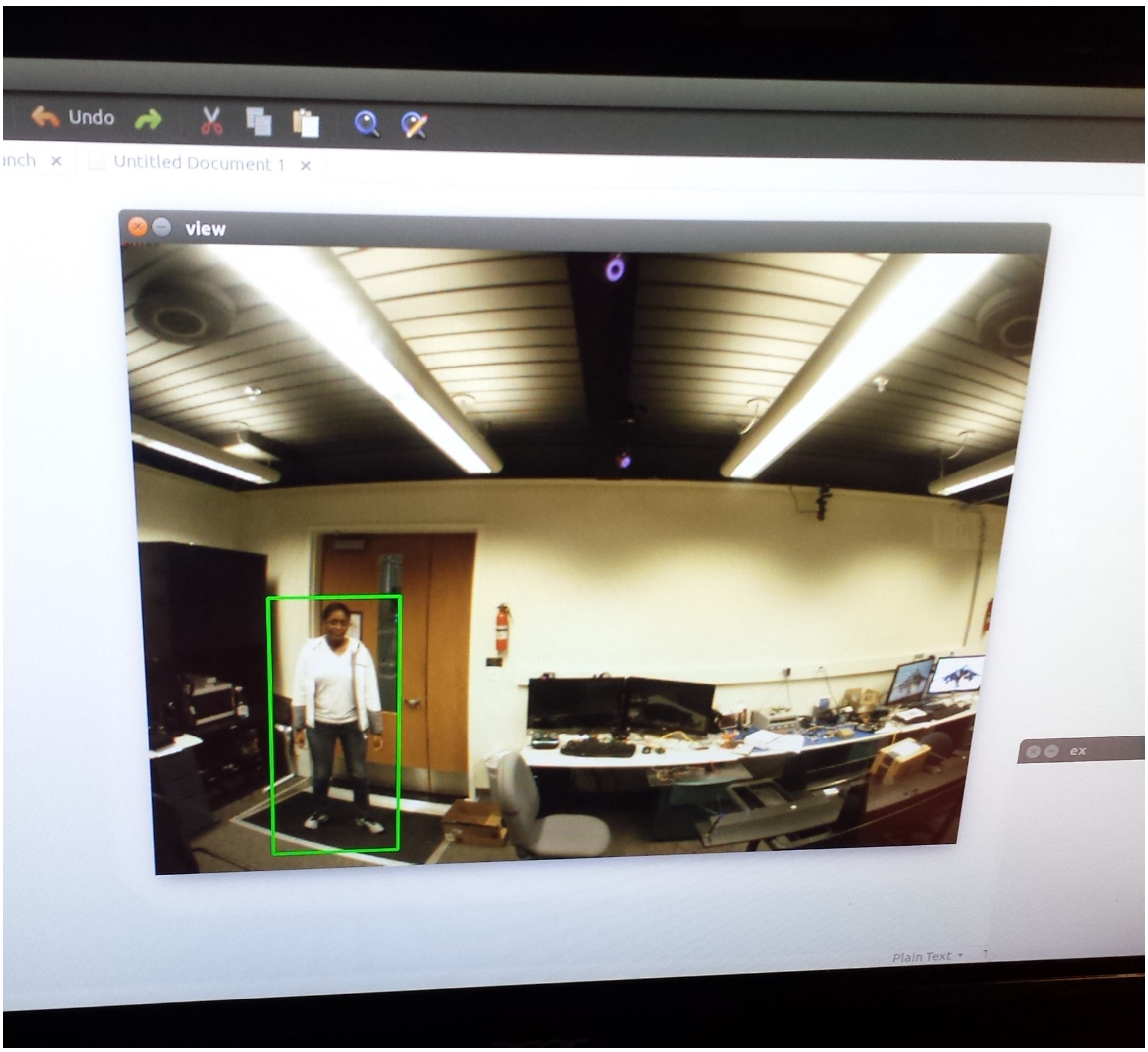

Figure 5.3: Example of passenger HUD

Figure 5.4: Passenger ICS Testing

Figure 5.5: Example Visual message displayed by the Intent Communication System

Figure 5.6: Example of golf car in testing environment

5.1.2 Real World Experiments

This golf car is equipped with several lidars, including a Velodyne lidar on top of the car, a front facing camera, several on-board computers, and numerous other proximity detection sensors. For these experiments, the golf car was driven by a human using a transmitter. Using the transmitter was chosen over using the autonomous capabilities due to safety precautions. The human subjects were unaware of the fact that the golf car was being controlled manually, hence the results that follow are unbiased. The transmitter allowed us to give the illusion of complete autonomy while still being able to drive the golf car manually and intervene if required.

There were a total of 91 participants in the experiment: 50 in a pre-survey on actions they would take around an autonomous car, 26 subjects in the real world testing of the exterior ICS, and 15 in the real world testing of the interior ICS. Between these 3 sets of participants, 9 were involved in the pre-survey and exterior testing, and 4 were involved in all three sets. The real world testing subjects were divided into groups as follows:

- With ICS and prior knowledge of golf car (6)
- With ICS and no prior knowledge of golf car (7)
- Without ICS and prior knowledge of golf car (7)
- Without ICS and no prior knowledge of golf car (6)

In this experiment, prior knowledge means that the participants were introduced to the golf car before testing. They saw how the ICS worked and also had an explanation of how the sensors on the golf car worked together to create the autonomous functionality. None of the participants involved were aware of if there was a human inside the vehicle. To explain the difference between each group, short descriptions of each group are provided below:

- With ICS and prior knowledge of golf car: this group had the ICS enabled during their encounter and they had also been introduced to the system before testing.
- With ICS and no prior knowledge of golf car: this group had the ICS enabled during their encounter, but they had not been introduced to the system before testing.
- Without ICS and prior knowledge of golf car: this group did not have the ICS enabled during their encounter, but they had been introduced to the system before testing.
- Without ICS and no prior knowledge of golf car: this group did not have the ICS enabled during their encounter nor had they been introduced to the system before testing.

First, the pedestrians were organized into a line at a distance away from the golf car in no specific order. Then they were called one by one to take part in the experiment. The participants were all given the same instructions to walk in front of the golf car as if there were walking to their car across the parking lot. After they have finished this step, they were given a survey over how they felt before and after interacting with the golf car and a video of their interactions was also recorded. The full survey can be found in the Appendix, but here are some of the questions from the survey:

- Did the car do what you expected it to do?
- Did you behave how you expected when confronted with the car?
- Did the intent communication create trust in what the car would do?
- Did you feel safe around the car?
- Did you feel the communication was effective?

In order to get feedback from the passengers on how effective the interior ICS was, the 15 participants were able to sit inside the golf car and watch what happened on the HUD. Due to safety limitations, they were not able to be driven around in the golf car during the experiment. Instead, they were given the scenario that the golf car was driving and a pedestrian wandered into the field of view of the camera. Each passenger was seated alone to help prevent any biased from another person that could potentially distract them from what is taking place on the screen. The HUD displayed the video feed, but when a person walked into the feed a box was placed around them to show that the car had detected them. After they had seen how the HUD worked, they were given a survey. The full version is in the Appendix, but here is are a few of the questions they were asked:

- I trusted the car more because of the display
- The display was effective
- The car communicated well

5.1.3 Simulation Setup

The simulations were used as a way to further study how people interact with an autonomous vehicle without the concern for safety. The simulations were run based on the same scenarios as the real world experiment. In the simulations as well as the real world experiment, there was only one pedestrian introduced to the car at a time. The reason for having just one pedestrian was to be able to focus solely on the vehicle-pedestrian interaction. When other humans or vehicles are introduced to the environment, the pedestrian could be easily distracted from what they are trying to accomplish. The simulations were based on the Dec-MDP model described in Section 4. The action set of the car included: forward, stop, left, right and the action set of the pedestrian included: forward, backwards, left, right, wait, get in car, don't notice car, stop. The difference between stop and wait is that the wait action means the pedestrian might never move if the car never moves (deadlock situation) whereas with stop, the pedestrian is only waiting temporarily.

The transition probabilities were updated based on the scenario that was being tested. If, for example, the pedestrian was in a group with prior knowledge, they would be more likely to take riskier actions (get in the car) at a close proximity as opposed to those in groups without prior knowledge. Each scenario had different proximity values as well to reflect how comfortable the pedestrian was based on their level of knowledge and if the ICS was enabled or not. All of these changes to the Dec-MDP parameters were a direct reflection of what was seen in the real world testing with the inclusion of more pedestrian actions and less concern for safety.

The connection between the simulation and real world experiments is that the pre-survey and post-survey results were used to determine what psychological factors went into the decisions that pedestrians used to determine what action would be appropriate. The focal point of the simulation is when there is an interaction between the car and the pedestrian. The other components of the simulation, such as when the car and pedestrian are moving about independently, are factored in where trust is considered. Trust consideration is the link between the real world experiments, simulations, and the mathematical formulation.

Chapter 6

Results

6.1 Results

6.1.1 Real World Results

During the testing event, the participants were unaware of what group they belonged to. Each participant was introduced to the experiment individually and they were given the same instructions to walk through the parking lot as if they were going to their car. They were not sure of any actions the golf car would take unless they had prior knowledge of the golf car. Half of the participants had prior knowledge of the golf car so that the difference in trust could be compared to those who had never seen the golf car. Half of the participants had the ICS enabled so that the difference in trust could be measured against those with the ICS disabled. Each group will be discussed separately to clearly distinguish the similarities and differences in their perceptions.

6.1.1.1 Group 1: With ICS and Prior Knowledge of Golf Car

The participants in this group were all introduced to the hardware (word display, lights, etc) on the golf car sometime prior to the experiment. When they were in the testing environment, they appeared to be the most comfortable around the golf car. Based on the answers from the survey, this group had the highest trust rating of the golf car before and after the testing. To see how they responded to the golf car, a question about their behavior was included in the survey to gauge how much they felt their actions changed when confronted with the golf car. This group was the only group where all of the participants behaved how they expected to. The most interesting finding lies in the answer to the question: Do you feel the car is trying to replace humans or work with them? There was an approximately 50 percent split in this aspect.

6.1.1.2 Group 2: With ICS and no Prior Knowledge of Golf Car

Surprisingly, this group felt that the car's actions were predictable, but they didn't trust the car more than a human driver when compared to the following groups which didn't have the ICS enabled. This was gathered from a question on the survey which is attached in the Appendix. Another contrast to Group 1 is that about 80 percent of Group 2 felt that the car was trying to work with people instead of replacing them. They had similar behaviors compared to Group 1 like, they were comfortable around the golf car and they had a relatively high trust in the golf car.

6.1.1.3 Group 3: Without ICS and Prior Knowledge of Golf Car

These participants were disappointed when they didn't see the ICS during their test time. They did feel like they behaved as they expected, ie they thought the actions they would take were the same as the ones they did take. About 60 percent of the group felt the car was completely unpredictable and they actually felt somewhat unsafe around it when compared to Groups 1 and 2. After the experiment, trust in the car was higher than before the experiment. This was the only group where a positive change in trust was noted after exposure to the golf car without the ICS. They also believed that the ICS was made to replace humans instead of working them. The participants may also have felt like the ICS wasn't working properly. While the system was fully functional, to get a realistic range of situations that can happen in the real world, this scenario needed to be included in order to learn more about how pedestrians' trust is affected by seemingly faulty systems.

6.1.1.4 Group 4: Without ICS and no Prior Knowledge of Golf Car

These participants had the lowest trust level of all the groups before and after their interactions. This result isn't surprising since they had no previous exposure to the golf car and the ICS gave them no feedback. This was the only group where most of the participants (about 80 percent) said they behaved differently than they expected to when they encountered the golf car. They didn't feel safe at all around the golf car and they felt like the purpose of the ICS was to replace human drivers.

Table 6.1: Pedestrian Trust Results

Group Number	1	2	3	4
Communication was adequate	28	24	19	9
Communication was clear	28	26	9	7
Communication was effective	29	25	13	8
I trust the communication of the car	27	25	9	6
I trust the car to make the appropriate actions	25	23	15	12
I trust the car more because it communicates	28	22	8	6
I trust the car more than a human driver	18	15	19	9
I feel safe around the car	22	21	15	11

Figure 6.1: Group 1: With intent communication system and prior knowledge of golf car, Group 2: With intent communication system and no prior knowledge of golf car, Group 3: Without intent communication system and prior knowledge of golf car, Group 4: Without intent communication system and no prior knowledge of golf car

The results in Table 1 are based on the information gathered from the surveys after the testing was complete. To account for some groups having more participants than others, the score was scaled so the maximum number of points a group could give would be 30 because this is the maximum number of points that could be generated by the smaller groups. As seen in the table, Groups 1 and 2 had higher trust values overall compared to Groups 3 and 4.

The testing took place in a parking lot in the evening, so the participants weren't able to see inside of the golf car clearly to notice if there was someone controlling it. By keeping all of the participants blind to which group they were in, it was easier to keep the experiment unbiased from an exposure perspective. Another method used to study how people reacted to the golf car was filming the test. After reviewing the video, it was seen that the Groups 3 and 4 were more hesitant to walk in front of the golf car. They typically moved a little further away from the golf car than Groups 1 and 2. Groups 3 and 4 were also more likely to look at the people around them for a while before they made their first step. They also were more likely to walk faster than the Groups 1 and 2.

Groups 1 and 2 were more likely to get closer to the golf car and they spent more time observing the golf car as they walked by it, unlike Groups 3 and 4 where they would look at the golf car very briefly as they walked by it during the test. The participants in Groups 1 and 2 appeared more confident when they crossed in front of the golf car. Some were a little startled when the display turned on, but they only paused long enough to read it and they kept moving. They seldom turned around to see what the other participants were doing. Those in Group 1 were almost over-confident as they sometimes didn't even take the time to look at the golf car as they crossed in front of it.

The passengers were all in the same scenario where the people detection software was displayed on the HUD. Below is a table showing the results from their surveys:

Table 6.2: Passenger Trust Results

The graphics display made me feel safe	58
The car communicated well	63
The display was effective	62
The display was like I expected	51
I felt the display was similar to a human driver	52

Figure 6.2: The results from the passenger surveys are based on the maximum number of trust points which is 75. Each question has a trust value assigned to it based on the survey responses.

The most interesting result of the passenger testing is the number of people who felt like the pedestrian would be hit. Only 26 percent of the participants felt like the pedestrian would be hit. Another result is that only 33 percent of the participants felt like the car was trying to replace human drivers. This is interesting considering more of the pedestrians felt the car was trying to replace human drivers. About 86 percent of the participants trusted the car more because of the display and also claimed they would be more likely to trust the car if they were pedestrians after seeing the interior ICS. Roughly 93 percent of the passengers felt that the interior ICS helped them understand what the car was doing because they could see that it was detecting pedestrians.

6.1.2 Simulation Results

The simulation results from the Dec-MDP model followed what was seen in the real world experiments by modeling the human trust factor after the results taken from the post-surveys. The pedestrian model was created using a probability distribution on the actions seen in the video from real world testing as well as from the data gathered from the pre-survey. The transition probability was then taken from this overall probability distribution based on the scenario being tested. The simulation was based in a gridworld area in which only one vehicle and one pedestrian were placed.

A detailed explanation of each scenario follows below. To accurately represent each scenario, parameters for the pedestrian in the simulation, such as, distance away from vehicle's effect on trust, probabilities on pedestrian actions, and the pedestrian's likelihood of following the vehicle's directions. These parameters were updated according to the scenario being tested. The probabilities on the pedestrian's actions and the likelihood of the pedestrian following the vehicle's directions were changed to reflect what was seen in the real world experiment and the trust is modeled after the results taken from the post-surveys of the participants from the real world experiments to get as close as possible to real human variations in trust. None of the vehicle's parameters were changed due to the fact that it's actions or probabilities are the same in all scenarios.

6.1.2.1 With ICS and Prior Knowledge

To appropriately model this scenario, the distance factor between the pedestrian and vehicle was reduced to one grid-space. This distance factor was chosen because of the high comfort level seen in the video results. The results, seen in the plot below, show how trust was affected throughout the simulation run.

As the pedestrian and vehicle interacted, the value of the trust fluctuated accordingly. As the two came in closer proximity to each other, the trust was lower than when they were further apart. The pedestrian in this scenario took more risky actions than the pedestrians in the other scenarios. In one instance, the pedestrian actually got inside of the vehicle.

6.1.2.2 With ICS and No Prior Knowledge

In this scenario, the distance factor between pedestrian and vehicle was updated to be three grid-spaces to include a higher factor of safety to account for the lack of previous knowledge.

A striking difference between this scenario and the scenario where there is prior knowledge is the drastic reduction in trust. As soon as the vehicle starts moving, the pedestrian loses trust. The pedestrian here also takes some bold actions and sometimes doesn't notice the vehicle.

6.1.2.3 Without ICS and Prior Knowledge

This scenario was the most interesting for updating the parameters. Like in the real world experiment, the pedestrian will be expecting commands from the vehicle, therefore the distance away from the vehicle will be the same as in the first scenario. The distance factor was set for one grid-space.

The results from this scenario were the most unexpected. The trust value was never consistent. During some encounters between the pedestrian and vehicle, the pedestrian would have a higher trust value than at other encounters, but the trust tends downward during the duration of the simulation. Also, this group in the simulation has the lowest trust of all the groups. This is a significant find because it demonstrates how expectations play into the development of trust in machines.

6.1.2.4 Without ICS and No Prior Knowledge

Since this scenario is the one where the pedestrian has no prior knowledge, the distance factor between pedestrian and vehicle is taken to the maximum of six grid-spaces.

Like its real world experiment counterpart, trust here is always low. It seldom moves in the positive direction and when it does, the gains are almost negligible compared to the overall trust value. This scenario always tends downward, with no upward movement at any point.

All of the simulation results stop at 10 iterations because this is amount of time it takes either the vehicle or pedestrian to reach their goal.

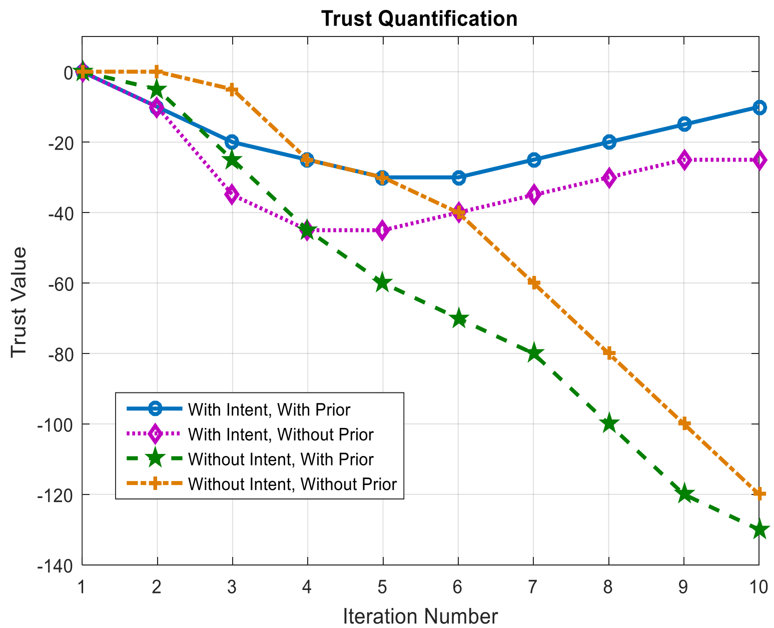

Figure 6.3: Trust quantification plot comparing all four scenarios discussed above

Because there wasn't a concrete way to assess different confidence levels in the real world testing, multiple confidence levels were considered in the simulations. To determine how confidence level affects the trust values in the simulations in the different scenarios, the upper and lower bounds on the results were calculated. The equation used to calculate the bounds on the results was:

$$C = b \pm t \times \sqrt{S} \tag{6.1}$$

where b is the coefficient produced by the curve fit to the data, t is the confidence level, and S is the is a vector of the diagonal elements from the estimated covariance matrix of the coefficient estimates, $(X^T X)^{-1} s^2$. X is the design matrix and s^2 is the mean squared error. The design matrix will follow the simple regression model because there is only one explanatory variable, trust value, with several observations in each scenario. The design matrix is a matrix of two columns, the first column being ones to allow for the estimation of the y-intercept while the second column contains the x-values associated with the corresponding y-values. For each scenario, the design matrix is based on the x-values from the simulations.

There were five confidence levels tested for each of the four scenarios: 20 percent, 40 percent, 60 percent, 80 percent, and 99 percent. These confidence levels reflect varying degrees of the pedestrian's trust in the vehicle's actions. The confidence levels can also be described as a weighting on the trust values. The following plots group together each scenario at the stated confidence level.

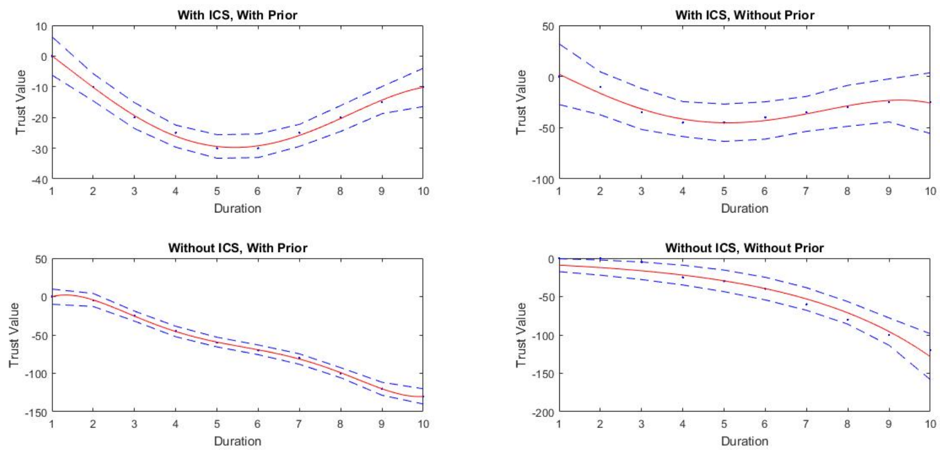

Figure 6.4: 20 Percent Confidence Level

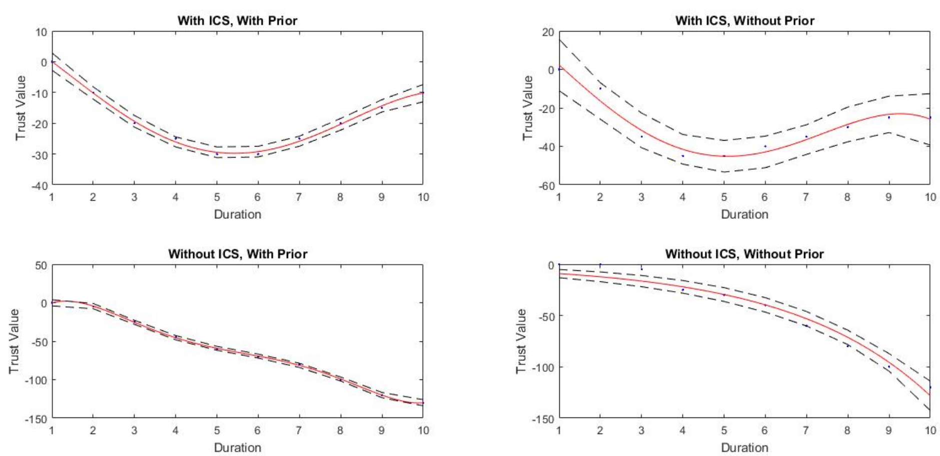

Figure 6.5: 40 Percent Confidence Level

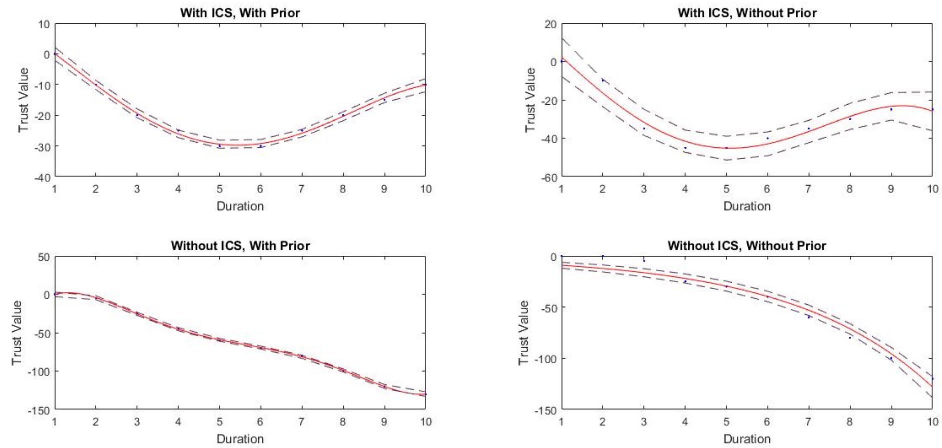

Figure 6.6: 60 Percent Confidence Level

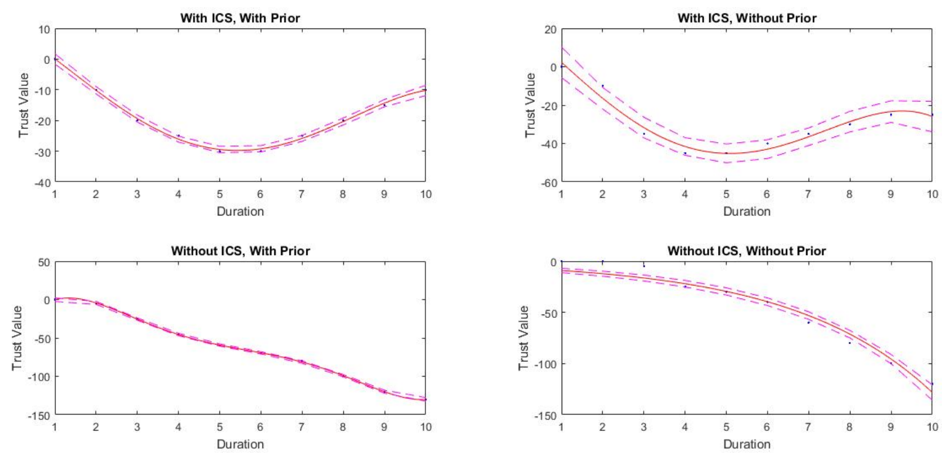

Figure 6.7: 80 Percent Confidence Level

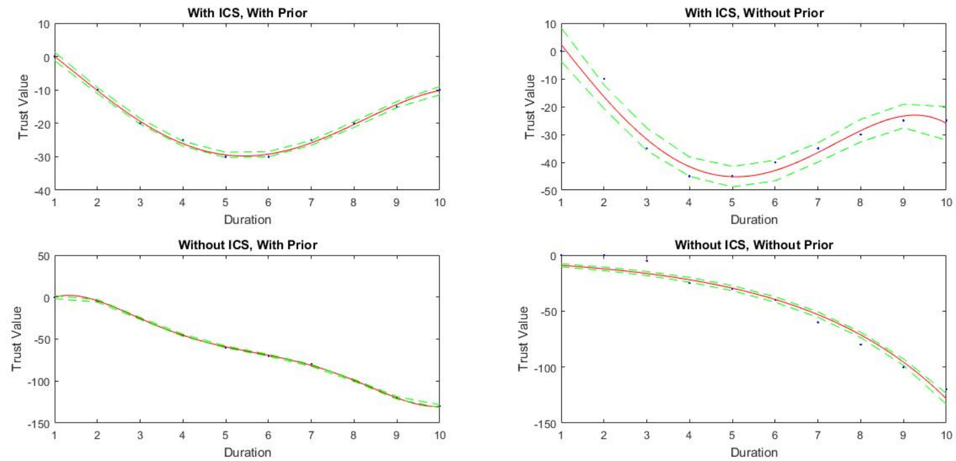

Figure 6.8: 99 Percent Confidence Level

The confidence level plots reveal that as the pedestrian's confidence improves, the trust values have less variance from the baseline. The largest variance is seen in the With ICS, Without Prior scenario, while the smallest variance is seen in the Without ICS, With Prior scenario.

The most interesting finding from the simulations was that no matter what scenario the pedestrian was in, the trust value was always negative with some having larger trust gains than others. This reinforces what was seen in the real world experiments. Although the range of actions was larger in the simulation, the real world participants showed a form of hesitation at some point in time during their interaction with the golf car. The survey conducted after each participant finished was a good indicator of how they viewed the golf car, but the simulations show that there may be an underlying difference between how people report they feel about autonomous cars and how they actually view them. It should also be noted that the pre-survey results provided a broader range of actions than the real world experiment. The pre-survey allowed people to express what they thought they would do without having any fear of being harmed, thus allowing for more creative answers.

Chapter 7

Conclusions and Future Work

7.1 Conclusion

Our results clearly demonstrate through experimentation that an ICS can help in resolving potentially dangerous and inefficient deadlock situations by 38 percent. This result comes from a survey question directly asking about if a deadlock situation was observed. This value is based on 10 out of the 26 participants noting this in their surveys. Both the real world testing and simulations were designed to evaluate how trust is affected and quantified when a pedestrian encounters and autonomous vehicle. It was seen that trust is dependent on how comfortable a human is around the vehicle, how much prior knowledge they have of the vehicle, the distance the vehicle is away from the human, among other factors. While this is true for most machinery, this is one of the first tests involving autonomous vehicles that confirms this holds true for type of vehicle-human interaction. In general, those individuals who had more knowledge about the workings of the intent communication system (ICS) were more likely to trust the vehicle than those who had never seen the ICS or the vehicle. The simulations, which were based on data taken from the real world experiments, provided a safe environment to test more risky pedestrian behaviors, including the pedestrian getting into the vehicle or not noticing the vehicle. The simulations showed that as the pedestrian interacts with the vehicle, trust levels fluctuate but never leave the negative region which shows the underlying skepticism people have of autonomous vehicles at this point since the same group of people would not have been affected in this way if they were just interacting with a regular golf car.

In the 4 scenarios tested, the individuals in the groups which had prior knowledge of how the ICS worked had approximately 10 percent (Group 1 compared to Group 2) and 6 percent (Group 3 compared to Group 4) higher trust in the golf car than the groups who hadn't seen the ICS before the experiment. The groups who had the ICS enabled, regardless of prior exposure had a 33 percent (Group 1 compared to Group 3) and 24 percent (Group 2 compared to Group 4) higher trust in the golf car than the groups that didn't have the ICS enabled.

To handle a potential deadlock situation where neither the autonomous vehicle or pedestrian will move, the intent communication system (ICS) was developed and implemented. The ICS concisely tells the pedestrian what to do through visual and audio signals. The purpose of the ICS is to compensate for the dialog that takes place between a driver and pedestrian so that they can both safely continue on their individual paths.

In order to learn more about how trust between the pedestrian and vehicle develops, a simulation model was created using a Dec-MDP to represent the relationship between the two agents. The variables that changed during the simulations were on the pedestrian due to the fact that the vehicle is programmed to perform a specific way when it encounters different obstacles. The simulations allowed for more diverse situations than could be safely created in a real world environment.

The study after the real world experiment provided crucial information about how people perceive autonomous vehicles. The groups who had the ICS enabled were more likely to trust the vehicle, but they also had slight hesitation in crossing in front of it. The groups that had the ICS disabled were more likely to not trust the vehicle and they had considerably higher hesitation. Some of the key findings were that when people were introduced to the technology beforehand, they were more likely to trust it, people had a different view on the vehicle before and after interacting with it, and they sometimes felt like the ICS was a threat because they saw it as a replacement for human drivers.

After studying the results of the passenger surveys, it was surprisingly easy to gain their trust in the car. 93 percent of participants felt like they knew what the car was doing based solely on the HUD.

7.1.1 Future Work

Areas where improvement can be made include: a better study to understand how to increase trust between pedestrians and autonomous vehicles, introduce more than one pedestrian at a time into experiments in either real world tests or simulations, and to study what people expect from autonomous vehicles to better design systems around them.

Another area worth researching is how risk can be factored into the calculations for trust. Risk research involves both confidence and trust levels based on model specifications and there is a larger body of work supporting it. The real world experiments could also be altered to include how much difference in trust there is between a human driver and an autonomous car.

There are numerous other parameters that can be changed in the real world testing. For example, comparing trust results between an autonomous vehicles and vehicles operated by a human driver could reveal more areas for improvement of the ICS. Also, having participants that are not familiar with the conductor of the experiments could also slightly change the results as they won't have a bias on what they think is expected of them. The experiments can also introduce more than one pedestrian at a time to the autonomous vehicle, giving an even more realistic scenario. Having the experiment take place in daytime would have an effect on the results as the car would be more visible. The pedestrian detection software could also be changed to another algorithm instead of HOG to give potentially different results. Testing the passenger responses in the real world would most likely give more accurate results than the stationary experiments as well.

For simulated experiments, introducing the concept of risk could also provide some important insights to trust between autonomous vehicle and pedestrian. Having more than one pedestrian in the simulation could possibly provide more realistic results. Changing from a Dec-MDP model to a risk model could also reveal more about how humans see robots' role in society.

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APPENDIX A

Acronyms

Acronym	Expanded Version
ICS	Intent Communication System
MDP	Markov Decision Process
POMDP	Partially Observable Markov Decision Process
Dec-MDP	Decentralized Markov Decision Process

A.1 Pedestrian Surveys

Please rate the following questions on a scale of 1-5 with 5 being the highest:

1) Communication was adequate
1 2 3 4 5
2) Communication was clear
1 2 3 4 5
3) Communication was effective
1 2 3 4 5
4) I trust the communication of the car
1 2 3 4 5
5) I trust the car to make the appropriate actions
1 2 3 4 5
6) I trust the car more because it communicates
1 2 3 4 5
7) I trust the car more than a human driver
1 2 3 4 5
8) I feel safe around the car
1 2 3 4 5

Please answer the following questions yes or no:

9) Did the car do what you expected it to do?
yes no
10) Did you behave how you expected when confronted with the car?
yes no
11) Was the intent of the car clear?
yes no
12) Did the intent communication create trust in what the car would do?
yes no
13) Did you feel the car was safer with/without intent communication?
yes no
14) Did you feel the car was more predictable with/without intent communication?
yes no
15) Did you feel like the car was trying to replace people or work with people?
replace work with
16) Did you trust the car more with/without intent communication?
yes no
17) Did you feel the car knew what you were going to do?
yes no
18) Did you feel there was a time where neither you nor the car would move?
yes no
19) Did you trust the car more or less after interacting with it?
more less

WOO

Please rate the following questions on a scale of 1-5 with 5 being the highest:

1) Communication was adequate

1 2 3 4 5

2) Communication was clear

1 2 3 4 5

3) Communication was effective

1 2 3 4 5

4) I trust the communication of the car

1 2 3 4 5

5) I trust the car to make the appropriate actions

1 2 3 4 5

6) I trust the car more because it communicates

1 2 3 4 5

7) I trust the car more than a human driver

1 2 3 4 5

8) I feel safe around the car

1 2 3 4 5

Please answer the following questions yes or no:

9) Did the car do what you expected it to do?

yes no

10) Did you behave how you expected when confronted with the car?

yes no

11) Was the intent of the car clear with/without intent communication?

yes no

12) Did the intent communication create trust in what the car would do?

yes no

13) Did you feel the car was safer with/without intent communication?

yes no

14) Did you feel the car was more predictable with/without intent communication?

yes no

15) Did you feel like the car was trying to replace people or work with people?

yes no

16) Did you trust the car more with/without intent communication?

yes no

17) Did you feel the car knew what you were going to do?

yes no

18) Did you feel there was a time where neither you nor the car would move?

yes no

19) Did you trust the car more or less after interacting with it? No comm

yes no

Please rate the following questions on a scale of 1-5 with 5 being the highest:

1) Communication was adequate

1 2 3 4 5

2) Communication was clear

1 2 3 4 5

3) Communication was effective

1 2 3 4 5

4) I trust the communication of the car

1 2 3 4 5

5) I trust the car to make the appropriate actions

1 2 3 4 5

6) I trust the car more because it communicates

1 2 3 4 5

7) I trust the car more than a human driver

1 2 3 4 5

8) I feel safe around the car

1 2 3 4 5

Please answer the following questions yes or no:

9) Did the car do what you expected it to do?

yes no

10) Did you behave how you expected when confronted with the car?

yes no

11) Was the intent of the car clear with/without intent communication?

yes no

12) Did the intent communication create trust in what the car would do?

yes no

13) Did you feel the car was safer with/without intent communication?

yes no

14) Did you feel the car was more predictable with/without intent communication?

yes no

15) Did you feel like the car was trying to replace people or work with people?

yes no

16) Did you trust the car more with/without intent communication?

yes no

17) Did you feel the car knew what you were going to do?

yes no

18) Did you feel there was a time where neither you nor the car would move?

yes no

19) Did you trust the car more or less after interacting with it?

yes no

Please rate the following questions on a scale of 1-5 with 5 being the highest:

1) Communication was adequate

1 2 3 4 5

2) Communication was clear

1 2 3 4 5

3) Communication was effective

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1 2 3 4 5

8) I feel safe around the car

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Please answer the following questions yes or no:

9) Did the car do what you expected it to do?

yes no

10) Did you behave how you expected when confronted with the car?

yes no

11) Was the intent of the car clear with/without intent communication?

yes no

12) Did the intent communication create trust in what the car would do?

yes no

13) Did you feel the car was safer with/without intent communication?

yes no

14) Did you feel the car was more predictable with/without intent communication?

yes no

15) Did you feel like the car was trying to replace people or work with people?

yes no

16) Did you trust the car more with/without intent communication?

yes no

17) Did you feel the car knew what you were going to do?

yes no

18) Did you feel there was a time where neither you nor the car would move?

yes no

19) Did you trust the car more or less after interacting with it?

yes no

Please rate the following questions on a scale of 1-5 with 5 being the highest:

1) Communication was adequate

1 2 3 4 5

2) Communication was clear

1 2 3 4 5

3) Communication was effective

1 2 3 4 5

4) I trust the communication of the car

1 2 3 4 5

5) I trust the car to make the appropriate actions

1 2 3 4 5

6) I trust the car more because it communicates

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A.2 Passenger Surveys

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yes no

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yes no

8) I understood what the car was doing because of the display

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VITA

Milecia Cherelle Matthews

Candidate for the Degree of

Master of Science

Thesis: INTENT COMMUNICATION BETWEEN AUTONOMOUS VEHICLES AND HUMANS

Major Field: Mechanical and Aerospace Engineering

Biographical:

Education:

Completed the requirements for the Master of Science in Mechanical and Aerospace Engineering at Oklahoma State University, Stillwater, Oklahoma in May, 2016.

Completed the requirements for the Bachelor of Science in Mechanical Engineering at Oklahoma State University, Stillwater, Oklahoma in 2014.

Experience:

Engineering Intern at Linde Process Plants in 2015
Teaching Assistant at Oklahoma State University in 2013 - 2014

Professional Memberships:

American Association of University Women – Selected Professions Fellow
National Science Foundation – Bridge to Doctorate Fellow
National Society of Black Engineers – Graduate Adviser