Modeling Pedestrian Traffic in the Presence of Unmanned Mobile Robots

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Abstract

Interactions between pedestrians and robots are becoming more commonplace. In public areas, for example, robots may be used for information dissemination, security, or patrol tasks. Based upon existing literature in the field of human-robot interaction, the ISAPT simulation system was revised to model pedestrian behavior in the presence of an autonomous robot. Using an agent based modeling approach, pedestrians are statistically assigned one of four reported behaviors when a robot is encountered: stop to interact, stop to observe, slow down to look, and uninterested. The modeling methods for incorporating these behaviors include modifying a pedestrian’s existing agenda, while the pedestrian continues to make navigation decisions based on their overall utility function. Simulation results demonstrate effective integration of the ISAPT system’s added capability of modeling pedestrian-robot interaction. These results illustrate an effective means for adding this capability to microsimulation modeling systems.

Keywords
Pedestrian traffic, microsimulation, mobile robot

1. Introduction
With the rising popularity of mobile robots for various applications, we are now beginning to see them appear in public settings involved in such tasks as information assistance, security, navigation aids, and personal assistants. One question that arises is how the presence of mobile robots impacts pedestrian traffic. This paper reports on efforts to model the reaction of pedestrians within a general public setting. These reactions are based on what has been reported from observational studies reported in the literature. The basis for this work is the extension of the capabilities of an existing microsimulation system, ISAPT, so as to incorporate these new modeling capabilities. The ISAPT (Intermodal Simulator for the Analysis of Pedestrian Traffic) system was originally developed for the purpose of modeling pedestrian traffic within intermodal facilities, so that designers may evaluate the impact of building design on the level of service provided [1-3]. This paper begins with a review of pedestrian simulation followed by a section discussing the results of the observation studies on human-robot interaction in public settings. The fourth section then presents the methodology used for modeling the pedestrian behavior followed in the fifth section with simulation examples of various significant scenarios. The last section provides a summary of the work and presents ideas for future research.

2. Background
The modeling and simulation of pedestrian traffic and crowd behavior has been a popular area of research over the last decade. These microsimulation systems have been applied to such areas as transportation facility design [4], evacuation modeling [5], and safety assessment [6]. Several common approaches that have been employed for pedestrian simulation include cellular automata models, social force models, and agent-based models.

The cellular automata approach defines the area to be simulated as a 2D grid of equal sized cells where each cell is in one of several states (e.g., empty, occupied by pedestrian, occupied by object type x, etc.). The state of each cell is updated at each discrete time step based on the states of surrounding cells and the evaluation of a set of rules. Cellular automata was already being applied to vehicular traffic flow, when Blue and Adler [7] began investigating its application to pedestrian flow modeling. Although cellular automata systems are not as commonly employed as other approaches, due to its computational simplicity this approach is favored by some for large scale systems comprised of large populations, such as the ship evacuation system developed by Roh and Ha [8].
Social force models define the movement of each pedestrian based on its response to a set of attractive and repulsive forces in its environment using a series of nonlinearly coupled Langevin equations. Attractive forces within the model would include a pedestrian’s destination, other pedestrians identified as friends (e.g., walking together) or objects in the environment they want to be near (e.g., window displays). Repulsive forces include other pedestrians (to avoid collision) as well as statics objects (e.g., walls, furniture, etc.). The strength of these forces is defined by such factors as object type, distance, and location within the defined simulated area. This approach was first introduced by Helbing and Molnar [9] to illustrate its ability to reproduce the self-organizing behavior of pedestrian traffic. This approach is still commonly used for a variety of pedestrian simulation applications such as behavior analysis at signalized crosswalks [6].

The third common approach, agent based modeling, uses virtual agents to represent each pedestrian which are each driven by a set of rules that governs the interaction between the agents of the system. Each pedestrian is a fully autonomous entity operating within an environment with other pedestrians, out of which arises collective behavioral patterns with an ability to replicate observed traffic patterns. Some recent examples agent based pedestrian simulation systems include the system developed by Wagner and Agrawal [10] for modeling concert venues to test and assess alternative disaster scenarios with respect to emergency evacuation of the facility, and the system of Pluchino et al. [11] which models the Castello Ursino museum in Italy to assess facility capacity and visitor safety when faced with emergency evacuation.

3. Pedestrian-Robot Interaction in Public Settings

A review of the literature was conducted to identify existing studies related to the interaction between pedestrians and robots in public spaces. The literature results served as a basis for the simulation model. The literature review on human robot interaction in public settings produced results from three primary sources which are pertinent to this study. The first source involves E.T. Hall’s work with proxemics, and the other two sources were empirical studies of human behavior toward robots.

The work of E.T. Hall addressed the spacing of people during communication, which he called proxemics [12, 13]. Hall proposed classifying the distances between people into four categories: intimate (<1.5 ft), personal (1.5-4 ft), social (4-12 ft), and public (12-25 ft). Later research by Walters et al. [14, 15] shows that those classifications are applicable to human robot interaction. These distances are helpful for defining how close pedestrians will get to the robot in the current simulation model.

Empirical studies have also been conducted that provide our model with useful quantification of pedestrian behavior in the presence of a robot. The first of these studies was done by Bergstrom et al. [16] in a shopping mall. For this study, a robot, which could rotate but not travel, was placed next to a pair of escalators. Researchers watched and recorded pedestrians’ behavior toward the robot. Pedestrian behavior towards the robot was categorized as being not interested, indecisive, hesitating, or interested in the robot. The four behavior categories along with the percentage of pedestrians falling in each category were:

- **Not Interested (53%)**: People coming in from the side walking towards the robot, but diverting from the robot and passing it. They are not slowing down, something that could have indicated an interest in the robot.
- **Indecisive (13%)**: People walking in front of the robot, but when slowing down or making a brief stop when doing so, thus indicating their interest in the robot.
- **Hesitating (27%)**: People who have been walking slowly and who stopped in front of the robot and faced it. Someone standing for three seconds or more was classified as hesitating.
- **Interested (7%)**: People coming from any direction and approaching the robot directly all the way to start an interaction.

The other empirical study was performed by Kidokoro et al. [17] in a Japanese shopping mall. For this study, a robot was allowed to travel back and forth on a predefined course, and pedestrians’ behaviors toward the robot were recorded. Researchers described pedestrian behavior towards the robot as stop to interact, stop to observe, slow down
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to look, or uninterested. The four behavior categories along with the percentage of pedestrians falling in each category are:

- **Stop to interact (STI) (11.39%)**: People who approach the robot and stop to interact at a social distance of 3 feet or less, and stay there for a while.
- **Stop to observe (STO) (11.48%)**: People who stop to observe the robot outside of the social zone of 3 feet or less.
- **Slow down to look (SDL) (8.07%)**: People who slow down to look at the robot, but do not change their course or stop.
- **Uninterested (69.06%)**: People who show no interest toward the robot.

Based on this review, it was determined that in our model there should be an outer boundary of 25 feet set around the robot for possible meaningful interaction. There should be four categories within the 25 foot boundary; the categories are: stop to interact (STI), stop to observe (STO), slow down to look (SDL), and uninterested. Each pedestrian who enters the 25 foot boundary will be statistically assigned a category. The pedestrians who are “uninterested” will not change their behavior. The pedestrians who “slow down to look” will change direction when entering the 25 foot radius around the robot to pass through the 4-12 foot radius and slow down 25% of their original speed while passing through. The pedestrians who “stop to observe” will change direction when entering the 25 foot radius around the robot, continue to the 2-4 foot radius, and then wait 10 seconds before continuing on. The pedestrians who “stop to interact” will change direction when entering the 25 foot radius around the robot, continue to the 0-2 foot radius, and then wait 30 seconds before continuing on.

4. Modeling Methodology

4.1 The ISAPT System

The ISAPT system used in this study is an agent based system that simulates the behavior of each individual pedestrian in the system. Each pedestrian moves in continuous 3D space within the simulated environment employing probabilistic navigation at the local level and route based planning at the strategic level. Each pedestrian’s purpose within the environment is defined by an agenda that contains a list of activities they intend to complete during their trip. For more details on the navigation and planning components the reader is referred to [1, 2].

The simulation uses a fixed time advance mechanism with a user-defined time step. The user provides a graphical 3DS file containing the fixed geometry representing the facility and a network of nodes defining the resource positions along with entry and exit positions within the facility [18, 19]. As the system runs, it provides the user with a 3D graphical view of the pedestrian traffic within the facility allowing them to move around the facility and zoom in and out to view areas in greater detail (see Figure 1). XML files are used to provide the input data for the simulation. Each pedestrian is uniquely defined by a set of attributes (i.e., gender, size, desired speed, etc.) and an agenda (including their starting location). These pedestrians can either each be defined one at a time explicitly, or auto-generated randomly from a population whose attributes are defined by various population statistics.

Once a pedestrian enters the system, they will work through their agenda traveling from one location to another carrying out functions at various resources representing such entities as shops, restaurants, waiting areas, information kiosks, etc. Route based planning takes care of defining a route from one resource to the next, but it is at the local level where real-time navigational issues arise.
4.2 Pedestrian Navigation

Given a destination, it is the responsibility of a pedestrian’s navigation system to successfully move through its simulated environment to reach that destination taking into account both the stationary and dynamic objects in its path. The basic idea of the navigational system is to provide each pedestrian agent with a range of alternative decisions they can choose from for their next step. The field of view of a pedestrian is divided into 11 different sized angular sectors illustrated in Figure 2. These sectors represent the different directions the pedestrian could take for their next step. However, when circumnavigating a person actually has the choice to change their direction, speed, or both. A change in speed is denoted as three zones in each sector of the pedestrian’s field of view representing that they either slow down by 50%, stay at the same speed, or increase their speed by 50%. Including the ability for the pedestrian to stop, results in a total of 34 possible alternative actions a pedestrian must decide between at each iteration.

Given the availability of alternative actions that a pedestrian can choose from, the system employs a utility function to assess the value of each alternative taking into account the current status of its environment (both static and dynamic entities). The utility function is a weighted sum of individual utility factors that each focus on some characteristic that influences a pedestrian’s navigational decisions. This equation is an outgrowth of the work by Antonini et al. [20] and Robin et al. [21]. The overall utility function is:

\[
\text{Utility} = w_1 U_{\text{KD}} + w_2 U_{\text{TD}} + w_3 U_{\text{FF}} + w_4 U_{\text{CF}} + w_5 U_{\text{CN}} + w_6 U_{\text{PA}} + w_7 U_{\text{OA}}
\]  

(1)

The individual utility factors include a desire for a pedestrian to keep their current travel direction (KD), make progress towards their current destination (TD), travel at their desired free-flow speed (FF), consider the influence of crowd following (CF), navigate the corridor (CN), while avoiding collisions with other pedestrians (PA) and obstacles (OA). Additional discussion of the details of these factors can be found in [2]. So, given a pedestrian’s knowledge of their environment, the utility value of each discrete movement alternative is computed. However, to simulate pedestrians’ incomplete knowledge or attention in decision-making, a probabilistic approach is employed to determine which alternative is selected. The actual utility values of the alternatives, \( U_i \), represent random variables and the probability of that alternative being the best is computed using a multinomial logit (MNL) model that defines the probability a pedestrian chooses each alternative from among the set of alternatives. These probabilities are normalized on a scale of [0, 1] where the higher the utility the greater the probability of an alternative. A uniform random number is then generated to determine which option is selected. Therefore, just like any person may do in actuality, it is possible for a simulated pedestrian to select a movement that is not necessarily the best, resulting in such actions as “bumping” into another pedestrian.

4.3 Navigation in the Presence of Mobile Robots

When the original utility equation was created, we had not thought about how pedestrians would interact with dynamic, unfamiliar entities, like robots, while navigating through a corridor. The main foci were addressing the behavior of pedestrians interacting with other pedestrians and their environment. One of the strengths of using the utility equation is the ability to tack on other utility factors that do not overlap with the factors currently in the equation. Therefore, a new factor was added to deal with pedestrians interacting with robots that is termed Vehicular Avoidance (VA). The VA factor needs to incorporate ways to look ahead in the pedestrian’s current path to determine how probable a collision with a robot will be. Pedestrians need to be able to choose a path that will lower their chances of such a collision occurring. Both the PA and OA utility factors do just that for pedestrians and objects, respectively. Given that the dynamic behavior of robots is similar to pedestrians, the VA utility factor borrows heavily from the PA utility factor. The VA utility factor function is as follows:
For each sector, the number of potential collisions with robots is calculated and represented by the variable \( N_c \). The more potential collisions there are in a sector the greater the penalty the first term places on the likelihood of the pedestrian using that sector. ISAPT incorporates a user-specified \"look-ahead time\" in determining the number of potential collisions a set number of seconds into the future given the pedestrian’s and the robots' current speeds. This enables pre-emptive navigation adjustments to avoid robots if the current direction has detected them in the way. The second term takes into account the time until the most imminent collision, \( t_c \). The greater the time until an imminent collision, the more likely the sector will be selected. Testing to determine the best parameter values to use for this term has not been completed. The current values were selected based on their impact on observed behavior.

The reason for the distinction between the PA and VA utilities is that pedestrians react differently to robots than to other pedestrians. At the very least, the utility weight for VA should be different than the PA utility weight. The new utility function becomes: 

\[
U_{VA} = -(0.25N_c)^{0.5} - 0.1 \left( \frac{6}{t_c+0.02} \right)^{0.5}
\]

(2)

To ensure that the proper utility weights are restored when a pedestrian finishes interacting with a robot, all of the current pedestrian utility weights are stored when the pedestrian crosses the 25 foot boundary of a detected robot, but before any changes to the pedestrian’s behavior are made. Changes to the weights of the utility equation allows the system to change how a pedestrian behaves while in the presence of a robot. To match observed behavior, another change required for the SDL response is a change in the desired and max speeds for the pedestrian. Therefore, as with the utility weights, the current speed values are stored and restored in the same manner.

For the STI and STO cases, another oddity appeared after a pedestrian would finish interacting with a robot. The pedestrian’s original utility weights and speed preferences were restored after completing the new task and leaving the destination. The pedestrian would avoid the robot just like normal but the pedestrian’s movement leaving the robot was sharp and portrayed a sudden drastic change in behavior. To fix this issue, a delay was added that is termed \‘memory\’. The pedestrian’s original utility weights and speed preference would not be restored until the \‘memory\’ of the robot faded. The length of a pedestrian’s memory is an input parameter and value of 4 seconds was initially selected to give the pedestrian enough time to make the transition between interacting with a robot and returning to the original path seem more natural.

5. Simulation Results
As reported in literature [16, 17], most pedestrians’ response fall into the \“uninterested\” category. For this category, since there is no new agenda item nothing will happen when they are within 25 feet of the robot. The only robot-related interaction the \“uninterested\” pedestrians may have in the simulation is to avoid walking into the robot if they happen to get close enough to the robot as they execute their current agenda task. Figure 3 shows the pedestrian (entity
with the number 2 near it) ignoring the robot (entity with the number 1 near it) as it continues on its current agenda task. Figure 3A shows the pedestrian on a path to accomplish an agenda item. Since the pedestrian is in the “uninterested” category, the pedestrian will not alter its list of agenda items which may be seen in Figure 3B and 3C as the pedestrian continues on their path unaffected by the presence of the robot. Figure 3C shows the pedestrian leaving the robot behind while having not interacted with the robot.

For the other three cases (SDL, STO, and STI) pedestrians will walk toward their new destination once they cross the 25 foot boundary around the robot. Figure 4 shows a pedestrian crossing the 25 foot boundary and turning toward the robot to start walking toward it. For these three cases, SDL, STO, and STI, the response associated with the new agenda task will result in the creation of a new destination node that is between 4-12 feet, 2-4 feet, and up to 2 feet from the robot, respectively. As a part of the new task the pedestrian’s VA utility factor weight is altered. Given this new task node, the pedestrian will start moving toward the node’s position instead of the destination of the pedestrian’s preempted task. The pedestrian’s walking speed toward his new destination node will be affected based on the selected response. The only response case that currently affects speed is SDL which slows the pedestrian to 25% of their prior speed preference.

When the pedestrian has reached the new node one of two actions will occur. The pedestrian will either continue on to his original destination or the pedestrian will stop and face the robot. The SDL response will cause the pedestrian to continue on to his original destination but will maintain the reduced speed and altered utility weights until the memory of the robot fades. For both the STO and STI cases the pedestrian has to stop in order to watch or interact with the robot.
with the robot. Figure 5 shows a pedestrian observing a robot in the STO case. Currently the stop time is set to 10 seconds for the STO case and 30 seconds for the STI case, but both of these wait times are modifiable by an input parameter controlled by user (which can also be set to a random value based on a specified distribution). While stopped at the new destination the pedestrian’s “front” will face the robot so as to give the appearance of observing or interacting with the robot. Once the time interval has been completed for either the STO or STI cases, the pedestrian will continue on with the prior (preempted) task with the utility weights being restored once the memory of the robot fades. Figure 6 shows a pedestrian walking continuing on their journey after interacting with the robot. The pedestrian walks close to the robot in Figure 6 because the VA utility weight is still low which shows a lingering interest in the robot.

6. Conclusions
In comparing the simulation results to behaviors reported in literature, the simulated behaviors appear to be a valid representation of actual behaviors. The high incidence of uninterested pedestrians reported in literature has been successfully operationalized in the simulation. Pedestrians will continue pursuing their original tasks, not slowing down or interacting with the robot. For observing and interaction behaviors, the pedestrian’s speed and/or path are modified to attend to this behavior. Empirical studies have demonstrated the presence of these behaviors in real-world settings. The simulation settings can be modified to allow for additional parameters related to pedestrian-robot interaction, such as dwell time and speed change.

The modeling methods used effectively integrated pedestrian-robot interactions into the existing ISAPT system. The enhanced capability of the system will be beneficial as additional use-cases are presented. For example, the impact of additional autonomous vehicular navigation aids on pedestrian flow in an airport can be explored. Additional enhancements to the system are possible, including modeling pedestrian group behavior, mobile robots, and robot-person companion groups. Future expansions will be based on existing literature or empirical data related to human-robot interaction.

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