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MODELING PEDESTRIAN MOVEMENT IN A CROWD CONTEXT WITH URGENCY PREEMPTION

Susan K. Aros[1], and Dale Frakes[2]

[1]Operations Research Dept., Naval Postgraduate School, Monterey, CA, USA
[2] Systems Science Program, Portland State University, Portland, OR, USA

ABSTRACT

Realistic crowd modeling is essential for military and security simulation models. In this paper we address modeling of the movement of people in the types of unstructured crowds that are common in civil security situations. Early approaches in the literature to simulating the movement of individuals in a crowd, typically treated the crowd as consisting of entities moving on a fixed grid, or as particles in a fluid flow, where the movement rules were relatively simple and each member had the same goal, such as to move along a crowded sidewalk or to evacuate through an exit. This paper proposes a 2-part approach for more complex pedestrian movement modeling that takes into account the cognitively-determined behavioral intent of each member of the crowd to determine their own movement objective while also allowing each to temporarily react to a short-term urgent situation that may arise while pursuing their movement goal.

1 INTRODUCTION

There are many approaches to modeling and simulating the movement of individuals in a crowd. In early approaches, crowds were often modeled as if they were made up of entities moving on a fixed grid, or as particles in a fluid flow, where the movement rules were relatively simple and each member has the same goal, such as to move along a crowded sidewalk or to evacuate through an exit. Helbing's Social Force Model (SFM) (Helbing and Molnár 1995) adds more complexity, allowing each member of a crowd to weigh different objectives and choose a movement option that considers multiple influences on their movement. While this approach represents a significant advancement, additional realism is needed to more accurately model human movement in models that represent more complex situations and possible human behaviors. This paper proposes a 2-part method of pedestrian movement planning that takes into account the many influences on an individual's overall movement goal while also allowing them to temporarily adjust and respond to short-term urgent situations that may arise while pursuing their overall movement goal.

We describe our movement modeling approach in the context of a simulation tool called Workbench for refining Rules of Engagement against Crowd Hostiles (WRENCH), developed at the Naval Postgraduate School. WRENCH is an agent-based simulation model, coded in NetLogo (Wilensky 1999), that models interactions between potentially hostile crowds and a security force (Aros et al. 2021). WRENCH models individual people as members of dynamic groups within a population that may become a hostile crowd. WRENCH can be used to assess the effects of the security force's use of various non-lethal intermediate force capability weapons under different tactical rules of engagement (ROE) and escalation of force (EOF) guidelines. Agents in WRENCH are endowed with detailed physical, emotional, and social needs, along with human-like cognitive processing in order to achieve a more realistic simulated behavior of diverse crowds. An extensive variety of scenarios can be simulated in WRENCH, producing outputs on a wide range of performance metrics (Aros and McDonald 2023a; Aros and McDonald 2023b).

The main contribution of this paper is a pedestrian movement algorithm that incorporates the evaluation of a longer-term objective (e.g. moving to a specific location to protest) by each agent while allowing them to react to urgent diversions in the short-term. A 2-part decision-making process is proposed where an agent moves about according to a movement goal that has been determined based on their behavioral intent, which is the output of a complex cognitive process and is updated periodically, while also considering urgent, emergent situational factors when deciding how to move. A major benefit of this method is that temporary urgent situational conditions do not cause a simulated person to 'forget' their overall behavioral intent, thereby providing greater continuity in their behavior over time.

This paper proceeds as follows. First, we discuss relevant literature, and then provide more information about the simulation context for our movement modeling approach. Next, we provide an overview of the individual's movement context, i.e. the generation of a behavioral intent, before proceeding with the main topic of the paper: movement modeling with urgency preemption. We then provide additional discussion and conclusions.

2 LITERATURE REVIEW

Literature pertaining to the modeling of collision avoidance as simulated people move about is quite extensive, as is literature about modeling movement actions taken toward a single goal such as evacuating a building or moving away from an explosion. However, literature pertaining to the modeling of an agent that is acting on one of a variety of long-term goals and also immediate, urgent situational factors, is sparse. The essential components of modeling the movement of people consist of specifying a destination goal and avoiding collisions with other agents or with obstacles. Some early efforts at modeling pedestrian movement used the cellular automata approach, modeling the pedestrian zone as a grid, with pedestrian agents moving from one cell in the grid to another, choosing from adjacent empty cells and selecting the one that moves it nearest to its movement goal (Bandini et al. 2007). This approach is mathematically straight-forward but suffers from the lack of fidelity in that pedestrians do not move from amid a grid of cells, but rather in continuous geographic dimensional space.

Many current pedestrian movement models are based on the SFM (Helbing and Molnár 1995) where the pedestrian agent can be at any location and the agent is subject to a number of attracting and repelling forces represented as vectors (with direction and magnitude), such as a vector towards a target goal, a vector away from fixed obstacles (such as buildings or walls), and vectors away from other pedestrian agents. The pedestrian agent's heading is determined by summing those "social force" vectors. Under a standard SFM, for example, the urgent need to flee from a weapon strike would be modeled as a vector in a direction away from the weapon strike; similarly, a desire to move to a particular location for a given objective would be modeled as a vector in the direction of the desired location. The person's movement would then be determined by taking a weighted sum of these vectors.

Recent advancements in social force modeling also take into consideration emotional and psychological factors. For example, Ren et al. (2023) include dynamic hazard considerations and emotional contagion in emergency situations using a panic-generation process driven by direct perception of danger and from other agents disseminating panic. Deng et al. (2024) incorporate a virtual repulsion force to model the psychological role in determining individual movement in crowds facing a hazardous situation. Ding et al. (2024) incorporate psychological influences by modeling psychological forces resulting from the *Time-Headway* force (the force resulting from the wish to be a certain movement time away from an object or obstacle) along with the collision-avoidance force. In each of these models, the additional emotional and psychological considerations are ultimately incorporated into the model as additional force vectors, or as a change to the weighting of different force vectors. These advancements bring important additions to the standard social force modeling approach; however, fundamental differences between our approach and social force modeling remain. For example, in an SFM, all of the movement drivers are still considered simultaneously, side-by-side, thereby considering short-term movement influences in the same way as longer-term movement influences.

In addition to the ways of determining the movement of a single individual, there are different ways to consider how individuals comprise a crowd. One approach is to model the movement of a structured crowd where people move in one direction with the same goal or destination (Edris 2022) such as a crowd of people evacuating a dangerous environment through the same exit. The second is the movement of an unstructured crowd where people head towards different goals or destinations. The methods of this paper are generally focused on the latter, where an example might be a large protest where some members of the crowd may wish to seek safety while others want to protest, or possibly render aid to fellow injured protesters. A simpler example could be a crowd of pedestrians on a busy city sidewalk where each is heading to a different destination of personal interest. However, the proposed approach is a hybrid in that, while the pedestrians are generally free to move about as they desire, they are also constrained by factors such as staying near a group they're a member of.

While it's not unusual for pedestrian agent simulations to decouple navigation from local collision avoidance (Kapadia et al. 2016), our proposed approach adds the additional consideration that an agent can encounter sudden and urgent situations, apart from possible collisions, that temporarily alter their navigation goal. For example, an agent may be moving to a specific location in order to protest but suddenly experience a non-lethal weapon (NLW) strike by a security force member that causes an automatic, short-term flee response but does not necessarily alter their overall objective to protest.

Turning to agent-based modeling (ABM) of pedestrian movement in the literature, there are several relevant modeling papers that involve crowd movement during protests or incorporate the SFM concept. Posadas and Teknomo (2016) develop an ABM of police officers using kettling as a crowd-control tool. This model incorporates seeking and separation force vectors to steer agents towards a desired target location while avoiding moving too close to other agents. It also adds formation-vectors allowing agents to a specific formation geometry. Hedlund and Vinsa (2022) develop a crowd control ABM where the agents move using a simpler flocking mechanism, which incorporates attractive and repulsive force vectors to maintain relative positions while moving but also adds a force vector to allow motion towards a specific goal. It then measures the effectiveness of different crowd-control tactics deployed against a rioting crowd moving under the established force model. In Hozhabrossadati (2022), an ABM is developed in NetLogo that also incorporates steering elements from the SFM to control movement of agents in a crowd. It includes elements of psychological state that incorporate the perception of hardship or grievance as well as risk-aversion based on Epstein (2002). Van Haeringen et al. (2022) conduct a review of agent-based simulation of crowds, particularly focusing on emotional contagion. They determine that such models can generally be grouped by their approach to modeling emotional contagion such as: 'group statistic' where an agent's state is determined by a measure of their neighbors' states, epidemiological where emotional contagion is modeled as an infection that spreads, and 'dyadic relations' where emotional exchanges occur between pairs of agents when they interact (Van Haeringen et al. 2022).

3 MODELING CONTEXT: WRENCH

The Workbench for refining Rules of Engagement against Crowd Hostiles (WRENCH) is a simulation tool for examining the effectiveness of a security force in managing a crowd of civilians, some of whom may have hostile intent. The initial application of WRENCH was to address questions regarding the use of NLWs, particularly addressing weapon selection and rules of engagement. The goal is to effectively deescalate potentially violent situations while maintaining force legitimacy. In terms of the PMESII-PT framework, WRENCH explicitly models the Military, Social, Physical, and Time aspects.

WRENCH is constructed as a stochastic agent-based simulation model, essentially a complex adaptive system. It is a bottom-up model, where each agent's internal construction determines its responses to interactions with other agents and changes in the environment. Each individual person and security force member is modeled in detail, including having its own demographic characteristics, emotions, needs, experiences, perceptions, intentions, behaviors, and possibly group membership. Additionally, each group is modeled as having constituents, needs, intentions, and possibly a higher-level group identification.

A typical WRENCH scenario includes a variety of people moving about a specific geographic area while security forces maintain the security of the area. People who have increasing anger, unmet needs, or hostile intentions may develop hostile behavior toward the forces. Once a crowd begins to form and exhibits hostile behavior, the forces engage the crowd according to the rules of engagement specified for the scenario, utilizing the weapon options made available for the scenario.

WRENCH has been developed for modeling civil security missions and is currently set up to model a compound security mission, though it can be adapted to operate with different scenarios and in different locations. The compound security mission is modeled at a focused, tactical level with a map that includes a portion of an urban area with roads and buildings and a small compound in the center that contains several buildings. WRENCH has been used to model scenarios with hundreds of civilians and multiple security force patrol units, along with the compound security unit, across a wide variety of input parameters. Aros and McDonald (2023a) provides an example of a WRENCH experiment, funded by the Joint Intermediate Force Capabilities Office, which demonstrates insights WRENCH can offer for security forces that engage in civil security missions.

While WRENCH is a complex agent-based model covering many different aspects of crowd behavior, the focus of this paper is on the movement determination of the people agents as they decide how to move in order to act on their behavioral intent. For example, a person will need to make movement choices to act out an intention such as protesting or rendering aid to another, while also reacting to urgent circumstances that arise.

4 MOVEMENT PRECURSOR: BEHAVIORAL INTENT DETERMINATION

In WRENCH, a civilian individual is modeled with a combination of a Person agent and an Identity agent, where the Person agent represents essentially the physical body of the individual, interacting with the environment and other agents, while the Identity agent represents the non-physical aspects of the individual. Therefore, much of the behavioral decision-making is undertaken by the Identity agent, which results in the determination of a *behavioral intent* that is then acted on by the Person agent resulting in movement of the individual.

The focus of this paper is on the movement of the Person agent as they act on the behavioral intent of the individual, but first we provide a very brief overview of how the behavioral intent of an individual is determined. Figure 1 depicts the flow of the decision processing for an individual that results in the determination of the Person's behavioral intent. The process begins with the updating of the variables that track the physical and emotional status of the individual such as anger, fear, hostility, injury level, etc.

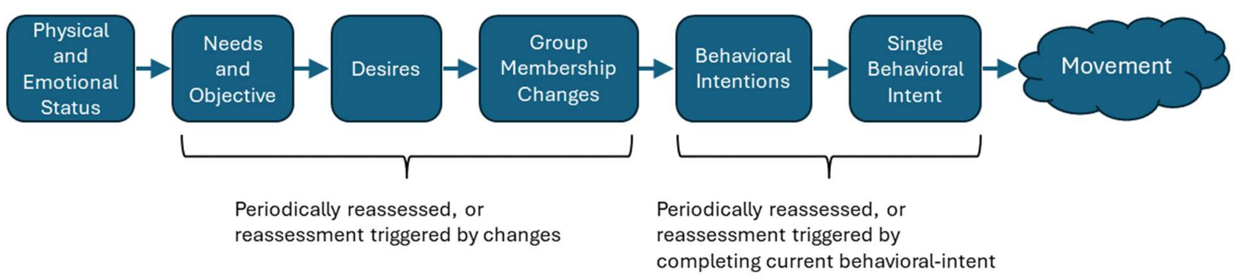

Figure 1: Origin of a behavioral intent.

Next, the levels of three different needs are updated, a simplified representation of Maslow's hierarchy of needs (Maslow 1943), and the Identity's overall objective is also reassessed. Each need level exceeding the individual's corresponding need threshold can produce a specific desire, as will the individual's objective. The individual then determines, for each desire, an intention toward satisfying that desire. This can produce up to four different behavioral intentions simultaneously, some of which may directly conflict with each other, so a set of deconfliction logic is required to produce a single behavioral intent for the Person to act on. More information on the modeling of the process that produces the behavioral intent is provided in Aros and Dyer (2025) and Dyer et al. (2024). While WRENCH runs on a 1-second time-step (tick), an individual's behavioral intent does not change every second; rather, it changes on a less frequent interval, or when circumstances have changed significantly enough to cause them to 'change their mind' about their intent. Their intent can also change once the individual has behaviorally satisfied their intent. A full listing of possible behavioral intents is provided in Table 1.

Table 1: Behavioral intents.

Behavioral Intent	Description
safety-obj	This agent has decided that they would prefer to be in a safe area, so will move in a direction away from the nearest security force member until they are out of firing range.
protest	The agent will move in proximity to the nearest gate patch and then mill about; their desired proximity to the gate depends on their own hostility level.
invade	The agent will move towards the nearest gate patch and then into the compound if possible.
find-safety	An injured agent will attempt to move away from the nearest SF member until they are out of range of lethal weapons to avoid further injuries.
seek-similar	The agent will attempt to move towards an agent they have previously identified as being similar to them
render-aid	The agent will attempt to move to a place close to an agent they have identified as someone they want to help.
victim-safety	Once an agent intending to render-aid has reached the agent they intend to help, they will help them move toward safety, away from the nearest security force member (they move together until they reach safety; the agent being helped will move with the agent helping)
wander	This is a catch-all for when none of the desires have produced a behavioral intention that calls for specific behavior. The agent will therefore move somewhat randomly about the area

5 MOVEMENT MODELING

As mentioned, a Person moves in order to act on their behavioral intent. However, changes to the individual's circumstances can also cause an urgent situation to arise that must be reacted to immediately. In an earlier version of WRENCH, an urgent situation was modeled as part of the cognitive decision-making process described above, which would result in a different behavioral intent in response to an urgent situation. However, there are some issues with that approach. First, urgent situations can arise any 1-second time-step in the simulation, and realistically a human is able to produce a basic reaction decision within 1 second; however, more complex decision-making takes more time (Madl et al. 2011). Therefore, it is not realistic to model the entire complex cognitive process of producing a behavioral decision as happening every second to determine the Person's next step, although modeling an immediate reaction within 1 second is realistic. Second, the former way of modeling the handling of urgent situations caused an either-or choice of either ignoring the urgent situation entirely, or completely 'forgetting' about their original intent when reacting to an urgent situation, both of which resulted in unrealistic behavior.

To address these issues, we introduced the modeling of two levels of behavioral considerations: behaving to act out a behavioral intent determined by the periodic complex cognitive decision-making process, or behaving in reaction to an urgent situation that has arisen. Therefore, the determination of the movement of the Person is modeled as consisting of a second-by-second evaluation of whether or not an urgent situation has arisen; if it has, then the person moved to respond to the urgent situation, and if it has not, then the person moves to act out their behavioral intent. This separation allows the Person to 'remember' their overall behavioral intent, while allowing them to react immediately to urgent situation when necessary.

Figure 2 provides an overview of the movement processing for an individual. When a Person's behavioral intent has changed, which happens periodically as described above, a suitable *goal* and *goal focus* are set to guide movement. Each tick, when the Person's next step is being determined, a check is made to see if an urgent situation has arisen; if it has then the step is determined based on the agent's reaction to the urgent situation, otherwise the step will be taken based on the Person's current goal and goal focus. There is one extra step required to be sure that the current goal and goal-focus are still suitable before taking a step, which will be explained further below. To provide an example, say a Person has determined that their behavioral intent is to protest outside a guarded compound. The goal is then set accordingly, which is to move towards an area to stage a protest near an entrance to the compound. The specific goal focus in this case would specify the exact location they intend to move to, which would be set to the nearest location that is at a specific protest distance from the nearest compound gate where the protest distance is set inverse to the Person's hostility level. A description of the goal and goal focus for each behavioral intent is provided in Section 5.1, and different urgent situations that could override the movement goal determined from the behavioral intent are described in Section 5.2: Urgency Preemption.

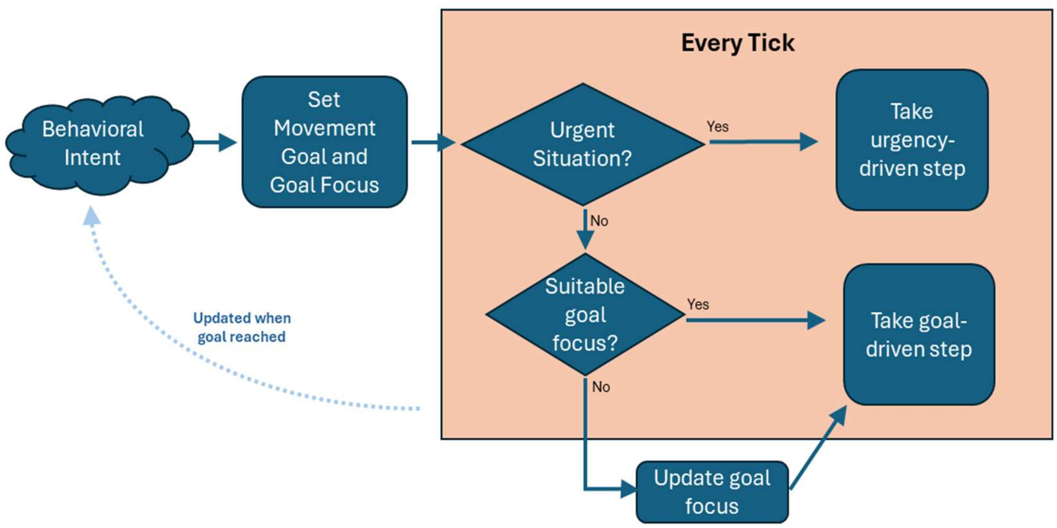

Figure 2: Simplified view of movement processing considering behavioral intent and urgent situations.

5.1 Goal and Goal Focus Determination

In determining how each behavioral intent will affect a person's movement, an explicit *movement goal* is described for each behavioral intent. Each of these movement goals will generally require movement in one of two directions – moving toward something or away from something – and will require this movement to be relative to a fixed location or to another agent that may also be moving. The combination of these results in four different movement action possibilities, as listed below.

- Moving towards a fixed geographic location
- Moving away from a geographic location
- Moving away from another agent (e.g. running away from a security force member)
- Moving towards another agent (e.g. a group leader or another agent the agent wants to join with), whether they are within sight or not in the next step

Therefore, to make a move toward satisfying a movement goal, each individual must identify the movement direction, as well as identifying the location or agent they must move relative to which we term the *goal focus*. Table 2 provides a description of the movement goal, goal focus, and movement direction for each behavioral intent.

Table 2: Behavioral intents and resulting movement goals and focuses.

Behavioral Intent	**Movement Goal**	**Goal Focus**	**Movement Direction**
safety-obj	move far away from members of the security force	nearest security force member	away
protest	mill about outside of the gates, at a distance reflecting own hostility level	nearby patch of desired range from gate	towards
invade	enter the compound	opening of nearest compound gate	towards
find-safety	move far away from members of the security force	nearest security force member	away
seek-similar	move toward someone who shares similarities	identified similar agent	towards
render-aid	go help an injured agent	most compelling nearby injured agent	towards
victim-safety	help injured agent move far away from members of the security force	nearest security force member	away
wander	meander about the area	anywhere ahead	any

The code algorithm for setting the goal focus and movement direction is provided in Figure 2. As can be seen in Figure 3, if an individual has no driving behavioral intent, they will just ‘wander’ and may move in any direction, generally continuing in the direction they are currently facing.

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Algorithm Set Goal Focus and Movement Direction
Require: Behavioral-Intent                          ▷ Already established elsewhere
if Behavioral-Intent ∈ {“safety-obj”, “find-safety”, “victim-safety”} then
    Goal-Focus ← “nearest security force member”
    Movement-Direction ← “away”
else if Behavioral-Intent ∈ {“protest”} then
    Goal-Focus ← “nearby patch of desired range from gate”
    Movement-Direction ← “towards”
else if Behavioral-Intent ∈ {“seek-similar”} then
    Goal-Focus ← “identified similar person”
    Movement-Direction ← “towards”
else if Behavioral-Intent ∈ {“render-aid”} then
    Goal-Focus ← “most compelling nearby injured person”
    Movement-Direction ← “towards”
else if Behavioral-Intent ∈ {“wander”} then
    Goal-Focus ← “any direction”                    ▷ randomly chosen
    Movement-Direction ← “towards”
end if
```

Figure 3: Algorithm to set goal-focus and movement-direction.

Additional details about the goal focus should be mentioned. First, while the distinction between a fixed-location goal focus and a goal focus of another agent may seem minor, it is an important distinction when considering whether the goal focus needs to be updated. The distinction is most important when considering a movement goal toward another agent that is also moving – once the agent being followed moves out of sight, the following individual then needs to move toward the corner of the building the agent disappeared behind rather than that agent's actual location. In addition, it is possible that a moving goal focus, such as the nearest agent with a specified type/characteristic, could move beyond another agent with the same specified type/characteristic; in this case the goal focus should be updated to reflect who is now the closest qualifying agent. The check for the suitability of the current movement focus can be seen in Figure 1. A final detail is that the location of the goal focus may be specified in the form of x, y coordinates, or as a particularly specified "patch" location as defined in NetLogo. For example, 'opening of nearest compound gate' goal focus is specified as a patch rather than a pinpointed x, y coordinate, while x, y coordinates are used for agent locations.

It is important to note that a simulated person in WRENCH takes many factors into consideration in the determination of their behavioral intent. The considerations of different factors that would affect their movement goal are assessed in a simulated cognitive process that first determines the person's desires, based on things such as their emotional state, beliefs, needs levels, and cognitive objective, and determines what types of behaviors would be needed to satisfy those desires; these potentially conflicting desired behaviors are then aligned where possible, and deconflicted when necessary, using a complex decision logic with rules for prioritization. This process is alluded to in Figure 1 with the Behavioral Intent shape on the left that drives the initial setting of the movement goal and focus. A person's behavioral intent can change over time as the agent is affected by others, the environment, and the situation, and the bottom left dotted-arrow indicates that the achievement of their movement goal is one situational change that can prompt a reconsideration of their behavioral intent. Once the agent's primary behavioral intent and resulting movement goal are determined, the movement modeling deals considers this goal along with urgent situations that may arise and changing situational conditions that may affect the goal focus.

5.2 Urgency Preemption

Several urgent situations can arise that may cause a person to alter their movement choice from what their overall movement goal would dictate. Three specific situations in WRENCH that can temporarily override a person's movement goal include:

1. The person is in a group and find that they are now too far from their group, as assessed by their distance to their group leader; similarly, the person is a child who finds they've wandered to far from their mother, or a mother who finds their child has wandered too far from them;
2. A person experiences a weapon hit that renders them unable to move for some amount of time
3. A person experiences a weapon hit that cause an immediate 'flee' type of response

The key characteristics of these urgent situations is that they will have an immediate, temporary, effect on movement, but do not automatically change the person's overall movement goal. The person may ultimately decide to change their behavioral intent based on these situational changes, but that change is not automatic and would be an outcome of their cognitive decision-making process.

In our approach, during every 1-second time-step (tick) a person assesses whether an emergency situation has arisen. If so, they adopt a temporary goal focus to address the urgency, and select an appropriate goal focus. Otherwise, they decide how to move based on the current movement goal. As mentioned above, in certain circumstances the goal focus for the movement goal may need to be updated, so this is checked and updated as needed.

Whether the planned step is goal-driven or urgency-driven, the final movement is then determined and carried out. First, the agent orients toward, or away from, their goal focus as required by their movement goal or urgent situation. Then the intended step size in that direction is determined based on the agent's speed, with an adjustment being made to the speed if necessary. If a step of that size, in that direction, will not result in a collision with another agent or obstacle then it is taken; otherwise, a collision-avoidance algorithm is used to determine the step that can be taken that will not result in a collision. Preferred and required personal space considerations are also made at this point, and the final step size and direction is determined. The agent is then moved.

The overall movement planning hierarchy is provided in Figure 3. The top and middle portions present our 2-step approach, and then the bottom section covers the mechanics of orienting and collision avoidance, and the actual movement of the agent. Whether the next step, effected in the bottom section, is goal-driven or urgency-driven, it is carried out while ensuing the avoidance of collisions. So, once the agent has a heading based on an urgent-situation or an intent-driven movement goal (which may include navigating around a building to get to their desired location or other agent), the agent will avoid nearby obstacles such as people and buildings. This collision-avoidance is carried out similarly to that found in the literature, with the important additional consideration of maintaining a preferred or minimum personal distance while taking their next step. The preferred personal distance can be set as desired, to better represent different cultures, but the minimum personal distance is used to represent the boundaries of the body of the individual, and therefore cannot be violated. This ensures that the blocking of movement, such as would be experienced in a tightly packed crowd, is properly represented.

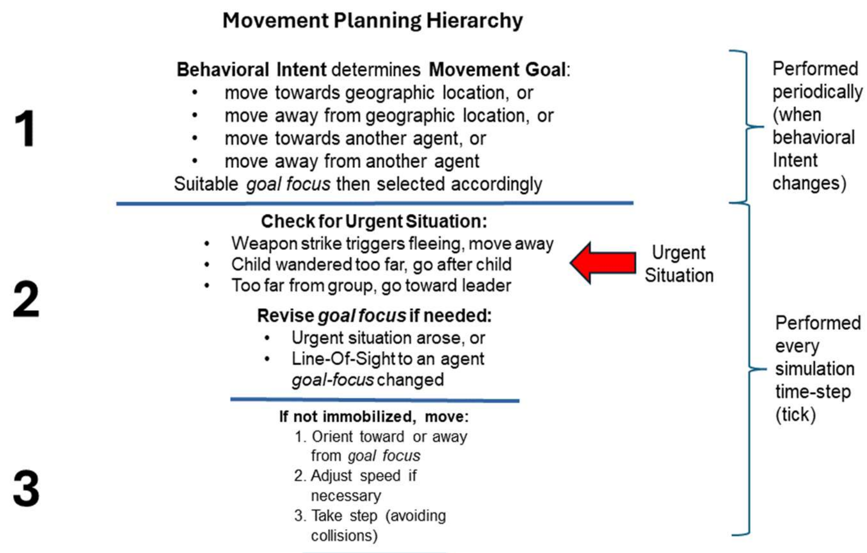

Figure 3: Movement planning hierarchy.

Figure 3 expresses the proposed movement logic in the larger context of the psychological state of the agent and provides a concise depiction of this approach. Any changes to an agent's behavioral intent will result in the setting of the agent's movement goal accordingly, and the identification of a suitable movement focus. This process happens periodically, when the individual's cognitive processes have led to a decision to change their behavioral intent. Then, every 1-second time-step the agent takes a step toward achieving that goal; however, at any time an urgent situation can arise which requires the agent's immediate attention. In this case the agent will take a suitable step to address the emergent issue. It is important to note that it is possible for a goal focus to need to be updated even while the movement goal hasn't changed. This possibility needs to be checked for every tick, but the actual updating of a goal focus will only occur periodically.

6 DISCUSSION

The issues that arose when using the original single-step approach to determining movement, i.e. considering behavioral intent and urgent circumstances side-by-side, were discovered during V&V efforts using simulation animation. Animation showed unrealistic movement behaviors that were determined to result from the individual either 'forgetting' their overall intent after reacting to an urgent circumstance, or ignoring an urgent circumstance (such as finding oneself farther away from one's own group that desired) when acting on a specific behavioral intent. Once these unrealistic behaviors were identified, and the causes determined, we developed and implemented the two-step approach described in this paper. We did not conduct a 'before vs. after' experiment; rather, we confirmed that the unrealistic behaviors had been eliminated and deemed the improvement a success.

Our use of animation is one of a variety of methods used in V&V efforts for WRENCH. As the conceptual model was being developed, we worked to construct a valid model by drawing heavily on social and psychological theories, as well as military doctrine and available information about various NLWs. Wherever possible, we used data and parameter values drawn from literature, although little suitable data was actually found. Further insights regarding NLW use and effects was gathered by watching videos of the use of NLWs in civil security situations and the testing of NLWs effects. We also verified complex model logic using Monterey Phoenix (Aros and Dyer 2025; Dyer et al. 2024). The outputs of the model have been evaluated using animation as well as data farming methods (large-scale experimentation and results analysis to verify that the model is functioning as expected without errors and to validate model results (Aros and McDonald 2023b). We have also interviewed military and police personnel with civil security and NLW experience. V&V efforts are also ongoing as improvements are made to WRENCH.

7 CONCLUSION

In this paper we presented a 2-step approach for modeling the movement of pedestrians. Our intention within WRENCH was to model the movement behavior of people more realistically. In WRENCH, a person' overall movement goal results from emotional and cognitive modeling that considers many factors and determines the individual's behavioral intent. However, in an unstructured crowd situation, such as found in civil security scenarios, it is important to consider urgent, emerging situational factors that may temporarily take precedence over a person's overall movement goal.

We contrast our modeling approach with the more common social force modeling approach that considers multiple influences on pedestrian movement, social force modeling. Social force modeling uses vector math to model the movement decision-making of a pedestrian; in less complex environments this simplification can model pedestrian movement well, but in complex environments where a person in considering longer-term goals and short-term urgent situations, in addition to collision avoidance, we believe that a more realistic modeling of the human decision process is needed. In particular, our incorporation of urgency preemption allows a simulated person to respond to and resolve an urgent situation and then return to their original movement goal based on an overall behavioral intent, representing well how people's behavior may change due to sudden reactions in complex situations while not overriding their ultimate objectives.

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AUTHOR BIOGRAPHIES

SUSAN K. AROS is a Research Assistant Professor in the Naval Postgraduate School's Operations Research Department, Director of NPS's Center for Modeling Human Behavior, and Co-Chair of the NATO MSG-222 "Representing Human Behavior and Decision-making in Modeling and Simulation". She holds a Ph.D. in Information, Risk, and Operations Management; Master's degrees in Operations Research and Industrial Engineering, and in Spiritual Formation and Soul Care; and a Bachelor's degree in Psychology. She has published research in the areas of civil security operations; use of intermediate force capabilities; disaster response operations; inter-organizational communication; production planning and scheduling; and RFID use in remanufacturing. Her email address is skaros@nps.edu.

DALE FRAKES is a Ph.D. candidate in the Systems Science Program at Portland State University and an external affiliate of the Naval Postgraduate Schools's Center for Modeling Human Behavior. He holds a Masters in Business Administration and Bachelor's degree in International Studies. He uses agent-based simulation modeling, with his research covering the modeling of individuals in complex environments, disease modeling for the Oregon Health & Science University, and modeling "Fake News" as a consultant with Decision Research Inc. His dissertation topic builds on the work done with Decision Research, which was presented at the 2018 CREATE-TSA Symposium, for which agent-based models were developed to study the use of Inoculation Theory to mitigate the spread of misinformation and disinformation (e.g. "fake news") in social networks. His email address is dfrakes@pdx.edu.