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Strolling Down the Avenue with a Few Close Friends

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Abstract

This paper describes a methodology for simulating small groups of pedestrians in urban environments. We propose a system of distributed preference voting to guide pedestrian movement along a walkway. Our voting system finds compromise solutions that enable members of a group to walk side by side, negotiate obstacles in tandem, and pass through a constriction.

1. Introduction

City sidewalks bustle with pedestrian activity. People scurry to make appointments. Couples leisurely stroll and window shop. Friends congregate at cafes. Commuters queue at bus stops. Much of the ordinary pedestrian activity on urban streets happens in the company of friends and acquaintances. This paper focuses on the interactions between and among small groups of pedestrians on urban walkways.

Social psychology studies of public gathering places report that pedestrians most frequently travel alone or in pairs [5]. Groups of size 3 and 4 occur less frequently; groups of 5 or more people are relatively rare. Our work aims to simulate the everyday activity on the sidewalk of a business district. Our goal is to generate plausible, coordinated walking and standing formations of individuals and small pedestrian groups for use in virtual environments.

Pedestrian groups travel as a coordinated unit. They walk in formations that facilitate communication. Group members are cognizant of the needs of other members in the group. When rounding a corner, members on the outside of the turn choose a course that allows sufficient room for the members of the inside of the turn to avoid running off the path or into a wall. When the path is constricted, members politely line up and pass through in single file.

This paper presents methods to control the behavior of autonomous walkers traveling alone or in small groups on a network of paths. We first describe a powerful and efficient method to represent three-dimensional, curved pathways as ribbons in space. Next, we describe a technique for controlling the behavior of a single walker that decomposes control into independent, goal-oriented processes, each responsible for some aspect of performance. A key challenge in distributed control methods is the resolution of competing constraints. Our approach seeks to find compromise solutions by requiring control processes to return not just a single value, but to express preferences on all possible values of the control variables. Moment-to-moment preferences are combined to find a control value to best satisfy the immediate needs of all control processes. Lastly, we present a set of control processes for small group walking and describe the results of experiments testing pedestrian behaviors in simulated urban environments.

2. Related Research

The dynamics of groups in public spaces has been studied from a variety of perspectives. Social scientists study crowds to understand how individual interactions lead to collective actions. Animators working on entertainment applications, such as movies and games, seek convenient ways to create and manage large casts of synthetic characters. Pedestrian simulation is an important tool for

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architects and urban planners designing massive structures such as hotels, malls, and sports stadiums to predict pedestrian flows and locate probable bottlenecks in emergency evacuations [9]. Research in virtual environments investigates ways to generate pedestrians that will plausibly interact with users in real-time simulations.

McPhail [5] defines the basic collective form he calls a cluster as "two or more proximate persons, standing, sitting, or reclining, who orient in a common or convergent direction, who talk with or touch one another, or who proceed together from one point in space to another." He summarizes sociological studies of the distribution of individuals and clusters in public gatherings and reports that less than half the people were individuals, and that clusters typically ranged in size between two and five members, with groups larger than five being rare. He also notes that the frequency of occurrence of a cluster was inversely proportional to its size.

Computer simulations of crowds, for the most part, have focused on either the behavior of individuals in a crowded scene or on the behavior of the crowd as a whole. In a landmark paper, Reynolds [7] introduced a distributed control methodology for simulating the flocking behavior of birds and animals. As a general method, flocking has come to be associated with control methods in which group behavior emerges from a simple set of rules independently applied by each member of a flock. Typically, flock members, called boids, react only to local information, such as the position, speed, and orientation of neighboring boids. Collective flocking behavior emerges from the interactions of independently controlled boids. Reynolds [8] presented a variety of steering behaviors to follow paths, avoid obstacles, wander, and evade predators.

Tu and Terzopoulos [12] used flocking rules to help create schooling behavior for fish in their physics-based virtual marine environment. Flocking was also employed by Brogan and Hodgins [3] to produce dynamically simulated group motion for hopping robots and cyclists.

Rule-based behavior models have recently been explored as a means to control pedestrians on simulated urban sidewalks. In the ViCrowd system, Musse and Thalmann [6] explored techniques to guide pedestrian behavior with varying degrees of autonomy. Thomas and Donikian [11] incorporated pedestrians into an urban traffic simulator. In their system autonomous vehicles and pedestrians interact with one another as they navigate through a network of city streets.

In rule-based systems, each rule typically generates a recommended value for one more control parameters. A key problem in distributed, rule-based control systems is the resolution of competing constraints inherent in the rule set. Conflicts are commonly resolved by either combining the recommendations (which can lead to outcomes that satisfy neither rule) or by selecting the highest priority rule (called a "winner-take-all" strategy)[1][12].

A third resolution strategy, introduced by Sukthankar [10] to control the behavior of simulated vehicles, is to have component sub-behaviors produce preferences for **all possible values** of the control parameters. On each time step of a simulation, an election is held to determine settings of control parameter values. Every active sub-behavior expresses its preference by assigning a desirability value to all possible (quantized) values of the control parameters. An electioneer combines the votes and calculates the most acceptable parameter settings. The advantage of the scheme is that compromise solutions are discovered that can not be found by winner-take-all strategies.

In this paper, we investigate using distributed preference voting to control small groups of pedestrians.

3. Modeling Walkways as Ribbons

Urban walkways are complex, 3D spaces cluttered with posts, planters, and fire hydrants. Walkers must perceive their surroundings and negotiate their way around static obstacles and through pedestrian flows. Our simulator, Hank, provides a real-time database to inform autonomous pedestrian behavior processes about their surroundings.

Building on our work in ground vehicle simulation, we represent walkways as ribbons in three-dimensional space. The walkway defines the geometry of the navigable surface and gives a local orientation to the path. The ribbon shape creates a conduit that channels pedestrian traffic into parallel streams by defining two preferred directions of travel (along the two opposing tangents of the central axis of the ribbon). It is important to emphasize that the representation places no restrictions on pedestrian behaviors. Autonomous pedestrians can choose to move across the path to look in a shop window or they can pause to chat with friends.

In addition to providing geometric information for navigation and route planning, a walkway provides the basis for defining spatial relations among occupants of the walkway. Pedestrians must be aware of obstacles in their way and step to avoid them. On a curved walkway, objects in front and beside are defined with reference to the contour of the underlying ribbon structure.

Walkways interconnect with other walkways through intersections. In contrast to a walkway, an intersection has no central axis and hence imposes no local orientation. An intersection defines a surface area with a well-defined boundary along which incident walkways connect to it. Intersections can represent spacious city plazas or street corners. Pedestrians typically enter and exit an intersection through a walkway incident on the intersection. To facilitate navigation through an intersection, we overlay the intersection with corridors (essentially simple invisible walkways) that correspond to natural routes connecting points of entry and exit.

A walkway is represented by a 3-dimentional space curve. This curve provides a central axis or spine for the pathway. A surface normal is defined at each point on the curve allowing the ribbon to twist about its spine. The ribbon defines a curvilinear coordinate system in which points on the walkway are expressed in coordinates of distance along the spine and offset from the spine (see Figure 1). These local coordinates are convenient for both navigation and obstacle avoidance computations. The database provides efficient code to map from walkway ribbon coordinates to global Cartesian coordinates and to compute the inverse mapping (from global Cartesian coordinates to local ribbon coordinates.) It is essential to map in both directions in order to communicate with gait generation and rendering processes.

In another paper [4], we give the mathematical model based on arc-length parameterized spline curves. In this paper, we concentrate on how we use the ribbon model to control walking behavior of autonomous pedestrians traveling in small groups.

4. Walking Behavior

Our walkers are controlled by two parameters that incrementally adjust walking speed and direction. We discretize acceleration into 3 levels: increment speed a small amount, maintain the current speed, or decrement speed by a small amount. Turning is handled analogously by staying on course, making a small turn to the left, or making a small turn to the right. Using a frequent update rate, we have found this coarse discretization leads to smooth, continuous motion. On each iteration of the simulation, speed and orientation are updated and passed to a lower-level process that generates the walking gait (we currently use Di-Guy [2] to synthesize articulated movements.)

In combination, there are 9 possible pairs of the acceleration and turn parameters defining the 3-x-3 action space charted in Table 1.

Accelerate Turn Left	Accelerate No Turn	Accelerate Turn Right
Coast Turn Left	Coast No Turn	Coast Turn Right
Decelerate Turn Left	Decelerate No Turn	Decelerate Turn Right

Table 1. The action space of a pedestrian. Rows define three levels of acceleration. Columns define three levels of turning.

4.1 The Voters: Constraint Proxies

Pedestrian movement is governed by a delegation of voters. Because each voter acts on behalf of some behavioral constraint, we call the voters constraint proxies. Through voting, this delegation makes their best collective judgement on how a pedestrian should move during the next time step. Our control system relies on their decisions over time to successfully guide our walkers down a pathway.

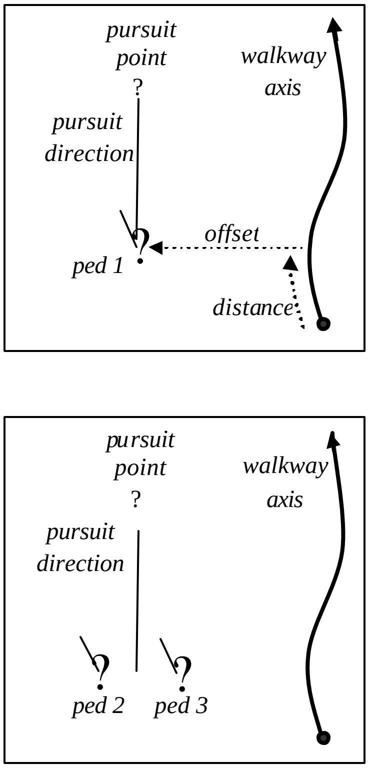
Each proxy is responsible for regulating some aspect of behavior, such as heading towards a goal position or walking at a desired speed. At each time step, proxies independently vote on each cell of the pedestrian action space. Proxies are aware of their surroundings (e.g., the layout of the walkway and the locations of nearby objects) through the world database. However, no explicit communication between pedestrians is modeled.

Votes are cast in the range [-1.0, 1.0]. The magnitude of the vote reflects how strongly the proxy feels about that cell of the action space. A positive vote indicates a favorable disposition towards the cell, a negative vote expresses opposition, and a zero vote indicates ambivalence. Sukthankar [10] allowed voters to veto cells, but as yet we have not found that necessary.

Pursuit Point Tracking Pedestrians navigate a path by aiming towards a succession of pursuit points. At each time step, a walker queries the path to determine a new pursuit point located at the current pursuit point's offset from the center spine of the path, but at a small distance ahead of it on the path. A pursuit direction is then calculated from the walker's current position to the pursuit point. This proxy votes to adjust a pedestrian's orientation to match the pursuit direction, and thereby head towards the next pursuit point.

When a group of two or more walkers is steering down a path, the pursuit direction is calculated from the group's center (average position of all members of a cluster) to the pursuit point (see Figure 1.).

Since all members of a group will calculate the same pursuit direction, this proxy votes to keep a pedestrian's orientation the same as all other members of the cluster. The result is that members track parallel paths



	Turn Left	No Turn	Turn Right
Accelerate	-1.0	-1.0	+1.0
Coast	-1.0	-1.0	+1.0
Decelerate	-1.0	-1.0	+1.0

Figure 1. The *pursuit direction* is measured from the average position of members of the group to the *pursuit point*. The top diagram shows one pedestrian labeled *ped 1.* The middle diagram shows a group of two pedestrians labeled *ped 2* and *ped 3* The Pursuit Point Tracking proxy votes to align the pedestrian's orientation with the *pursuit direction*. The matrix on the bottom shows the vote made in both cases. This proxy has no preference regarding acceleration so all rows within a column have the same value. The column of +1.0 indicates a desire to turn right, while the columns of –1.0 show an opposition to both turning left and not turning.

Maintain Formation Members of a group walking down a city block adjust their spacing and gait to produce a collective formation that allows for eye contact and conversation. To an observer, this is a visual clue that a relationship exists between members of the group. For example, when space permits, pairs of pedestrians walk side by side. Interestingly, (based on our informal observations) triples tend to prefer non-linear alignments that allow clear lines of sight for group members to see one another.

Slip is a measure of how far one member is in front of or behind of the average position of other members in a group. A simulation parameter called group slip represents the maximum slip allowed for any of its members. Group slip is set directly proportional to a group's size (more members mean a larger slip).

For a single walker, this proxy votes neutrally on all cells of the action space, since no formation is required. If this walker is a member of a group, and its slip is within the allowable group slip, this proxy votes to maintain the current speed; otherwise, it votes to accelerate or decelerate in order to reduce its slip.

Avoid Pedestrians Each walker seeks to maintain a personal space (i.e., a minimum separation from other pedestrians). If one or more pedestrians violate a walker's personal space, this proxy votes to steer away from the closest of these intruders.

Avoid Obstacles A special process is in charge of anticipating future collisions between a walker and large obstacles (i.e., with a radius greater than a predetermined level). When a large obstacle lies ahead of the walker and the time-to-collision is below a given threshold, this process will gradually shift the pursuit point around the closest edge of the obstacle. The pursuit point is nudged by increasing or decreasing its path offset until it is far enough from the obstacle to allow room for everyone in the group to comfortably pass.

The job of this proxy is to monitor the environment for imminent collisions with any obstacles that lie in a walker's path, whether large or small. If a collision is at hand (i.e., the time-to-collision is below a given threshold; the threshold used here is smaller than that used by the special process above), this proxy votes to steer the walker towards the obstacle's nearest edge. The result is that smaller objects are averted individually by walkers, while larger objects are generally negotiated as a group. Some examples are illustrated in the next section.

Maintain Target Velocity Each pedestrian has a parameter that specifies its preferred (target) velocity. This proxy compares a walker's current velocity with its target. If they match (within a given allowance) it votes to maintain the current speed (coast); otherwise it votes to accelerate or decelerate towards that target.

In contrast to many flocking systems, our pedestrians do not explicitly try to match the speed of neighboring group members. Instead, a common speed is attained for group members as a by-product of maintaining a group formation.

Centering Walkers want to stay within a certain distance from their group companions. In the flocking literature, this behavior is called flock centering. Along with maintaining a formation, this characteristic is essential to making a collection of pedestrians look like a group.

For a single walker, this proxy votes neutrally on all cells of the action space. If the walker is a member of a group, the average position of all other members is calculated. A group's centering distance is a simulation parameter that represents the maximum distance allowed between any pedestrian and the average position of all other members of the group. If the distance between the walker and the average position is within the centering distance, this proxy votes to maintain the current speed and orientation; otherwise, it votes to move in the direction of the average position.

The centering distance is set to be proportional to the size of the group. Other reasonable factors could be used in determining centering distance including pedestrian density on the walkway, open space ahead (more open space increases a tendency to spread out), or the presence of obstacles (e.g., several obstacles forming a constriction).

Inertia Dithering, the repeated switching between two activities, sometimes arises as a problem in action selection systems. In order to help avoid erratic fluctuations, this proxy introduces hysteresis by casting a positive vote for the incumbent cell (i.e., winner of the most recent election); all other cells receive a neutral vote.

4.2 The Election

Votes are tabulated at each step of the simulation. The winning cell determines the control parameter values sent to the gait generator. Votes are weighted before they are tabulated. The weight assigned to a proxy's vote remains constant during the simulation, and reflects the relative importance of the constraint it represents. Weights are determined experimentally and adjusted whenever a new constraint is added.

5. Results

The focus of our work is to investigate the collective behavior of groups of pedestrians. Our general philosophy has been to keep the design of our control system as simple as possible. By limiting our action space to three levels of each control variable, the number of possible voting patterns is greatly reduced. State is used sparingly to suspend a proxy only when that proxy's interests cannot be reasonably accommodated.

We have conducted a series of experiments examining the behavior of individual pedestrians and small groups moving on a circular walkway with and without obstacles placed in varying configurations.

5.1 Following a Circular Path

The most fundamental pedestrian movement is walking along a clear, open pathway. This experiment produces pedestrian motion along an empty circular path. Walkers are guided by a series of pursuit points that are generated just ahead of them as they advance down the path. We call that sequence of pursuit points the pedestrian's target path.

We studied the effect of varying several parameters, including the turn angle increment (amount a pedestrian can turn in one time step), look-ahead distance (constant distance maintained between the pedestrian and the pursuit point), and path curvature (radius of the circular path).

When only a single walker is created Pursuit Point Tracking, Maintain Target Velocity, and Inertia are the only proxies contributing non-neutral votes toward cells of the action space. In our simulation of this case the pedestrian followed a circular path inscribed inside the target path, while reaching and then maintaining its target speed.

If two or more walkers follow a path as a group, then Maintain Formation, Centering, and Avoid Pedestrian also contribute to the voting process. In our tests on pairs of pedestrians, couples moved side by side down the path. A plot of the their average position (i.e., group center) tracks a circular path inscribed inside the target path similar to that followed by a single pedestrian.

We found that changes in the turn angle increment had little effect on the path taken by either a single pedestrian or by the pair. Walkers negotiated paths with various path curvature equally well. A smaller look-ahead distance, however, kept the pedestrians closer to the target path. This suggests that it may be useful to adjust the look-ahead distance according to the path curvature. Figure 2 shows trajectories for a single walker with varying look-ahead distances.

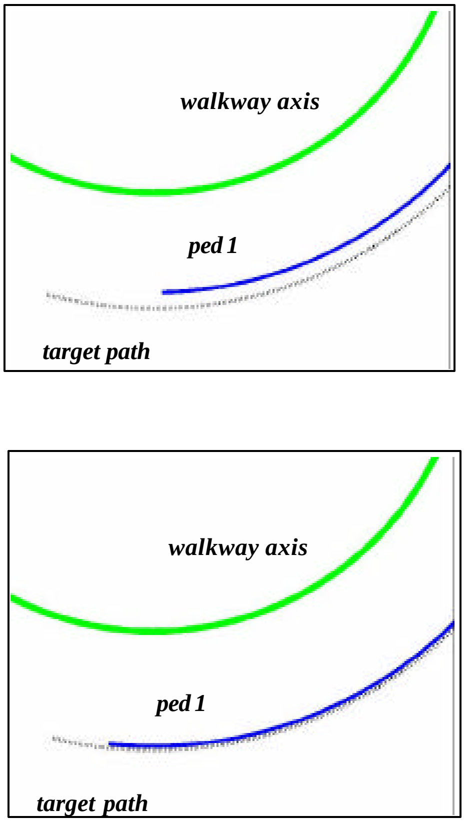


Figure 2. The top diagram shows a pedestrian's trajectory as it follows a sequence of pursuit points (*target path*). In the bottom diagram the pedestrian's trace is closer to the pursuit points due to a smaller look-ahead distance.

5.2 Avoiding an Obstacle

A couple walking down a sidewalk is likely to encounter a variety of obstructions in their path. The way the couple responds often depends on the size of the obstacle and how much effort is needed to avoid it. The pair might decide to slightly split as they step to the side of a lamppost, but stay together as they bypass a group of people that have stopped to chat.

Successfully negotiating an obstacle as a group requires members to balance the desire to avoid the obstacle against the desire to stay together. Both behaviors are satisfied by our voting system as it determines a compromise solution. In contrast, a winner-take-all approach might decide to suspend constraints on formation until an obstacle is passed causing a loss of group coherence.

We created simulations of walkers avoiding both small and large circular obstacles. As described in section 4.1, Avoid Obstacles helps pedestrians steer to the side of small obstacles, while large obstacles are monitored by a special process that gradually shifts the pursuit point to a safe clearance for the individual or group. We also experimented with multiple levels of look-ahead distance.

In our simulations pairs of walkers preserved a consistent side-by-side formation as they negotiated the obstructions. We discovered that as the look-ahead distance increases, so does the smoothness of the actual path taken. In our judgement a smoother path looks more natural, so it might be appropriate to adjust the look-ahead distance when large obstacles are encountered. Figure 3 shows a tracing of a pedestrian pair avoiding both a small and large obstacle in their path with two different look-ahead distances.

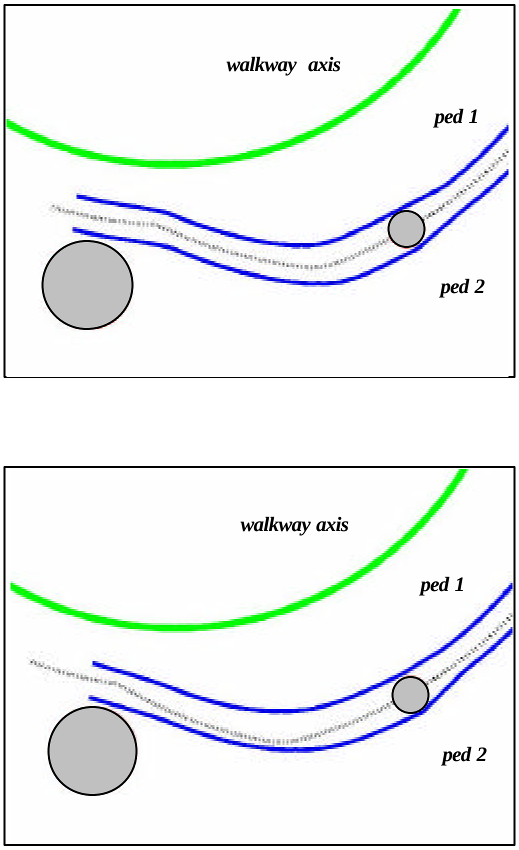


Figure 3. The top diagram shows the trajectory of two pedestrians as they avoid a small and large circular obstacle. The walkers' target path is indicated by the dotted curve. In the bottom diagram a larger look-ahead distance is used, producing a smoother trajectory.

5.3 Passing Through a Constriction

An urban setting presents many situations where a group traveling together might be forced to compress and/or alter their formation in order to pass through a narrowing of their path. These constrictions might be as brief as a shop's doorway, or as extensive as a length of sidewalk blocked off due to repair work.

In this experiment we aligned obstacles to form a narrow passageway. We observed that groups compressed at the entrance, moved down the corridor nearly single file, then emerged and reformed as a group at the exit.

Constrictions create an irreconcilable tension between the goal to avoid a collision and the goal to walk abreast. This conflict is resolved by assigning a sufficiently high weight to collision avoidance so that it always takes precedence over the formation constraint. However, the tension does seem to lead to some irregular motion caused by tentativeness in the voting patterns as the group approaches the constriction. To avoid this conflict, we introduced a state change in the voter set by deactivating the Maintain Formation proxy as the group neared a narrow passage. In simulations, we found that suspension (as opposed to suppression by way of weighting) of the voter led to smoother transitions. Figure 4 shows the trajectories of a group of three as they move through a passageway both with and without explicit state change.

6. Conclusions and Future Work

This paper investigates simulation of small pedestrian groups in urban environments. We propose a methodology for guiding pedestrian movement along a walkway. Our voting system finds compromise solutions that enable members of a group to walk side by side, negotiate obstacles in tandem, and pass through a constriction. We demonstrate how results can sometimes be improved by introducing state to temporarily suspend a voting entity.

We are currently experimenting with interactions among multiple groups, such as couples passing around other couples. While early results are promising, it remains to be seen how far our simple model can extended to handle increasingly complex behaviors. Each time a proxy is modified or a new proxy is added, the resulting impact must be carefully examined. Although proxies are designed as independent entities, their voting patterns and relative weights can sometimes combine to influence behaviors in unanticipated ways. So far we have been successful at finding a good balance among competing interests.

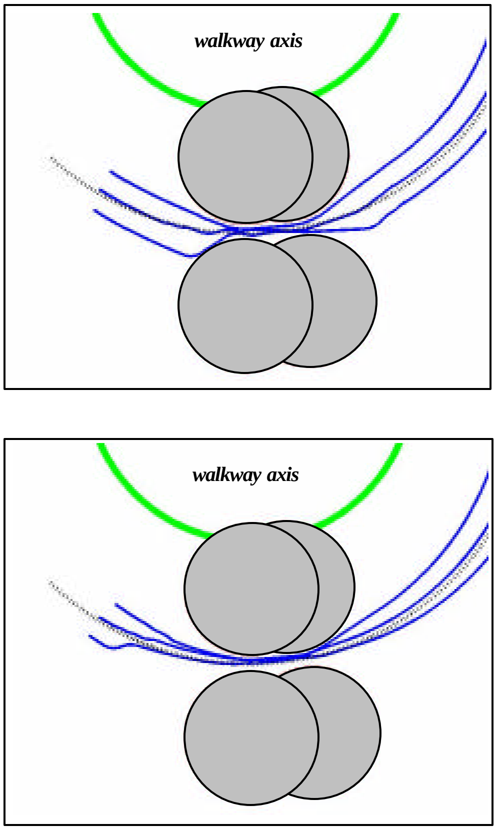


Figure 4. The top diagram shows the trajectory of three pedestrians (solid curves) as they follow their target path (dotted curve) and pass through a constriction formed by circular obstacles. In the bottom diagram the Maintain Formation proxy is suspended, resulting in a smoother transition as the group enters and exits the passage.

We plan to extend this work by introducing stationary formations such as queues at bus stops and standing groups. A key challenge will be create smooth transitions between moving and standing forms. We also plan to investigate dynamically changing group membership through natural aggregation and disaggregation in both moving and standing forms.

Acknowledgements

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