Statistical behaviour of mixed crowds of humans and automata

Guillermo A. Frank[1], Claudio O. Dorso[2]
[1]UIDI - UTN, Av. Medrano 951, C1179AAQ, Argentina
[2]IFIBA - CONICET, Ciudad Universitaria, C1428EGA, Argentina.

Abstract
The behavior of highly dense crowds under emergency situations caught the attention of researchers in the last years. But, it is now common the presence of automata among people in public buildings, malls, etc. Automata are set to do specific tasks and may or may not carry an emergency plan. This work simulates the dynamics of an escaping situation due to some kind of danger. A mixed population of humans and automata try to get out from a room. We handle the pedestrians' dynamics by means of the Social Force Model (SFM). The automata, however, evaluates the costs of deviation from a preset route. Both models interact, yielding quite unkown scenarios. Our aim is to identify the most favorable scenarios for the human safety.

Key Words: Crowd Dynamics, Social Force Model,Automata, Emergency, Safety

1. Introduction

The "social force model" (SFM) was proposed by D. Helbing in the late '90 as a quantitative theory for studying the collective dynamics of crowds under emergency (Helbing & Molnár, 1995; Helbing et al., 2000). The model was able to explain the "faster-is-slower" phenomenon occurring in overcrowded exits and corridors.

Soon after the SFM appeared, researchers focused on the role of obstacles as pressure "absorbers" and the convenience of creating a small area near the exit as a way of mitigating the clogging effects (Helbing et al., 2005; Kirchner et al., 2003; Escobar & Rosa, 2003; Frank & Dorso, 2011). This kind of investigations yielded novel designs of rooms and halls (Sticco et al.,2022; Sticco et al.,2023). The segmentation of the exit into two (or more) doors was another suggested innovation (Sticco et al., 2017).

Complementary to room designs, signals appear as an ally for improving the evacuation performance during emergencies (Frank et al., 2014). However, some kind of supervision seems to be required for a satisfactory performance (Frank et al., 2014).

Our investigation goes beyond architectural improvements towards a new ally in the evacuation performance: the robot assistants. As a starting point in this field, we study the benefits of introducing a few automata in the room that mimic the human behavior during the emergency. We avoid any complex behavior of the automata (and consequently, any complex programming).

The investigation is organized as follows: Section 2 outlines the Social Force Model (SFM). Section 3 shows the results obtained by means of simulations. Section 4 summarizes the conclusions.

We stress that this research is still open and some questions will remain open until an upcoming paper.

2. Background

2.1 The Social Force Model

The "social force model" describes human motion in term of three essential forces: the social force, the own desire to reach a certain destination and the granular force. (Helbing & Molnár, 1995; Helbing et al., 2000). These forces enter the classical movement equation (say, the Newton equation) as follows.

$$m_i \frac{d\mathbf{v}_i}{dt}(t) = \mathbf{f}_d^{(i)}(t) + \sum_j \mathbf{f}_s^{(ij)}(t) + \sum_j \mathbf{f}_g^{(ij)}(t) \tag{1}$$

where m_i is the mass of pedestrian i. The subscript j represents all other pedestrians (excluding i) and the walls. The right-hand side of the equation expresses the contribution of the desire, social, and granular forces, respectively.

The social force stands for the tendency of the pedestrians to preserve the "private sphere". This tendency becomes stronger as people get closer to each other or to the walls. Thus, it is commonly modelled as a repulsive monotonic force that depends on the pedestrian-pedestrian (or wall-pedestrian) distance d_{ij}. Its expression reads

$$\mathbf{f}_s^{(ij)} = A_i\, e^{(r_{ij}-d_{ij})/B_i}\mathbf{n}_{ij} \tag{2}$$

for ij representing either pedestrians or walls. $\mathbf{n}_{ij}$ is the unit vector in the $\overrightarrow{ji}$ direction and $r_{ij} = r_i + r_j$ is the sum of pedestrian radius i and j. If j represents a wall, then r_j should be set to zero. The parameters A_i and B_i are estimated from experimental observations (Helbing et al., 2000).

The desire force represents the accelerations (or decelerations) done by pedestrians to reach the desired velocity v_d. This is the most comfortable velocity for the pedestrian, according to his (her) anxiety level. Its mathematical expression for pedestrian i is

$$\mathbf{f}_d^{(i)}(t) = m_i\, \frac{v_d\, \mathbf{e}_d^{(i)}(t) - \mathbf{v}_i(t)}{\tau} \tag{3}$$

where v_i is the current velocity ans τ represents the relaxation time needed to reach his (her) desired velocity v_d (modulus). It is commonly assumed to be $\tau \approx 0.5\,\mathrm{s}$.

The desired velocity has magnitude v_d and pointing direction $\hat{\mathbf{e}}_d$. While v_d represents his (her) state of anxiety, $\hat{\mathbf{e}}_d$ indicates the target position where the pedestrian is willing to go. In the context of an emergency, we can assume that $\hat{\mathbf{e}}_d$ points to the exit.

The granular force corresponds to the compression and the sliding friction appearing when two individuals get in contact (or with the walls). Its mathematical expression reads

$$\mathbf{f}_g^{(ij)} = k_t\,(r_{ij} - d_{ij})\,\Theta(r_{ij} - d_{ij})\,\Delta\mathbf{v}_{ij}\cdot\mathbf{t}_{ij} + k_n\,(r_{ij} - d_{ij})\,\Theta(r_{ij} - d_{ij})\,\mathbf{n}_{ij} \tag{4}$$

where $\Delta\mathbf{v}_{ij}$ is the velocity difference between contacting pedestrians. $\mathbf{t}_{ij}$ is the unit tangential vector, orthogonal to $\mathbf{n}_{ij}$. k_t and k_n are experimental parameters. $\Theta(.)$ is the Heaviside cut-off function.

Further details on $\mathbf{f}_s(t)$ and $\mathbf{f}_g(t)$ can be found throughout the literature (Frank & Dorso, 2011, 2014; Sticco et al., 2017, 2022, 2023).

2.2 Simulation conditions for Humans and Automata

We simulated the evacuation of a 20 m × 20 m room with a single exit as shown in Fig. 1. We considered a mixed crowd of 190 pedestrians and 10 self-propelled robots (*i.e.* robot assistant or automata). The (human) pedestrians were allowed to rush to the exit at the beginning of the emergency. The automata mimicked the humans, although with their own

Table 1: Parameters for the Social Force Model.

Parameter	Value	Units
A_i	2000	N
B_i	0.08	m
k_t	3.05×10^5	$\mathrm{kg.m^{-1}s^{-1}}$
k_n	3.60×10^3	$\mathrm{kg.s^{-2}}$
τ	0.5	sec.
r_{human}	0.23	m
m_{human}	70	kg.
r_{robot}	0.153/0.345	m
m_{robot}	140/210	kg.

desired velocity. Thus, both moved towards the exit at different "anxiety levels".

Pedestrians and automata interacted by means of the social $\mathbf{f}_s^{(ij)}$ and granular $\mathbf{f}_g^{(ij)}$ forces. We assumed that either $\mathbf{f}_s^{(ij)}$ and $\mathbf{f}_g^{(ij)}$ were the same, regardless of been a human or a robot. However, we considered different weights and sizes for each kind. Table 1 summarizes the main parameters for each being.

Fig. 1 captures two scenes of the evacuation process. There can be seen the robot assistants moving among the human crowd. Both, humans and assistants update their position at each time-step in order to point straight to the door.

At least 20 evacuation processes were simulated for each scenario. However, the initial velocities were chosen at random at the beginning of each process for attaining a statistical behavior.

3. Results

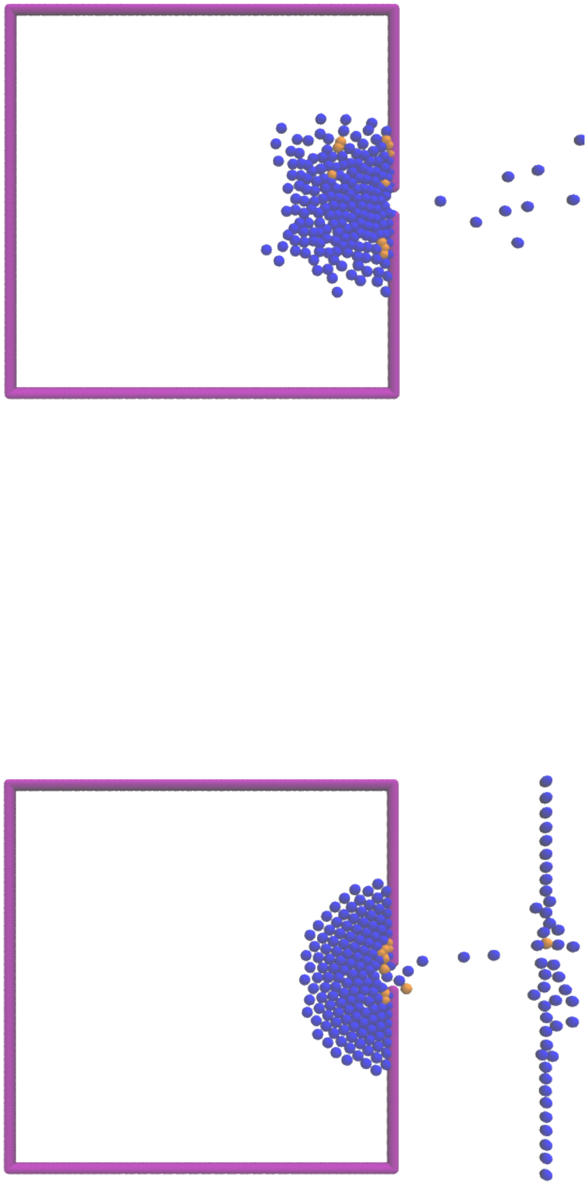
In this Section we present the most relevant results of the investigation. We first examine the "faster-is-slower" effect when robots mimic exactly the human behavior. We then move to more complex situations where the robot assistants do not push the same as humans for reaching the door. These situations introduce a wide variety of escaping possibilities, but our attention is placed on the ones that improve the time performance of the evacuation. We finally examine the robot features involved in the evacuation performance.

3.1 The "faster-is-slower" phenomenon

Our first step in the investigation focused on the "faster-is-slower" phenomenon for the mixed crowd of humans and robot assistants. Fig. 2 shows the evacuation time as a function of the desired velocity (see Section 2.2 for a visual representation). We can see that a minimum occurs around $v_d = 3-4\,\mathrm{m/s}$, regardless of the presence of automata. We also see the "faster-is-slower" phenomenon beyond this value, since the evacuation demands more time as v_d increases.

The mixed situation of humans and robots appears to worsen the time performance with respect to the "only human" situation. Recall that robots are wider and heavier than humans (see caption for details), and this is as possible reason for the worsening of the evacuation performance. We will come back to this point in Section 3.3.

Notice that at this stage the automata were only asked to mimic the human behavior during the emergency. That is, automata move in a somewhat "anxious" mode. But this seems not



(a)

(b)

Figure 1: Two snapshots of an evacuation process. The room is $20 \times 20\,\mathrm{m}$ and the door width is $1.38\,\mathrm{m}$ (*i.e* three pedestrian's diameter). The blue and orange circles represent humans and automata, respectively. The anxiety of the humans is $v_d = 6\,\mathrm{m/s}$. The automata resemble an anxiety level of $v_d = 8\,\mathrm{m/s}$. (a) Snapshot of the evacuation at the beginning of the process. (b) Snapshot of the evacuation a few seconds later.

to be the proper way of assisting people, since a calm attitude is commonly recommended in an emergency. Our next step focuses on this issue.

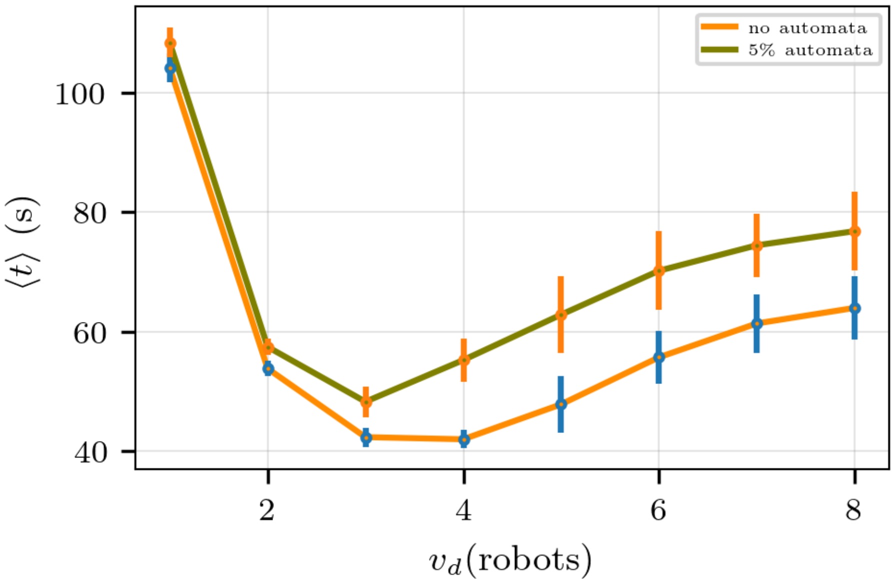


Figure 2: The (mean) evacuation time vs. the vesired velocity v_d. The simulation was done in the same environment as shown in Fig.1. The crowd included 190 humans and 10 automata (approximately 5% of automata). The error bars show the $\pm\sigma$ bounds for 20 processes. Either humans and automata have the same desired velocity. Each automata weights 210 kg and has a radius of 0.345 m. See Table 1 for the comparison between humans and automata.

3.2 The role of the automata pushing effort

We next examined in detail the highly anxious situation of $v_d = 6\,\mathrm{m/s}$ (for humans). As already shown in Fig. 2 this occurs in the well established "faster-is-slower" regime. However, we programmed the robot assistants to mimic different levels of anxiety. That is, the robots made pushing efforts (v_d) from a relaxed situation to a highly one. The resulting time performance is shown in Fig. 3. The dashed curve was copied from Fig. 2 for a comparison purpose.

The mean evacuation time in Fig. 3 exhits two regimes. Whenever the automata behave more anxiously than people, the evacuation time improves. But, if the automata move in a more relaxed way than humans, the evacuation takes more time to conclude. This result appears quite in disagreement with respect to the common expectation: the calm attitude favors the evacuation performance. Thus, this seems not to be entirely true, at least in the context of robot assistants within the Social Force Model.

Hard pushing assistants produce a faster evacuation process. However, this may result in harmed people because of the higher pressures within the crowd. We checked this issue and made sure that pressures ranged safety values within the explored situations.

It seems disappointing that the results exhibited in Fig. 3 favor the evacuation process for very high anxiety levels only. Thus, our task in Section 3.3 is to find more suitable assistants for emergencies.

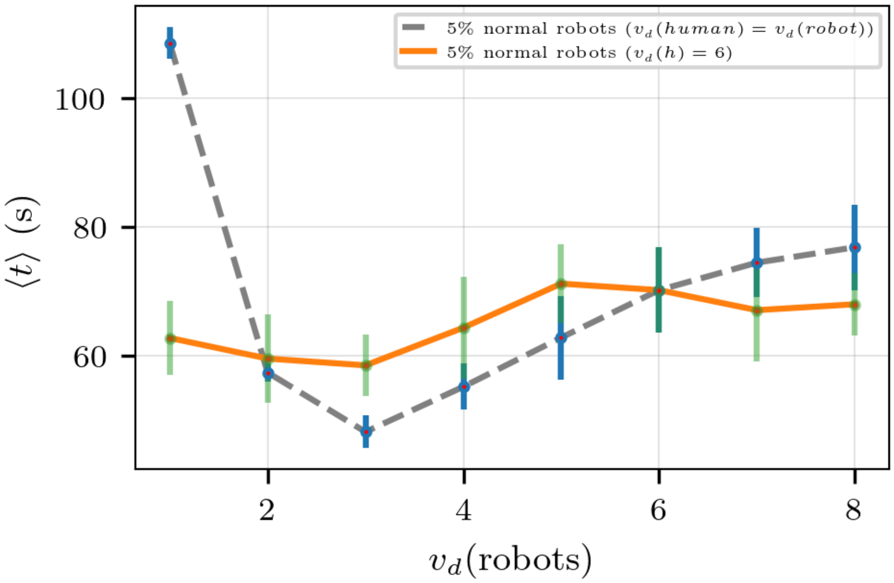


Figure 3: The (mean) evacuation time vs. the automata pushing effort. The simulation was done in the same environment as shown in Fig.1. The crowd included 190 humans and 10 automata (approximately 5% of automata). The error bars show the $\pm\sigma$ bounds. The humans desired velocity was $v_d = 6\,\mathrm{m/s}$. The automata weight is 210 kg and size 0.345 m.

3.3 The role of the automata size and weight

We noticed in Sections 3.1 and 3.2 that wide and heavy robots are not the best choice for helping people during the evacuation process. Fig. 4 explores the performance of slim and lighter robots. Surprisingly, thin automata exhibit a much better performance than the wide ones. Indeed, the performance is better no matter the pushing effort performed by the robots.
Notice that the curves for slim automata in Fig. 4 do not exhibit a "faster-is-slower" behavior at all. This means that no long-lasting delays due to blockings are actually present. This is a major milestone in our investigation.

The above result is quite independent of the automata weight, as can be seen in Fig.4 (within the explored range). Thus, it appears for now that the size of the automata is the relevant feature in the robot design. Fig. 5 examines this feature in more detail. It becomes clear that the wider the robot, the less helpful the automata will be.

4. Conclusions

The investigation explores the statistics of the evacuation time during an emergency in the context of the Social Force Model. We explored the scenarios of a mixed population of pedestrians (humans) and automata (robots). But since automata are assumed to be an expensive piece of engineering, we only studied crowds containing 5% robots.

Our major conclusion is that robot assistants are a very useful tool for helping the evacuation in an emergency situation. However, it is extremely important to choose the right features for this purpose. We arrived to the conclusion that slim robots (say, slimmer than humans) yield a surprisingly good time performance. We emphasize, however, that this may not be the only required feature and that the reasons for the nice performance of slim robots is still under investigation.

Many questions still remain open and will be answered in an up-coming investigation. Nevertheless, a few comments can be outlined as follows:

- We explored situations with only a few automata and realized that a small number of assistants can make a big difference in the evacuation performance. Thus, we expect this strategy to be an affordable one in the near future.
- As a first approach, it appears not to be necessary to implement complex capabilities for the automata. This is a quite surprising issue, although further investigation is required on this point.

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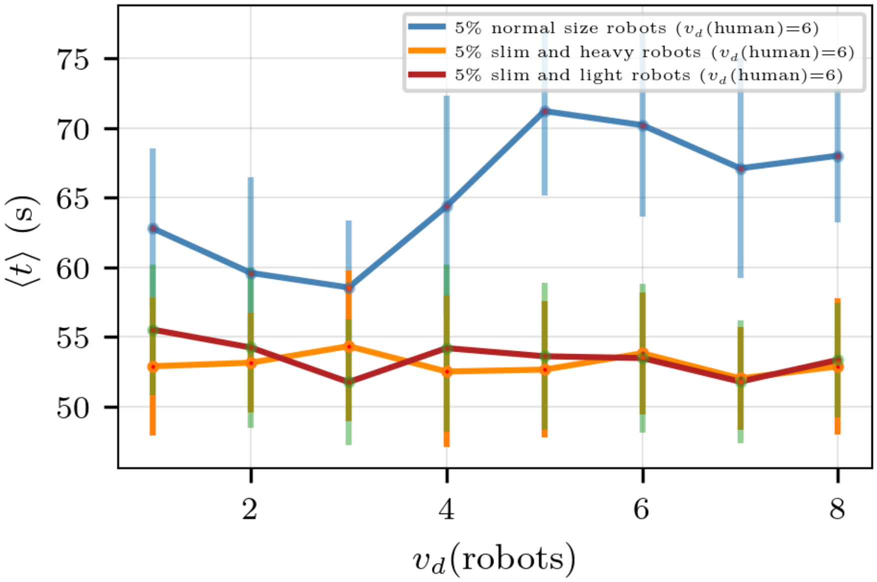

Figure 4: The (mean) evacuation time vs. the automata pushing effort. The simulation was done in the same environment as shown in Fig.1. The crowd included 190 humans and 10 automata (approximately 5% of automata). The error bars show the $\pm\sigma$ bounds. The humans desired velocity was $v_d = 6\,\mathrm{m/s}$. The red curve corresponds to the situation where the automata weight is 140 kg. The orange curve corresponds to the situation where the automata weight is 210 kg.

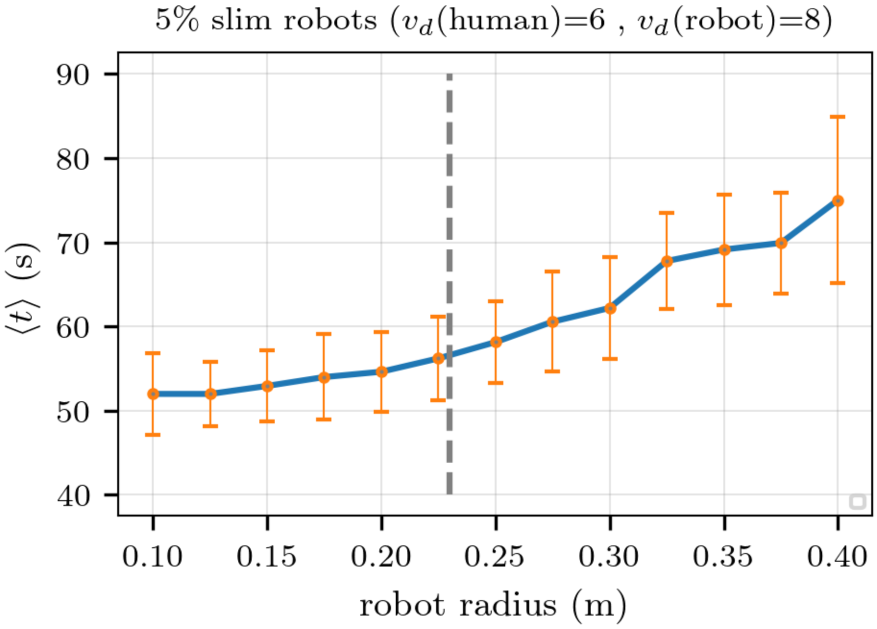

Figure 5: The (mean) evacuation time vs. the automata radius. The gray line stands on the people radius (say, 0.23 m). The simulation was done in the same environment as shown in Fig.1. The crowd included approximately 5% of automata (say, 190 humans and 10 automata). The error bars show the $\pm\sigma$ bounds.