SURVEY

A history of crowd simulation: the past, evolution, and new perspectives

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Abstract
This paper aims to discuss the past, evolution, and new perspectives in crowd simulation. Many work have been produced and published in this area that was launched approximately 30 years ago. In this paper, we re-visited the main aspects of the area, presenting the periods and evolution we had in the past. In addition, we also discuss the present and possible trends for the future.

Keywords Crowd simulation · Virtual humans · Behavioral animation

1 Introduction

To have a credible application using crowds in virtual environments, several aspects of the simulation must be addressed. The most relevant are environment modeling, behavioral animation, and crowd rendering [70]. Such aspects are essential in order to provide a positive impact of performed simulations. However, some of them may be more or less relevant depending on the application. If there is no appropriate environment model, the characters will not behave accordingly, as they can perform actions in the wrong places or not performing at all. Serious simulations like evacuation scenarios are examples of the relevance of credible and realistic environments. If there is no satisfactory rendering, even the best behavior model will not be compelling. In this case, we can mention games and movies, where the visual impact is undoubtedly essential. However, computer animation to be used in training applications should also take care of visual aspects to provide better immersion and user experience. If there is no good behavioral model, even a simulation

using the best rendering method will not look believable just after few seconds. Finally, interactive applications must simulate and display a varied ensemble of virtual characters and their behaviors efficiently. Rendered characters must visually adjust to the environment in terms of visual reactions, i.e., they must be affected by light and other effects in the same way as their surroundings. Therefore, when considering crowd simulation, the effort to be made is actually a compromise between many aspects (rendering, animation, behavior, frame rates) and the purpose of the application.

Since the seminal paper by Craig Reynolds [88], where he proposes a way to control and animate groups of entities as one only entity, many have been achieved in the crowd domain. In this paper, we want to trace the area since 1987, discussing the evolution and problems that have been solved and the critical challenges that are still open. In particular, we focus on crowd simulation techniques, i.e., behaviors, panic situations, flocks, collision avoidance, navigation, path planning, environments when populated with crowds, emotions, psychological aspects, data-driven approaches, personalities and emotions in crowds, and recently methods that use machine learning techniques.

Some crowd surveys have already been proposed. Some of them are mainly focused on crowd analysis, like crowd behaviors studies, as crowd density estimation or counting [40,90,110]. Azahar et al. [3], in 2008, presented the pioneers' authors in crowd simulation, organized in an excellent timeline until 2006, and focus mainly on real-time applications and their challenges. Nasir et al. [73] discuss the crowd domain in a more general way considering environment mod-

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eling, simulation methods, and animation in a shorter paper containing approximately 30 bibliographical references. In 2015, Ijaz et al. [42] presented a survey paper specifically on crowd simulation using hybrid techniques. So, the contribution of the present paper is to analyze more than 300 papers, even if approximately 100 are cited here, regarding the historic context and evolution of papers and methods in crowd simulation, not focused on one specific technique. Although it may be possible that a paper focused on virtual environments or virtual reality is cited in this manuscript, it happens because they contribute with the proposed method to simulate crowds as well, in the authors' point of view. So, this text does not intend to provide a survey on crowd interaction, rendering, virtual environment, parallel processing, even if all these subjects are co-related with the theme. The main reason is that we want to avoid a general text by citing as many methods as possible from the studied papers. Therefore, our goal is to propose a way to see the history and imagine the future with respect specifically to crowd simulation techniques.

We organized all the studied methods in this paper into six main periods: before 2000, from 2000 to 2004, from 2005 to 2009, from 2010 to 2014, from 2015 to 2019, and then papers from 2020 and 2021. Our objective is to highlight the proposals for new methods in these defined periods. It is essential to point out that, in general, we indicated the periods of the proposal of methods, but this does not mean that these methods have not being studied in future periods of time.

2 Literature review: an analysis of crowd simulation techniques over the past decades

Firstly, in this section, we describe the methodology applied in this work, i.e., the scope of our systematic review and the selection criteria used to select the papers included in our study. Then we present details about the proposed word clouds used to illustrate each period. After we have presented our methodology, subsequent sections detail each period of research.

2.1 The Research Methodology

To proceed with the systematic review, we used search engines at ACM, IEEE, Elsevier, Springer, and Google Scholar. The keywords used are: Crowds and Simulation, and this process results in thousands of papers from which we selected 319 based on the main topic, distributed along the time as shown in Fig. 1.

Due to the high number of papers in crowd simulation and co-related areas as rendering, parallel processing, crowds on GPU, etc., we focused only on papers that describe methods in simulating crowds concerning motion, navigation, colli-
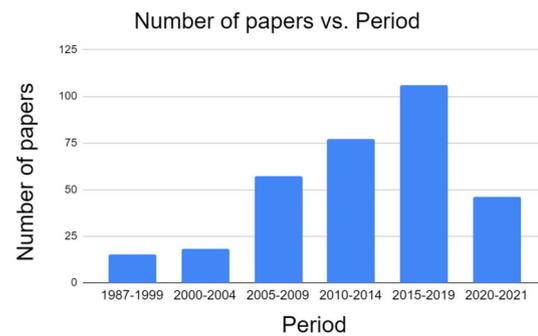

Fig. 1 Distribution of selected 319 papers along the time.

sion avoidance, perception, personality, emotion, and other simulation methods. From such papers, we extracted authors, full references, abstracts, keywords, and titles. Papers were grouped by period, firstly before 2000, and then one period at every 5 years.

We selected some papers to be cited in this work for each period, since we avoid mentioning all 319 selected. The selection of papers was made based on two simple criteria: (1) We tried to include the most known and cited methods in the area presenting diversity in the proposed methodologies, while (2) trying to distribute citations among most relevant and cited authors in the area. From this selection, we have 115 papers cited in this paper.

We use word clouds to illustrate the most mentioned words in the titles of the selected papers. Firstly, it is essential to mention that our goal with word clouds was not to guide the papers we will discuss in this work but only to illustrate the primary terms (probably related to the techniques) proposed at each period. At each period, we focus on the proposals showing how the different ideas emerged as a function. Of course, many techniques has been proposed until nowadays, as different ways to provide collision avoidance, for example. Indeed, we tested word clouds with words from abstracts; however, the words from the title seem to us more interesting because usually the titles are innovative, so new terms and ideas are typically used. Please, note that stop words have been removed [1]. Figure 2 presents a word cloud formed by the conferences and journals where we found such selected papers. The conferences where we found most papers in crowds domain are MIG[2], SCA[3], IVA[4] and CASA[5], while

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[1] We used framework available in wordart.com to generate the word clouds

[2] ACM SIGGRAPH Conference on Motion in Games

[3] Symposium on Computer Animation

[4] Intelligent Virtual Agents

[5] Computer Animation and Social Agents

journals are IEEE CG&A[6], IEEE TVCG[7], Elsevier C&G[8], and ACM TOG[9]. In the next sections, we describe some of these papers organized in periods, as mentioned before.

2.2 Crowd papers before 2000: the age of flocks and behaviors

Reynolds in 1987 [88] proposed the first method to control and animate groups of characters. In his method, he innovated proposing a distributed model where each member of the crowd (called boids) could perceive and react individually to the environment and the other boids. Reynolds suggested the term flock to indicate the immediate group an individual belongs to. Also, boids into a flock interact to avoid collisions as well as to compute speeds and orientations. Tu and Terzopoulos [101] have worked on behavioral animation for creating artificial life, where virtual agents are endowed with synthetic vision and perception of the environment. The repertoire of fishes' behaviors relies on their perception of the dynamic environment, and the fishes' reactions are not entirely predictable because they are not scripted.

Helbing et al. [35] proposed a model based on physics and sociopsychological forces to describe human crowd behavior in panic situations. The model is set up by a particle system where each particle has a predefined speed in a specific direction to which it tends to adapt its instantaneous velocity within a certain time interval. Simultaneously, the particles try to keep a velocity-dependent distance from other entities and walls controlled by interaction forces. Musse and Thalmann in 1997 [69] proposed the first method to simulate crowds based on a hierarchical control, having the crowd formed by groups which are formed by individuals. In this case, individuals are homogeneous and interact only with closer agents to avoid collisions. Agents have distributed and known goals generating a goals-based method. Also, in this paper, sociological aspects such as leadership were mathematically formulated to be taken into account in crowd decisions.

In 1999, Reynolds [87] proposes steering behaviors as a solution to model autonomous characters in animation and games by endowing them with the ability to navigate around their world in a life-like and improvisational manner. This paper divides motion behavior into three levels: the middle level of steering behaviors, the lower level of locomotion, and the higher level of goal setting.

Figure 3 shows the word cloud formed by the titles of 15 papers (from selected 319 papers) selected from 1987 to 1999. We only discarded the term "crowd simulation"

because it appears in all periods. As we can see, words as pedestrian, behaviors, flocks, artificial, fishes, schools, herds, and physics illustrate the techniques proposed in this period, where authors firstly think and elaborate about groups of characters. In addition, we notice the presence of words evacuation, human collision locomotion, however, less mentioned in the titles (smaller in the figure), indicating that researchers were starting to work on these issues.

2.3 Crowd papers from 2000 to 2004: virtual humans behaviors and environments

Figure 4 presents the word cloud generated as a function of the titles of 18 papers selected in this period. Firstly, it is interesting to see that, after discarding the term "crowd simulation," the most cited term is "virtual human." It contrasts with the last period, where we found in most cases the word pedestrian. It can indicate that researchers, in the last period, used most of the term pedestrians (e.g., [35]), which may be because in computer vision, people refer to pedestrians in video sequences. In the case of calling virtual humans, it may represent that the researchers in this generation focused their attention to animate and simulate individual behaviors. This period is characterized by the definition of crowd structures, behaviors, and the connection with the environments.

Farenc et al. [29] presented an architecture to simulate virtual humans in complex environments. The work proposes to create an environment not only represented with geometry but also with behavioral rules that virtual humans could apply. Lamarche and Donikian [53] propose a navigation algorithm to evolve in a topological structuring of the geometric environment to allow fast pathfinding and an efficient reactive navigation algorithm for virtual humans evolving inside a crowd. Also, in this period, we observe the terms panic, evacuation, escape, steering, and controlling in the word cloud (Fig. 4), showing that researchers were concerned with evacuation techniques. For instance, Helbing et al. [34] in 2000 investigate the mechanisms of panic and jamming caused by the motion in crowds. Their simulations suggest practical ways to prevent dangerous crowd pressures while proposing an optimal strategy for an escape from a smoke-filled room. Braun et al. [14] extend the Helbing's model to provide crowd evacuation where agents can rescue others and have different individual intentions and states.

One important word in the cloud, in this period, is "behavior," as we could see many papers proposing ways to model the behavior of crowds, groups, and individuals in this period. One example is the proposed ViCrowds described by Musse and Thalmann [71], where authors propose that a crowd is formed by groups, which in turn are formed by individuals. In this case, users can control each level of the hierarchy, as desired, with different types of information. Constrained animation of flocks proposed by Anderson [2] focuses on

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Fig. 2 Journals and conferences from where we selected papers

Fig. 3 Main terms collected from 15 papers published between 1987 and 1999. The word cloud is composed by 48 words

the generation of constrained group animations, where users can position constraints on agents' positions at any time in the animation or constrain the entire group to meet the center of mass or shape constraints. Loscos et al. [62] provide, in 2003, a technique that allowed the simulation of up to 10,000 pedestrians walking in real time. The main focus of the work is to present a pedestrian crowd simulation method to improve the local and global reactions of pedestrians.

In this period, the virtual human was the most used term in the 18 papers analyzed after crowd simulation. However, other terms also appeared as Environment, Real, Urban,

Escape, steering, etc. It may indicate that many methods describing the integration between environments and crowds, and how to structure crowds (in terms of groups) have been proposed.

2.4 Crowd papers from 2005 to 2009: the age of virtual agent navigation and the beginning of data-driven techniques

In this period, many navigation techniques have been proposed. In 2005, Lai et al. [52] propose the group motion

Fig. 4 Main terms collected from 18 papers published between 2000 and 2004. The cloud is composed by 57 different words

graphs, a data-driven animation technique for groups of discrete agents, such as flocks, herds, or small crowds. Sung et al. [96] describe a fast path planner based on probabilistic roadmaps to navigate characters through complex environments. Also, Pettre et al [83] propose a navigation graph to animate crowds in terrains. And, our last example here, from many others (e.g., corridor map [32] and hierarchical path planning [104]), is Continuum Crowds [99], that present a dynamic potential field that integrates global navigation with moving obstacles efficiently, providing the motion of large crowds without the need for explicit collision avoidance. Yersin et al. [109] present an improved short-term collision avoidance algorithm and a simple efficient group behavior for crowds. Rodrigues et al. [89] propose a model for generating groups of characters' steering behaviors based on a biologically motivated space colonization algorithm. In this case, agents into the crowd could apply formations like letters in a word.

Interestingly, 2007 was a year that some researchers propose data-driven methods to simulate crowds. Musse et al. [68] call their method a way to simulate crowds based on computer vision. Indeed, pedestrian trajectories were tracked and used to clustering groups of paths distributed in vector fields to fed virtual humans with motion stimuli. Courty and Corpetti [19] also propose to represent crowd motion as a time series of velocity fields estimated from a real crowd, and Lerner et al. [56] propose that, during a simulation, autonomous agents search for examples taken from real people that closely match the situation that they are facing and guide them in the applied behavior. Also, the last work in data driven, also published in 2007, proposes that agents learn how to move based on observed trajectories [55].

Also, in this period, Pelechano et al. [82] propose incorporating psychological models, roles, and communication in crowd simulation and also model crowds with leaders [81] that could influence the other agents. Cho et al. [18] propose integrating the known BDI (Belief-Desire-Intention) model to simulate crowds. The intention was to allow the characters to perform realistic behavior by adapting their actions with the sensed information in a changing environment. Grillon et al. [33] introduced gaze attention behaviors to crowd animation, while Maim et al. [63] proposed the use of accessories like bags or glasses or even carrying gifts to improve the realism of crowd behaviors.

Other topics have also been proposed in this period as methods for collision avoidance [45,77], to simulate dense crowds [72], and the two first books in crowd simulation have been published in this period by Musse and Thalmann [98] and Pelechano, Allbeck and Badler [79].

This period was very rich in terms of new ideas and insights. Concerning the word cloud illustrated in Fig. 5, we can observe a great diversity of words used in the paper titles. Interestingly, in this period, researchers started to use the term "virtual agent" more than virtual human or pedestrian. It may indicate the search for more autonomous and "intelligent" agents, as it reveals the published papers in the period. Other words highlighted in Fig. 5 are Navigation, Path, Control, Avoidance, Motion, BDI, etc.

Fig. 5 A set of 146 words compose the cloud of terms from 57 papers published between 2005 and 2009

2.5 Crowd papers from 2010 to 2014: the consolidation of navigation and collision avoidance techniques, and the beginning of personalities and synthetic vision methods

Synthetic vision for virtual humans was first introduced by Renault et al. [86] in 1990. In 2010, Ondrej et al. [75], and in 2014, Dutra et al. [28] explored a vision-based approach of collision avoidance between agents into a crowd. Some researchers work with synthetic vision in crowds until nowadays. Other authors proposed techniques for panic situations as Oguz et al. [76], as proposed in the first period of analysis, and data-driven techniques [16,31,113], as firstly described in 2007. In particular, Ju et al. [43] proposed a method that blends existing crowd data to generate a new crowd animation, called morphable crowds.

Indeed, from 2010 to 2014, some important navigation and collision avoidance algorithms were proposed. The first version of the very known Optimal Reciprocal Collision Avoidance (ORCA) method was proposed in 2011 [8], and until now, it is a method very used in crowd domain benchmarks. BioCrowds was proposed by Bicho et al. [11] and claimed to be the first proven free-of-collision algorithm for crowds. The method is based on space subdivision, where agents compete for space with others and move only if there is enough space.

Personalities [26], human relationships [74], and populations with purpose [57] are examples of features used to endow agents into the crowds in this period. Durupinar et al. [26] extend the HiDAC (High-Density Autonomous

Crowds), proposed by Pelechano et al. [78], by providing each agent with a personality model based on the Ocean (openness, conscientiousness, extroversion, agreeableness, and neuroticism) personality model. Each personality trait leads to the automation of low-level behavior parameters. Okaya [74] proposes a human behavior model in evacuation scenarios based on BDI and Helbing's model. Human relationships affect the states of BDI, and altruism forces among agents affect Helbing's computed movements.

Nevertheless, some frameworks and methods to test and compare crowd models have been proposed. Musse et al. [70] propose an approach to compare crowds using 4D histograms having velocities, orientations, and positions of agents in the space. Wolinski et al. [103] presented a framework to evaluate multi-agent crowd simulation algorithms based on real-world observations of crowd movements. Shoulson et al. [93] propose ADAPT, a tool to develop prototyping testbed in crowd scenarios. In addition, SteerPlex, a model to estimate the complexity of crowd simulation scenarios, is proposed by Berseth et al. [9], as its extension SteerFit, which goal is to propose an automatic parameter fitting for steering algorithms [10].

Looking to Fig. 6, we can see the titles of 77 papers selected in this period. We perceive that most of the words are similar to Fig. 5, so in our analysis, we can say that in this period, researchers in crowds seem to consolidate methods for navigation and collision avoidance, steering behaviors, and start other areas such as synthetic vision, for instance.

Fig. 6 The 173 words extracted from 77 papers published between 2010 and 2014

2.6 Crowd papers from 2015 to 2019: the era of learning techniques

From 2015 to 2019, we keep having papers related to data-driven methods, and a significant number include machine learning and statistical prediction techniques. Authors describe methods to extract real crowds data to describe efficient trajectories and combine with a learned crowd-simulation model [7]. Ahmet et al. [6] propose a data-driven approach for tuning, validating, and optimizing crowd simulations by learning parameters from real-life videos. Liu et al. [60] describe a method to predict crowd dynamics' aggregate characteristics using regression neural networks (NN). Ravichandran et al. [84] model pedestrians as autonomous, learning, and reactive agents employing reinforcement learning (RL). Amirian et al. [1] present a data-driven crowd simulation method that can mimic pedestrians' observed traffic in a given environment learned using generative adversarial networks (GANs). Also, using artificial neural networks, Testa et al. [97] propose a novel approach to estimate the total evacuation time of a given complex environment with an average error of 5% when compared to evacuation time in a real-life environment. The authors train artificial neural networks (ANNs) to learn the evacuation time of various size rooms, therefore aggregating per-room information, so the full environment can be properly estimated using ANNs.

One topic that is recurrent in all periods is evacuation. Cassol et al. [15] publish a book just on crowd evacuation, showing many applications and real case scenarios. Wong et al. [105] present an algorithm to compute the optimal route

for each local region of an environment. The idea is to reduce congestion and maximize the number of evacuees arriving at exits in each time. The system repeats until an optimal state is achieved. Bianco et al. [22] describe a statistical method to provide the crowd motion in a future time based on a specified time. The authors use Pedestrian Dead-Reckoning (PDR) to project future positions $t + K$, based on a time t, where t is a specific time, and K is the desired shift in the future time. In addition, the authors considered the complexity of the environment and a statistical distribution to represent, respectively, the impact of obstacles and the other agents in future positions of agents. Mathew [64] propose an inverse approach that is useful both to crowd simulation in virtual environments and urban crowd planning applications. Indeed, the authors propose a way where the crowd impacts the environment using optimization algorithms. Ren et al. [85] combine physics-based simulation methods with data-driven techniques using an optimization-based formulation to simulate tens or hundreds of agents at interactive rates. Results of simulation are compared with real-world datasets in terms of accuracy.

In addition to learning techniques, authoring systems have also been proposed at this period. In particular, Ho et al. [37] propose an authoring system to edit crowd distributions in different time instances, as an extension of the method proposed by Krontiris [50], where the environment is modeled as an influence map based on attractors used to guide crowd simulation activities. In terms of navigation and crowd collision, in 2017, Stüvel et al. [94] present a novel dense crowd simulation method. In real crowds of high density, people maneuvering the crowd need to twist their torso to

pass between others. Their method does not use the traditional disc-shaped agent, but instead employs capsule-shaped agents, which permit to plan such torso orientations. Contrary to other crowd simulation systems, which often focus on the movement of the entire crowd, the method distinguishes between active agents that try to maneuver through the crowd, and passive agents that have no incentive to move. The authors introduce the concept of a focus point to influence crowd agent orientation.

In this period, we also have more papers in Virtual, Augmented, and Mixed realities [23,41,67]. Moussaïd et al. [67] propose a shared three-dimensional virtual environment as an experimental platform for conducting crowd experiments with real people. Interestingly, they showed that crowds of real human subjects exhibit typical patterns of real crowds, as observed in crowded real-life situations. In addition, some researchers propose papers that evaluate and measure the impact of user's presence, such as [51,80,108]. For instance, in [54], authors propose to investigate performance and user experience in Social Virtual Reality (SVR) embodied, immersive, and providing face-to-face encounters. The user study showed positive effects of presence feeling and the possibility of interaction and co-presence.

Furthermore, in this analysis, we included papers in cultural and personality aspects. Favaretto et al. [27,30] introduce a new method to crowd analysis extracting Hofstede dimensions from video sequences, to later be used in crowd simulation [24]. Durupinar et al. [27] propose to parameterize mobs' common properties to create collective behaviors. Their model associates psychological components with individual agents into the crowd providing emergent behaviors. Also, a recurrent subject is the group formation. Here we mention the work of Zhang et al. [111] where authors propose a way to control crowds based on constrained and controlled groups formation. Although there are many methods in crowds contagion nowadays, we mention two of them introduced in this period. Borg et al. [12] proposed an extension of Bosse's model [13] specifically to the crowds' domain. In their work, authors propose to propagate the emotion among agents in the crowd. Basak et al. [5] propose a data-driven approach for tuning crowd simulations with parameters from real-life videos. Authors demonstrate their method in three real-life incidents: a bombing attack, a panic situation on the subway, and a Black Friday rush, where agents' behaviors considered panic contagion.

Finally, analyzing Fig. 7 one can note the importance of data-driven and learning in the word cloud and interactive, experience, VR, AR, contagion, group behavior, emotion words, as discussed in this section.

3 New trends: papers from 2020 and beyond

This section presents some papers from the selected 46 published in this period. Indeed, we included some papers on the crowd domain published in 2021. Certainly, many more papers are going to be published in 2021. For the papers cited in this work, we searched in Google scholar with keywords crowd and simulation. We selected the papers that focus on crowd simulation and papers that were peer-reviewed in relevant forums.

Figure 8 shows the word cloud generated based on selected titles. It is interesting to see that the most used term, after crowd simulation, discarded in all periods, is again pedestrian (as the period before 2000), followed by Virtual Human (as in the period 2000–2004) and not Virtual Agent as the lasts periods. It may indicate the community tendency to simulate individuals with more human characteristics, as emotion [100,107], natural language [61], among others. Besides, authors propose methods to individualize agents into the crowd, as for instance providing door and doorway etiquette [38], distracted agents [49], providing agents which motion is impacted by fluid forces [91] and obeying social distance in pandemic situations [44]. We also saw papers mixing crowds in VR environments, as proposed by [102], where authors study the effects on users during interaction with a virtual human crowd in an immersive virtual reality environment or still exploring tactile feedback during immersive walking in VR applications [48].

In this period, we found some papers exploring artificial neural networks to predict crowd emotions [100] and to integrate data-driven walking behaviors [47]. Crowd analysis is still present in papers in 2020. Li et al. [58] propose quantifying and detecting collective motion through a multi-stage clustering strategy and a method to provide crowd anomaly detection and localization using histogram of magnitude and momentum [4]. Regarding crowds and environments: Sun et al. [95] propose to predict crowd flows using graph convolutional networks. Zhou et al. [115] present a case study of Beijing Subway stations. This paper proposes a modified social force model to investigate crowd evacuation dynamics taking into account the influence of emergency signs.

High-dense crowds and evacuation scenarios is kept being studied in 2020. Firstly, the study of the impact of panic on crowd movement is based on information entropy [114], and the investigation of the evacuation path optimization (EPO) problem using ant colony inspiration [39]. Finally, high abstractions of crowds have been proposed as BioClouds and Legion models [20,21], where authors want to simulate huge big crowds, e.g., a million of people, however without simulating each individual, but keeping the global crowd properties and the possibility to zoom in individual behaviors.

Fig. 7 276 words extracted from 106 papers published between 2015 and 2019

Fig. 8 The 173 terms extracted from 46 papers published in 2020 and 2021

In 2021, some methods have already been proposed to assist the mobility of people in scenarios of evacuation of buildings, dangerous situations such as a terrorist attack, strategies to find optimal routes, the impact of groups of agents on the efficiency of the crowd, and even to simulate human mobility during the COVID-19 situation. Here are some examples: Mirahadi and McCabe [65] propose a real-time model for building evacuation scenarios based on Dijkstra's very know algorithm [25]. Li et al. [59] present

a rule-based model based on an extended cellular automata model considering groups of agents to study Pediatric Hospital evacuation. Xie et al. [106] propose a model that accounts for social groups, based on a social force framework, to investigate evacuation dynamics in pedestrian crowds impacted by groups of agents. Other authors have also proposed approaches with group behaviors in recent years, for example [46,66]. Zhang et al. [112] investigate an optimal guidance strategy for large-scale crowd evacuations, increasing the

Fig. 9 600 terms extracted from 319 papers published since 1987 in crowd simulation

computational efficiency. Charrier et al. [17] propose an approach using the well-known Helbing's model [35] to include a nervousness propagation mechanism, and then the authors study its impact on a classical simulation setup. Furthermore, finally, Shi et al. [92] propose a work which goal is to verify the applicability of the Social Force Model (SFM), embedded in Viswalk software, to reproduce the effect of egress flow under normal and emergency conditions. As can be observed, many papers have been proposed in the context of evacuation and crowd mobility, as the example of Orallo and Martinez [36]. The authors study models for evaluating the temporal and spatial risk of transmission of the COVID-19 as a function of humans mobility.

4 Final discussion

This paper presented a history of crowd simulation focusing mainly on how the many techniques that were proposed in the past were organized over time. For instance, it is interesting to show the evolution of used terms, as Pedestrian (until 1999), Virtual Human (2000–2004), Virtual Agent (2005–2009), Virtual Agent and Pedestrian (2010–2014), again Virtual Agent (2015–2019), and finally, Pedestrian and Virtual Human, that appeared again in 2020 and 2021. In terms of research that keep being proposed since the early years, we can cite evacuation models, crowd, group, and individual behaviors, and all types of navigation methodologies. The recent tendencies that seem to be strong nowadays (and probably in next years) are: data-driven techniques, the usage of machine learning algorithms applied to crowds, the

Fig. 10 Histogram of occurrences of 600 terms extracted from 319 papers published since 1987 in crowd simulation

specialization of individual behaviors to be more "human" and "intelligent," and recent papers show intense energy focused on evacuation applications. In the latter case, we believe that more evacuation techniques will be proposed trying to include other methods such as individual behaviors and machine learning methods, at the same time. So, we believe the most relevant application is still the evacuation of scenarios in the crowd area. Figure 9 shows the word cloud generated using 600 different terms in the titles of papers in the crowd domain since 1987. Thirty-six of these words, shown in Table 1, were used more than ten times in the titles. We highlighted some words in the table as crowd (225 occurrences), Agent (32), Pedestrian (26), Human (21), and Evacuation (20). Also, Fig. 10 shows the histogram of terms repetition in the titles.

There is still a long way to go to achieve very realistic crowd simulations, as expected in real life. While crowd

Table 1 The table presents the terms used more or equal 10 occurrences in the titles of 319 papers, since 1987

Word	Count	Word	Count	Word	Count
Crowd	**225**	Simulate	153	Model	59
Virtual	55	**Behavior**	**44**	Use	42
Based	41	**Agent**	**32**	**Environment**	**29**
Real	29	**Pedestrian**	**26**	**Group**	**26**
Time	24	**Human**	**21**	Interactive	21
Approach	21	**Evacuation**	**20**	**Driven**	**18**
Navigation	**17**	Data	17	Motion	15
Dynamic	15	Animated	15	Steering	13
Density	13	Control	13	Generic	12
Plan	12	**Emotion**	**12**	Collision	11
Learned	11	Framework	10	Optimal	10
Large	10	Build	10	Populate	10

simulation is generally seen as the process of simulating the movement of many entities or characters, in reality, huge crowds generally do not walk, e.g., 90% of crowd images on Google Images shows static crowds. Nevertheless, even when crowds move, they can run or even swim in a crowded pool. Most path planning algorithms for walking will not work for swimming. People in a city generally walk and stop only to watch events or chat with people. Many people in public parks would sit down on the grass or on public seats. We should see more children, babies, old people, and disabled people in terms of crowd appearance. We should be able to mix people with cars, bicycles, etc. Currently, individuals in crowds can carry accessories, what we do not see is crowds manipulating objects, opening doors, eating, moving objects from one place to another, exchanging objects. Other examples of scenes we have not see until now in crowd simulations are large restaurants, crowded buses, trains, etc.

Most simulated crowds are composed of people with a goal, but in real life, on a Sunday afternoon, many people wander without specific goals. We ultimately need to introduce natural motivations to simulate more complex and realistic situations. For example, in an airport, people should not just check-in, go to the security then the gate, as in most simulations. They should be able to go to restaurants, cafes, shops, toilets, maybe meet someone, according to their internal motivations. Such models exist, but the problem is that it will be extremely CPU intensive to introduce them in simulations, having diversity and realism while being as autonomous as possible, avoiding creating extra work for designers. Indeed, the control is still an issue in crowd simulation because, while we want autonomous and emergent crowds evolving in a virtual environment endowed with realistic motivations to be credible, we also want to interact with the individuals and make a new narrative or play a game. Much have been studied in the crowd area, as this paper showed, but certainly, much more remains to be done.

For new perspectives, the following are some possibilities, among many others:

– To improve the crowd properties and realism in macroscopic behaviors, using machine learning techniques, as it has been made in recent papers. The goal is to have more intelligent crowds at the macrolevel;
– To increase the realism of individual behaviors, as personalities, cultural aspects, and emotions, providing more intelligent and specific individuals, even including facial and posture motion;
– The last two items must work together, providing a method to zoom-in and zoom-out in crowd simulation to enable the visualization of details at the desired level. Also, the individuals should be part of the collective behavior in a synchronized and coherent way;
– To provide realistic crowds in VR and AR applications, including macro- and microbehaviors, facial, body, and cloth animation. Users should be able to select the level of details they want to control, and finally
– New methodologies in highly dense crowds, including all micro-level behaviors and evacuation applications, integrated with computer vision techniques.

Since the seminal paper of Reynolds [88], much has been done in crowd simulation research. This paper presents a view of the history of proposed crowd simulation methods and the main achievements. A dataset containing more than 300 papers [10] published in specific conferences and journals is discussed in depth. The crowd domain is one area where many researchers have worked for many years, and we are still far from having a model where we can firmly believe in crowd behaviors at micro- and macrolevels. It indeed well resumes the challenge of the area. The future points

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[10] The list of papers is available upon request.

to integration with machine learning methods and hardware development, which will undoubtedly bring new achievements to this area.

Declarations

Conflict of interest The authors declare that they have no conflict of interest.

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