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Crowd behavior analysis: A review where physics meets biology

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ABSTRACT

Although the traits emerged in a mass gathering are often non-deliberative, the act of mass impulse may lead to irrevocable crowd disasters. The two-fold increase of carnage in crowd since the past two decades has spurred significant advances in the field of computer vision, towards effective and proactive crowd surveillance. Computer vision studies related to crowd are observed to resonate with the understanding of the emergent behavior in physics (complex systems) and biology (animal swarm). These studies, which are inspired by biology and physics, share surprisingly common insights, and interesting contradictions. However, this aspect of discussion has not been fully explored. Therefore, this survey provides the readers with a review of the state-of-the-art methods in crowd behavior analysis from the physics and biologically inspired perspectives. We provide insights and comprehensive discussions for a broader understanding of the underlying prospect of blending physics and biology studies in computer vision.

1. Introduction

> The one who follows the crowd will usually go no further than the crowd; the one who walks alone is likely to find herself in places no one has ever been before, Albert Einstein.

While this quote is lived by many, this paper is motivated by the contrary. Our work is based on the notion that literally, *one who follows the crowd will surpass solitary individual, and together with the crowd, 'venture beyond places' where no lone individual is capable of venturing to*; a phenomenon known as the emergent behavior. Emergent behavior arises in a swarm or crowd with certain class of entities (e.g. insects, human, animals, etc.); whereby, each entity is self-organized and together they portray a complex and coordinated collective behavior. The essence of the emergent behavior is based on a simple rule of thumb, where entities engage with one another using basic interactions. This in turn heightens ones' sense of responsiveness to the surrounding, and instantaneously brings them closer to their goal. What makes it interesting is that, this resultant phenomenon is not possible to be achieved by solo individuals.

Over the past years, biologists have observed the emergent of collective behaviors in organism, insects and animals and were constantly investigating the underlying mechanism that allows unity in a swarm [1–4]. For example, a school of fish that swims together and yet not colliding with each other, or a flock of starlings steering in the air with the uncanny synchronization. The slime mold that exist as a single-cell organism, congregate to form multicellular when food supplies is scarce, working in tandem to search for the shortest path to food source. Another well-known example is the foraging activity of a colony of ants. Although each ant follows a set of simple rules, the colony as a whole, acts in a sophisticated way that increases its foraging efficiency [5]. Fascinatingly, this similar behavior has been observed in human crowds as well. Amongst the early works that were motivated by the emergent behavior in human crowds was the concept of the 'mind' by Bon in [6] which stated that, when individuals in a crowd gather and coalesce, a new distillation of traits emerged. He referred to the emergent behavior as collective 'unconsciousness' that robs every individual member of their opinions, values and beliefs. He put forward that the emergent behavior is very subtle and ignorant to each individual, yet, is capable of forming intriguing collective 'group mind' that works wonders. This phenomenon can be seen commonly in a crowded scene. For instance, when two flows of people moving in the reverse directions, a uniform walking lanes for each direction would be formed spontaneously although there is no communication amongst the individuals in the crowd.

In existing literature, the dynamics of human crowd are often studied through analogies with theories in physics and biology. The idea of relating the motion of crowd with fluid, liquid or electrons in aerodynamics, hydrodynamics or continuum mechanics respectively, has generated many research in crowd analysis since the past years [7,8]. Accordingly, physics-inspired studies assume that the individual in a crowd tends to follow the dominant flow of the crowd and

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thus, the motion of highly dense crowd resembles fluid. Hence, theories and methods in fluid mechanics are adopted to comprehend the flow of human crowd. In another physics-inspired example, the kinetic theory of gases is applied to model the sparse and random interaction forces amongst individuals in a crowd. On the contrary, from the biology point of view, individuals in a crowd resemble the entities in a swarm. Each individual in the swarm exhibits diverse interaction forces towards achieving the final goal, which is apparently common amongst members in the swarm [9,10]. For example, the motion of individuals in a train station, where everyone is moving with different pace towards the common exit region, or the diverse motion of individuals finding their ways to the boarding area.

Nevertheless, there is no clear distinction between the approaches inspired by the two sciences: physics and biology. Instead, we observe that some terminologies or notions from both approaches share interestingly similar understanding and perspective, while holding on to some minor differences. The study of the human crowd behavior from the perspectives of the two sciences drawn into the field of computer vision is a new and rapidly developing study [11]. It is predominantly deemed as a notion for crowd behavior analysis to enhance and assist the analysis of visual crowd surveillance, which aims to imitate the human visual perception. The capability to emulate human visual perception allows the development of practical systems that provide meaningful and concise description of crowd behavior, to better assist human in crowd surveillance, which is the focal interest of this study.

1.1. Comparisons with previous reviews

Although there have been great interest and a large number of methods have been developed for crowd analysis in general, there are limited comprehensive reviews which focused on crowd behavior understanding [12]. Most existing survey papers [12–17] focuses on the computer vision techniques and review the essential features required for application specific crowd analysis. To the best of our knowledge, none of the aforementioned reviews provide in-depth discussion from the perspectives of physics or biologically inspired approaches in the context of crowd behavior analysis.

The closest attempt to bridge the studies between physics and biology in the context of crowd behavior understanding was by Hughes [18]. His work emphasizes on the key distinctions between physics and the actual crowd. Although the discussion was focused only on crowd modeling from the physics perspective, the concept that described aptly the 'thinking' component of fluids spurred thought that the interactions between individuals in a crowd is far more complex than particles in fluid. This coincides with the understanding of crowd motion in biology. Another work in [19] categorized the state-of-the-art methods in crowd simulation into three broad approaches which include (i) fluids, (ii) cellular automata and (iii) particles. He suggested the classification of existing work without discussing much on the underlying motives and attributes between these categories. In addition to the 3 broad categories proposed by Leggett [19], Zhan et al. [13] reviewed approaches to infer crowd events by further dividing the 'particles' category into agent and nature-based models; leading to 4 categories of crowd models from the non-vision approaches. This includes (i) physics-inspired, (ii) agent-based, (iii) cellular automation and (iv) nature-based. While their work acknowledged the advantages of integrating the non-vision models with computer vision methods for crowd analysis, the in-depth discussion on the different non-vision models from the physics and biology perspectives is lacking. Thida et al. [12] presented a review with systematic comparisons of the state-of-the-art methods in crowd analysis, where the merits and weaknesses of various approaches were discussed comprehensively. Their work is based on the three distinct philosophies for modeling a crowd by Alexiadis et al. [20], where crowd models are categorized as microscopic, mesoscopic and macroscopic. The microscopic model deals with the crowd as discrete individuals while the macroscopic model treats the crowd as a unit. The mesoscopic model combines the properties of the former two models, that is, the microscopic state of pedestrians are maintained with an addition of the general view of crowd. Yet, the gap between the two approaches has not been discussed clearly.

Other papers are more specific towards understanding crowd behavior, disregarding the point of whether the different methods of analysis are inspired by the studies from physics or biology. Each of the works provides critical outlook of existing literature pertaining to the different aspects of crowd analysis and serves as a reference point to all computer vision practitioners in the domain. However, we observed that a great deal of them are focused on *physics-inspired* approaches. Helbing et al. [21] discussed their analysis on using density and pressure attributes to infer two new phenomena in crowd: the stop-and-go and turbulent flows. Their discussions are highly influenced by physics and provide readers with insights to where and when accidents tend to occur in crowded scenes, and on how the proper management of crowd can ensure prevention of crowd disasters. In another review that is based on the notion that individuals in crowds behave in ways like particles in the fluid is by Moore et al. [22]. Their work adopted the concept of scale in hydrodynamics (the study of liquid in motion) as opposed to the common adaptation of aerodynamics (the study of gaseous or air in motion). The main difference between the two is that in the former, the interaction forces between individuals in the crowd tend to dominate the motion of the individuals, while in the latter, the interactions between individuals are few and random motion is most likely to dominate the crowd behavior. In a more recent review, Jo et al. [23] briefly highlighted the difference between physics-based and physics-inspired methods. Accordingly, physics-based methods are rooted in fundamental physic ideas whereas the latter are inspired by the laws of physics. In [10,24], the limitations of existing physics-inspired models to describe pedestrian behaviors and crowd disasters are discussed comprehensively. This includes the difficulty to capture the complexity of crowd behaviors using a single model and the insufficiency of current models in understanding the interactions between individuals and their environment. Thus, they introduced the integration of *cognitive science and physics* for a more holistic solution. Some examples of the heuristic rules which are derived from the natural cognitive of human include the assumptions that an individual tends to move towards a possible entry or exit, and that an individual is very likely to move its motion according to his or her gaze angle. Interestingly, the introduction of such simple rules adheres to the concept of emergent behavior, where the collective dynamics of a social system with many interacting individuals can be modeled through simple rules. A more comprehensive review of physics-inspired crowd models covering the 3 main aspects of crowd motion pattern segmentation, crowd behavior recognition and anomaly detection can be found in [17]. While this review provide broad discussion on existing models, algorithms and evaluation protocols of research in crowd, the outlook of computer vision approaches from the perspectives of physics and biology remains unstated. Other relevant researches include the study on crowd dynamics and how the different dynamics of crowd can lead to the various issues in crowd safety by Johansson et al. [25], the modeling of crowd dynamics from the viewpoint of *mathematics* [26], the analysis of human behaviors from the perspectives of *social signal processing* [27], the study of crowd dynamics from the *psychology* perspective by Reicher [28], the underlying rules that lead to collective behaviors for group intelligence problem-solving by Fisher [29] and the comprehensive review on the basic laws of *physics and mathematics* that describe collective motion which leads to the emergent behavior in groups of animals or humans [30].