A Survey of Latest Approaches for Crowd Simulation and Modeling using Hybrid Techniques

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***Abstract*— In recent past, computer simulation and modeling technologies have been used for variety of applications concerning crowds both in normal and emergency situations. Majority of models often fall into two extremes: either to simulate homogeneous high density crowd or to model individual social, physical and psychological behaviors of heterogeneous relatively small size crowd. Currently, researchers start exploring hybrid models that combine the benefits of both classical approaches to simulate large size heterogeneous crowds. In existing hybrid models, zones based in widely studied approach but have limited applicability due to its dependency on well defined boundaries of physical space. Other techniques like sequential and layer models need further investigations and provides limited crowd modeling features. Moreover, current hybrid models need to provide diverse behavioral features for crowd; further requires testing its impact on scalability and execution efficiency of simulation. There is significant need in literature for generic framework with flexible model selection capability to observe crowd dynamics. This paper assesses the major existing work in hybrid techniques for crowd modeling and simulation. We anticipate that this work will serve as useful insight on hybrid crowd modeling techniques, their issues and future research directions.**

Keywords– Crowd Dynamics; Simulation Models; Hybrid Models; Crowd Evacuation;

I. INTRODUCTION

Simulations and behavior modeling of crowd have been widely studied in past decades. Researchers have tried to investigate crowd behavior for various domains like: entertainment (movies and games), crowd planning and management, traffic flow, architectural design and other similar applications. Crowd dynamics is of great interest both under normal and critical situations. For instance, many buildings like schools, shopping malls and stadiums where large number of people gather to perform several daily routines are critical places in terms of proper design to ensure peoples' safety. Architects of such closed buildings need to provide a careful design where large number of people can exit using limited number of exit points both under normal and emergency situations. It is impractical in terms of cost and safety to verify building plans with real crowd. Crowd modeling and simulation can greatly assist authorities in such cases, to have efficient and safe public spaces.

Studying the behavior of crowd in specific situations is fascinating but a very complex problem. Each individual in crowd may react to a certain event in a different way. Also, behavior of an individual in a crowd may get affected by others as being part of the same crowd. In recent past, crowd modeling and simulation has gained tremendous popularity among psychologists, sociologist, physicists and computer scientists. To represent behaviors of crowd, various models and simulation softwares have been presented as summarized by Zhou and colleagues in their comprehensive review [17]. Crowd simulation models are critical to study behavior of crowd in various situations and they are building blocks for crowd simulation software. These models are mainly classified as macroscopic, mesoscopic and microscopic based on underlying space resolution, crowd size and granularity of crowd features/behaviors. Macroscopic and mesoscopic models mainly simulate overall crowd behavior and flow while ignoring behaviors/features of individuals in a high density crowd. On the other hand, microscopic models simulate relatively small size crowds and consider more detailed behavior of individuals or sub groups in crowd. These classic categories facilitate modeling of either large homogenous crowd or small heterogeneous crowd with detail behaviors.

To simulate a real crowd, it is often required to model large size crowd as well as the individual behaviors in certain situations in effective and efficient manner. Regardless of abundance of crowd modeling and simulation approaches, there are still many open questions to investigate for various potential applications. Recently, researchers felt the need for modeling high density crowd not only for observing its flow but also individual behaviors with better execution time. Hybrid techniques have been proposed for different crowd modeling applications where it successfully handles large crowd size while considering heterogeneous individual behaviors. In this paper, we provide an insight review of these hybrid crowd modeling techniques, their current limitations and future research directions.

The remainder of this paper is organized as follows: Section II provides the summary of classic crowd simulation models. Section III briefly outlines the need and advantages of hybrid techniques instead of selecting classic crowd

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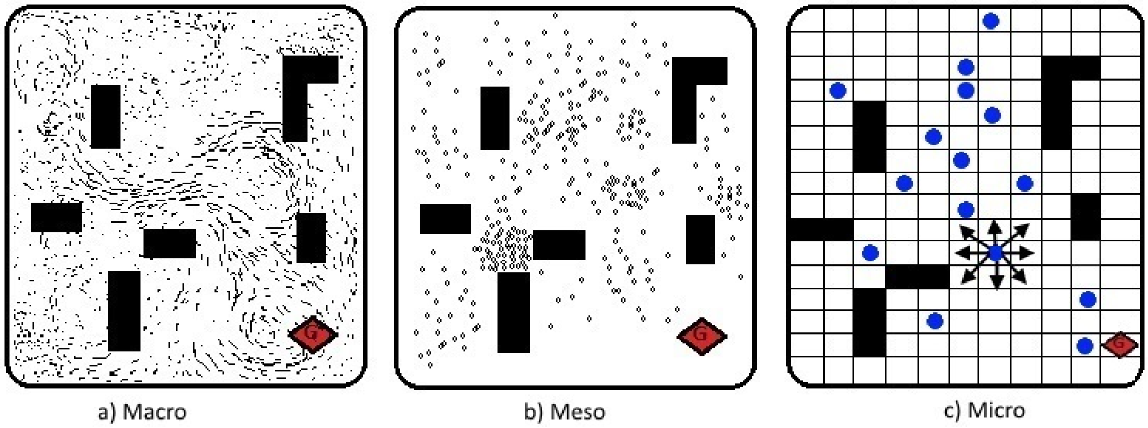

Figure 1: Basic Crowd Simulation Models

simulation models. In Section IV, we discuss existing hybrid models which are categorized based on their implementation details. Section V discusses limitations of hybrid models, open research problems and future research directions for crowd modeling and simulation. We summarize the conclusion drawn from our survey in Section VI.

II. Classic Crowd Simulation Models

In this section, we discuss crowd simulation models which were initially proposed to simulate crowd in various fields. Broadly, crowd simulation models can be classified into these three categories due to different spatial resolution:

- Macroscopic
- Mesoscopic and
- Microscopic.

While simulating very large size crowd, often is the case that user is only interested in observing moving pattern of whole crowd. Macroscopic models can play important role as it assists to simulate only abstract behavior of large crowd instead of modeling individualistic behaviors as presented in Figure 1(a). The basic concept resembles the fluid and particle motion in physics. This technique does not consider individual behaviors, unique characteristics of individuals and interaction of these individuals in the crowd. This makes it unrealistic approach when the individual behavior within the crowd in normal or emergency situations is a concern. However, these models enable simulating movements of very large density of crowd [1].

The second category of models is mesoscopic that provides much finer observation of individual movements and still be able to simulate relatively large size of crowd. Mesoscopic models are based on cellular automata [2] having a better spatial resolution on the cost of more execution time. Space is divided as a regular grid where each cell can contain one or no person at any simulation step as shown in Figure 1(c). Due to underlying geometry constraints, individuals move cell wise with fixed possible movement directions. This movement behavior makes it less suitable for realistic simulation of high density crowd. On the other hand, it has simple transition rules (8 positions to move from current cell) from one state to another and can easily integrate the some behavior modeling of individuals.

The most widely researched category to simulate crowd is microscopic models that focus on detailed behavior and unique features of individuals in a simulation. It includes techniques like social force model [3], centrifugal model [4] and agent based [5] approaches. These models implement individuals as discrete objects and carry the simulation in continuous space unlike fixed size cells in cellular automata. In this alternative, it is possible to have complex pedestrian movements/interactions while preserving physical, social and psychological features of individuals.

Social force and centrifugal models are based on particle system where individuals are considered as particles in a physical world. In these models, each object in environment has its own potential (attraction/repulsive force) which governs behaviors and movements of crowd by implementing global and local rules. It can also generate some interesting movement patterns among individuals like queuing and jamming during exit as shown in Figure 1(b). In contrast, agent based methods focus on each individual in crowd as an intelligent autonomous entity. Each individual can independently make its decision while considering the local environment factors and other individuals/objects in the simulation. This approach allows implementing more behavioral and social aspects of heterogeneous individuals in crowd. In such models, providing individuals with detailed path planning, intelligent actions and decision making has disadvantage of high computational cost for large density crowd. Thus, with this model it is impractical to simulate

TABLE I: CHARACTERISTICS OF CROWD SIMULATION MODELS

Feature	Macro	Meso	Micro	Hybrid
Density	Huge	Medium	Small	Huge
Group Behaviors	Nil	Nil	Yes	Yes
Social Factors	Nil	Nil	Yes	Yes
Heterogeneous Crowd	Nil	Nil	Yes	Yes
Computational Cost	Low	Low	High	Medium

high density crowd with detailed individual behaviors in reasonable execution time.

Over the years, researchers suggested many variants of these models. In result, the boundary between classic social force models, agents based models and cellular automata models became indistinct. Despite these improvements, most work in crowd simulation can be classified on two extremes (macro and micro models).

III. Need for Hybrid Approach

Hybrid models are further extension of classic crowd models to overcome problems faced in such techniques. While selecting suitable model for crowd simulation, following factors play major part:

1) Crowd size
2) Need for implementation of individual behaviors
3) Computation cost

Both macro and micro approaches suffer when the need of application is to consider high density crowd with requirement of individual behaviors. Moreover, high computation cost hinders implementation of real scenarios with both abstract and individual behaviors of large crowd. This tradeoff limits the researchers to select right tool based on underlying model. Recently, researchers started investigating hybrid approaches to simulate crowd where both high level crowd flow and low level individual behaviors can be implemented. In this paper, ”hybrid” refers to combining the various techniques across the macro and micro models. A comparison between classic models and hybrid approach is presented in Table 1. In the table Macro means macroscopic, Meso means mesoscopic and Micro means microscopic approaches.

As shown in Table 1, hybrid models are desired to combine benefits of both macro and micro approaches while achieving the results with affordable computational cost. Not only hybrid models can support huge density of crowd but also it can consider social and group behaviors for heterogeneous population as microscopic models. In comparison, Macro and Meso techniques are unable to deal with microscopic level of high density crowd as that incurs very large computational cost. In addition, due to involved cost microscopic model can only deal small size crowd. Often, in large crowd simulations interest is to have abstract flow of crowd as well as to observe certain individual behaviors for specific details. The overall flow of crowd is derived using a macro technique (e.g fluid motion) to reach the destination whereas predefined area(s) of interest is simulated using micro approach (e.g agents) to observe the behaviors of individuals. In next section, we will discuss existing hybrid approaches in literature.

IV. Existing Hybrid Models

Recently, researchers investigated the hybrid approaches by combining both macroscopic and microscopic techniques that complement each other. Existing work has attempted to use both types of models either partially or completely. These recent developments in hybrid models can be considered in following three categories:

A. Zone Based Models

In this approach, simulation space is divided into multiple zones. Based on application needs, each zone is simulated either for macroscopic or microscopic model. Zone simulated under macroscopic technique provides overall flow of crowd whereas zone simulated with microscopic model offers individual level behaviors observation.

Generally, the proposed techniques run both models simultaneously on pre-defined zones [6][7][8]. Usually, the macro model is used to simulate the homogenous crowd in large area where objective is to have smooth flow. In contrast, few parts are marked as decision points (road intersection, doors etc) to observe the behaviors of individuals. This allows having global crowd movement pattern as well as freedom of integrating individual characteristics, social and psychological behaviors of crowd with reasonable computational cost. This type of hybrid approach is well suited for traffic and indoor buildings simulations. Authors have combined continuum (macro) model with agent based (micro) to simulate the evacuation scenarios [6][7] and the normal flow of crowd in [8]. Combining these two techniques for a hybrid approach offers more simulation efficiency over microscopic method and also improves quality of simulation over macroscopic model. On any simulation step, it can simulate both homogenous large density crowds with macro method while in another zone of interest it simulates heterogeneous individuals with micro technique.

It is evident that such hybrid approach gives significant benefits instead of using traditional models. On the other hand, it is critical to simulate crowd movement between these two zones modeled by different approaches. Individuals in crowd need a smooth transition between the two different zones known as aggregation and disaggregation as shown in Figure 2. However, this approach restricts the possible movement direction of crowd which makes it less suitable for simulating large social events and gatherings in open space. Moreover, global and individual features of simulation could not be observed simultaneously in same zone.

On the contrary, dynamic coupling of macro and micro approach in desired zone to simulate large scale traffic

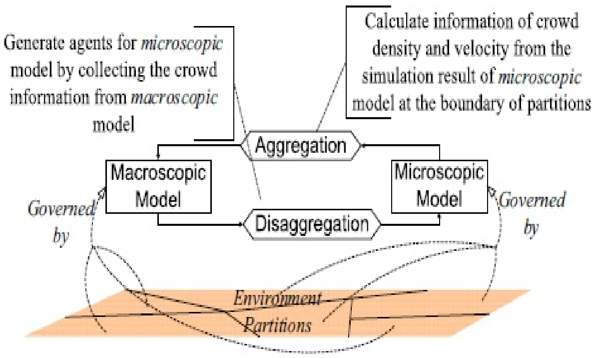

Figure 2: Deployment of Zones based Hybrid Model, Figure taken from [8].

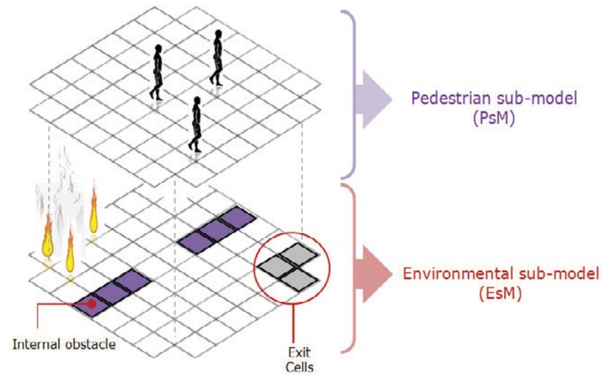

Figure 3: Hybrid Model with Separate Environment and Pedestrian Layers, Figure taken from [10].

flow has been proposed in [9]. This enabled automatic switching between two simulation models based on certain criteria (application requirement, volume and velocity of traffic, desired behaviors etc). It gives freedom to observe simulation as per user desire under macro model for overall flow of traffic or to simulate heterogeneous individual cars by a micro model.

B. *Layers Based Models*

Another approach to simulate crowd is by adopting both micro and macro techniques partially into different layers. Entire simulation space runs both techniques to drive smooth crowd flow as well as movement patterns for individuals in the crowd. It usually performs global path planning, local obstacle avoidance and other desired behaviors of crowd each on a separate layer [10][11][12].

Model is basically divided into two separate layers: overall movement of crowd is simulated by set of equations in first layer as macro model. This first layer gives the crowd movement pattern which goes to second layer as input. Where the movement of each individual is simulated based on a microscopic model in second layer. Since this approach requires a complete execution of microscopic model for all individuals in crowd which is not cost effective as density increases. For instance, in [10] cellular automata was introduced to model the environment (obstacles, exits, fire location etc.) in discrete cells on bottom layer. Simple rules govern the movement of crowd towards the exits on this level. On the other hand, top layer represents pedestrians as intelligent agents who can interact with environment as well as with other agents in surroundings as indicated in Figure 3 which has been taken from [10].

Layer based hybrid models offer extensibility in terms of adding new behaviors on a new layer. Though, aforementioned layered models have discussed limited capacity to exercise diverse macro and micro level behaviors. They do not consider the consequences of introducing complex social and psychological behaviors for large crowd density. As the micro model still needs to be executed for all individuals in crowd, efficiency of such simulation is directly affected by the crowd density and complexity of implemented behaviors. In contrast to zone based hybrid model, this particular method discards the whole macro model if it is not applicable for some part of the crowd.

C. *Sequential Models*

Similar to layer based hybrid models, another approach is sequential hybrid technique which also runs both macro and micro models for whole crowd. However, it first runs macro model to guide the movement pattern of crowd and then applies micro model to same crowd for observing the individual behaviors.

It executes both models in sequential manner where a synchronization method is required to transfer the crowd state between both modes [13][14]. Initially, macro model runs as in [13] based on speed-density relationship to simulate the crowd movement. Within same simulation time step, synchronization module helps to transfer macro results to microscopic model. Later, microscopic model is executed based on movement pattern and density generated in first macro step. Hence, synchronization mechanism is critical to transfer results of both simulations models within one time step between each another.

To avoid the disadvantage of executing micro model for whole crowd as in layer and sequential methods, a multi-resolution approach [15] was introduced to combine both macro and micro models in iterative manner. Macroscopic model was used to generate the crowd movement when it was stable; if some event disturbs the stable movement of crowd, simulation will switch to micro model to observe each individual's behavior more closely. In comparison to layer and sequential models, this approach improves the simulation efficiency by not applying both models for whole crowd. It also benefits by not applying macro model on part of crowd for which it is not applicable. However, this method

TABLE II: COMPARISON OF HYBRID MODELS

Model	Scalability	Efficiency	Behaviors
Zones based			
Pedestrian evac.[6]	1000	Not applicable	Yes
Crowd evac.[7]	20,000	Real time	Limited
Crowd sim.[8]	Unknown	Real time	Limited
Traffic sim.[9]	190k	Real time	Limited
Multi-Layer			
Emergency evac.[10]	670	Not applicable	Yes
Crowd sim.[11]	40,000	Real time	Limited
Crowd sim.[12]	640	Not applicable	Limited
Sequential			
Crowd evac.[13]	1000	Not applicable	Limited
Crowd sim.[14]	20,000	Real time	Yes

is more suitable for crowds with stable movements to have an efficient simulation.

D. Comparison of Hybrid Techniques

Three categories of hybrid models are discussed in last three subsections. In this section we evaluate these approaches based on following criteria:

- Scalability
- Execution efficiency
- Supported behavioral characteristics

Zone based hybrid model is most widely investigated approach and it also out performs other techniques in terms of execution cost and use of underlying models. In contrast, main drawback of layer based and sequential hybrid models is to apply both macro and micro techniques to whole crowd. By applying complex behaviors for individuals in these models further leads to higher execution time due to use of microscopic model for whole crowd. In summary, zone based hybrid models are most suitable choice for an application due to applicability of underlying macroscopic and microscopic models in specified zones. It can avoid the applicability issue of macroscopic model by simulating the part of crowd with microscopic approach where macroscopic model is otherwise not applicable.

In Table 2, we provide a comparative summary of the three categories of hybrid models on the basis of scalability in terms of individuals, execution efficiency of simulation and implemented behavioral features. Across these categories, some authors [9][11][14] have claimed the high scalability of these hybrid techniques where it also provides real time simulation efficiency for large density of crowd. However, most of the existing work in hybrid models does not consider complex implementation of social, physical and psychological behaviors [7][8][9] and [11][12][13] for heterogeneous crowd. Among the existing work, hybrid model mentioned in [14] is the only technique which has considered behavioral factors for relatively large crowd (20K) with real time execution efficiency. Furthermore, this comparison suggests more investigation of hybrid models to provide real time execution efficiency where it can incorporates behavioral features for large density of crowd.

E. Generic Framework

In existing literature, there is significant need to have a generic framework which is able to select models on user request for observing various crowd dynamics. Simulation of an application at hand requires using most appropriate software according to crowd density, desired level of individual behaviors (physical, psychological and social) and execution time. Simulation softwares are dependent on underlying models that cannot be changed as per end user requirement. This limits the choice of these softwares for certain type of applications where underlying model does not serve the purpose.

A recent effort to develop a generic framework for multi-scale coupling of pedestrian simulation models for transition zones is presented [16]. It asserts to be independent of associated models and therefore can be applied to any combination of macroscopic and microscopic models. By the help of an external data file, models can freely transfer important parameters (velocity, current position, next target, max speed etc) between themselves. It has used the concept of transit area and relaxation zones to seamlessly migrate the individuals from one model to other. This transit area also enables pedestrians to enter from any direction. However, this preliminary work towards generic coupling and multi direction entry to transit area needs further investigation.

There are a number of open issues related to this generic framework [16]. It needs to evaluate that how reading/writing data on each simulation time step affects the overall simulation execution efficiency. Such methods need a balance tradeoff among quality of simulation vs. execution efficiency. Moreover, incorporating dynamic switching of models as suggested by authors in future work based on user and application requirement in this approach may also outperform other hybrid models. However, a case study of open space high density crowd is required as a proof of concept of this framework.

V. Limitations and Future Research Directions

As mentioned in previous section that existing work on hybrid approaches in zone based, layered and sequential hybrid models have associated advantages and drawbacks. Evaluations of these techniques shows that zone based hybrid models are more widely explored. Nonetheless, hybrid models based on zones restricts the implementation of such models for many simulations due to their very nature of having well defined boundaries of physical space. Open space gathering of a large crowd with no specific entry/exit points are not possible to simulate with zone based models. Individuals in such simulation cannot enter from any direction due to transformation required between macroscopic and microscopic models on these entry points. Current transformation modules in zone based models allow only bi-directional movements [6][7].

On the other hand, applicability of sequential and layered hybrid models for large range of applications is still an open question. It depends on application requirement to select suitable macroscopic model as part of hybrid technique. If even this macroscopic model is applicable for all part of crowd, while using microscopic model for whole crowd may have negative impact on execution efficiency of simulation. Majority of existing layered and sequential hybrid models does not implement complex social, physical and psychological behaviors for individuals. Hence, another future research direction is to add more behavioral features for individuals in hybrid technique specifically for layered and sequential approaches; and further requires testing its impact on scalability and execution efficiency of simulation.

An interesting and much required research is to investigate generic framework for hybrid techniques where user can select underlying models according to application requirement. Initial work presented by Biedermann and colleagues [16] is a good step towards this direction. Nevertheless, it needs a comprehensive evaluation for large density of heterogeneous crowd, possible set of behaviors it can provide, diversity of applications which can benefit from it and most importantly execution efficiency while achieving these goal.

VI. Conclusion

In last few years, crowd modeling and simulation community have shown growing interest and need for hybrid models. Often, users need to simulate applications which not only require observing crowd movement pattern but also individual crowd behaviors under certain circumstances. Therefore, classic macroscopic, mesoscopic and microscopic models alone cannot provide user desired functionality in an efficient manner. In this paper, we provide an overview of existing hybrid techniques in crowd simulation and modeling. We classify and discuss these models as zone based, layered and sequential hybrid models based on their functionality related to physical space. Major features, types of applications and performance of these models have been discussed. This work evaluates the hybrid models based on scalability, execution efficiency of simulation and complexity of behavioral features implemented. We also present open research problems in the field of hybrid models. In conclusion, we attempt to provide useful insights and future research directions to allow applying of hybrid models to wide verity of applications.

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