A Group Behavior Model of Real-time Crowds in Virtual Environments

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***Abstract*—We present a real-time crowded model in virtual environments. In our model, we simulate the group behavior of huge crowds in real-time. Considering the limitation of computing speed, we adopt a hierarchical management model and construct the movement area in virtual environment by a dynamical potential field. The improved leader–follower structure yields realistic group behavior comparatively. Combination of global planning and local collision avoidance in a optimize framework solves the problems in motion of large crowds without effective collision avoidance. The test results illuminates that the smooth motion of every individual can be simulated on interactive rate in a mainstream microcomputer.**

***Keywords*—Multi-Groups Level, Dynamical Potential Field, Barycentric Coordinates, Force Resistance Model, Finite State Machine**

I. Introduction

The simulative individuals move not solely but in a crowd usually in many virtual reality environments. There are a lot of simple cases that the animals are wandering hillside freely, cropping on the grassland, attacking each other in computer animation. These technologies of group behavior are not limited in the simulation of animals and could be utilized in a crowd of human-beings. The simulation of behaviors in virtual crowds is basic research field in AI, making their simulation is a necessary thing for realistic interactive environment. This research is related to physical model building, motive psychology, agent-based or particle-based AI system. Our research focuses on providing an AI framework to simulate the crowds' behaviors at a real-time rate. Real-time simulation of crowds is a difficult task because large group of agents exhibit behavior of enormous complexity and subtlety. A crowd model must not only include individual motion or environmental constraints, but also considering dynamic interactions between agents. Furthermore, the model should reflect intelligent path planning in changing environment. These agents constantly adjust their paths to avoid the dangerous areas and reflect other dynamic factors. We sometimes even need add a few of collisions in dense crowds. Simulation for group behavior is difficult to strike a proper balance between realism and real-time simulation.

The main division of ways to implement group behavior is based on the forms of computed methods for the individuals. One of the most important sects is the agent-based approach, meaning that motion is computed separately for each individual. The most previous tasks mainly use this kind of model. For one thing, each individual has its own independent decision. The individuals can show their different characters in the same situation vividly. For another, when the simulation parameters conveyed to one individual, it can compute its resulted behavior solely and yield complex various motions. However, the agent-based approach brings some limitations in our model. One of the biggest drawbacks is the expensive computation leads it is difficult to generate the group behavior in huge crowd, particularly in real-time contexts. The other important part in group behavior is particle-based approach. It views motion as minimizing energy of every particle, and adopts a continuum perspective on the system. This way only need update the dynamic potential field for the individuals in the virtual environment. We can get the obvious effect of fast-computation by adopting this thinking. But if observed the individuals carefully, we could find the whole motions manifest a humdrum scene which looks like the explosion or vortex of particles. At present, the most models separate local collision avoidance from global path planning, and conflicts inevitably generated between these two competing goals. Moreover, local path planning results in myopic and less realistic group behavior. The conflict tends to be exacerbated in areas of high congestion or rapidly varying environments.

This paper presents a framework which is a real-time framework of group behavior model. To achieve the real-time goal, we construct a potential field and endow every individual a Finite State Machine (FSM). We improve the traditional leader-follower method by introduce the barycentric coordinates in the model of every group. Our framework takes the relationship between local collision avoidance and global planning into account particularly. Set a specific aim for a group, it could be found easily that the group started to accomplish the aim immediately. As a result of using a force resistance model, we just need to compute the dense area for collision avoidance. To illuminate our theoretic model vividly, we implement the model in the 3D Game Engine developed in

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our laboratory.

II. RELATED WORK

The commencement of group behavior research could be traced back to the end of nineteenth Century [1]. However, the attempts to simulate the group behavior by computer began in current years. The earliest paper about group behavior animation is written by Craig Reynolds [2]. He adopted the word "boids" to represent the group which he simulated. The group behavior that was constructed from his model seemed as a swarm of insects or a flock of birds in the sky. The model just based on simple three rules that called convergence, arrangement and division but yielded graceful results of group behavior. Tu and Terzopoulos mentioned a logic extension on the model of "boids" in their paper [3]. They presented the "Agent" is a perspective system and a simplified neural network model that could demonstrate a series of movements according to the expectations generated by themselves. In their simulation of fish, the fish model was driven by three impetuses which were hungry, sex and panic. The fish's reactions are completely dependent on the internal state and the external environment. Musse et al. simulated the cooperation of crowd in their paper [4]. Every agent was designed to be an artificial life body in the model and in possession of its own standards of behavior. Anderson et al. mentioned a constraint-based animation of group behavior [5]. The crowd that composed of agents move along the routine designated previously, whereas the constraint-based animation used the fixed paths and key-frames in traditional methods of production.

The former research about animation of group behavior concentrated comprehensive natural locomotion and path planning mainly. The animation of group behavior was attached importance by many investigators and became an important impetus to distributed behavior system which integrated the research areas of group behavior in low class animals such as flocks, swarms or herds etc. and in human beings, for example the human's characters or traits and so on [3] [6] [7]. The researchers of animation, Walt Disney Pictures and other studios all showed great zeal for making special effects in movies by use these technologies.

In the recent research, many works paid attention to establish the group behavior model of significant physics by particle system and dynamics [8] [9] [10]. Reynolds adopted a distributed behavior model to simulate the flocks with sentience [11]. Helbing et al. presented the method of simulating the movement of pedestrian [12]. Norser et al. developed the local rules for controling the collective behaviors [13]. Tu and Terzopoulos presented behavioral animation for the creation of artificial life [3]. The virtual agents in their model were provided with synthetic vision and perception of the environment. Blumberg et al. proposed building the autonomous animated creatures that could be operated from multi-hierarchies for interactive virtual environment [14]. Perlin et al. referred to a interactive system which could pre-defined behaviors of the interactive agents [15].

Our model was directly inspired by the parts related to group behavior of real-time crowds in the works mentioned before. We made an analysis of these theories and summarized the others' work mostly in the "Table Ⅰ". So we can found obviously that each implement method has its inherent advantages and limitations. To get a good real-time capability and make progress in the intelligent group behavior at the same time, our models was based on more than one implement method in the "Table Ⅰ".

TABLE I. THE SUMMARIZATION OF GROUP BEHAVIOR

Traits	**Classified by Implement Methods**			
	Particle-based System	***Flock & Swarm***	***Virtual Crowd System***	***Movement System***
Structure	Non-hierarchical	Hierarchical: Flock, Swarm & agent	Hierarchical: crowd, group & agent	Hierarchical: descriptively
Participant	A lot	Some	A lot	Several
AI Level	Non	Low	Low	High
Physics- based	Yes	Some	No	No
Collision	Detection & Reaction	Collision Avoid	Collision Avoid	Collision Avoid
Operation	Force field & Globle tendency	Local tendency	Degrees: Pre-defined behavior, Rules of behavior & Instructive operation	Rules
Real-time capability	Good	Good	Medium	Bad

III. THE HIERARCHICAL FRAMWORK

The fundamental idea in simulation of crowd is that moving the individuals in a group together and making an illusion about the group hold a certain goal. If just watch a group of individuals moving without any harmony, we couldn't take it for the group behavior.

We can see clearly from the "Fig. 1" that the integral model is divided by three levels which are crowd level, group level and individual level in the hierarchical model we presented. The individual is an object with the many characteristics; the group is composed of a lot of individuals (at least has one individual); the crowd is a set of the groups (at least has one group). The entities of the simulation are made up of the crowds, groups and individuals.

We use the term "intention" to denote the aim of an entity, for example, moving to somewhere. The term "state" denotes the internal state of an entity such as the emotional state. The term "knowledge" is regarded as the description of information in the virtual environment such as the location of obstacle. The special things which could change the state of an entity immediately called "event". The user could set intention and event for the entities and we named this action "operation". At last, the group behavior of an entity is dependent on the factors which include intention, state and knowledge to yield a set of actions. If there is a contradiction between low level and high level, the behavior generated in low level is identified with invalidated one at once. This rule ensures the consistency of the group behavior. Our basic model is based on the framework in "Fig. 1" and introduces the Multi-Groups Level (MGL) in the framework.

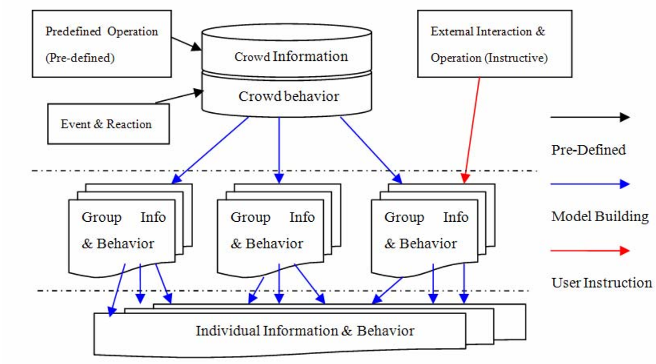


Figure 1. The Model of Hierarchical Structure

If only limited in the three levels from the "Fig 1", the hierarchy of model is monotonic and hidebound. Therefore we depict the structure of MGL in "Fig 2". All the groups in different levels adopt two types of data-structure. The one type of data-structure called "point-to-group" has the pointers to point its own data-structure. Then we could distinguish the "super-group" or "sub-group" as the "Tree-Structure". Another type of data-structure called "point-to-individual" has the pointers to point the structure of individuals. It looks like the "leaf node" in the "Tree-Structure".

It is very convenient that creation of MGL in the framework for our operations. The main advantage from the thinking of MGL is that we have all kinds of granularity in our model. Because the operation of a large group is same expedience to the operation of small one, we can choose the the individuals precisely we want to operate in one instruction. When construct a model of crowd, we could choose the appropriate singularity and hierarchical structure optionally. However, this flexible organization exist some problems. For example, it brings a lot of difficulties in the management of structure as we couldn't be aware of the detailed information of the model directly.

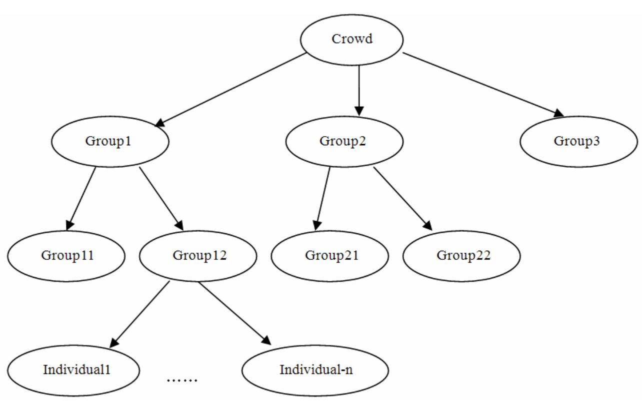


Figure 2. The Relationship between Different Groups in Hierarchical Model (MGL)

There are many benefits to adopt the hierarchical structure in the framework. On one hand, all the entities could be organized in perfect order. We get an efficient way of operation through the organization. On the other hand, hierarchical structure brings a good real-time performance by entity-oriented information distribution which could minimize the size of computation.

IV. The Model of Dynamical Potential Field

The group behavior yields a lot of contradictions which we can't understand in many aspects. For example, the group behavior which is composed of the discrete individuals' behaviors could manifest a smooth and continuous integral movement; a set of simple rules could bring us various kinds of complicated group behavior; the relationship between two individuals is loose and random. However, we could find the astonishing harmonic coherence in the group behavior level. It is difficult to simulate the group behavior in real-time due to the complexity of a huge crowd of individuals' behavior. The model of one group does not only include individuals' behaviors and the environmental constraints but also figure out the problem of interaction between two individuals. Furthermore, the model must reflect the intelligent path-planning in a dynamic context.

A. Construction of the Dynamic Potentional Field

The dynamical potential field was mentioned in the paper written by Treuille et al. [10]. We divide the area of our model in dynamical potential field into three types: unreachable area, force area and free area. We can understand the meanings of these three types from "Fig 3" immediately. Firstly, the unreachable area means the area that the other individuals can't reach. There are three sorts of symbols that indicate lake, tiger, and deer respectively involve all unreachable area in "Fig 3". The tiger and deer can't enter into the lake, so lake denotes the unreachable area. The animals become the unreachable area for each other as we all know that two animals couldn't overlap on the same location. Secondly, the force area represents the area which has different affection to some individuals. The force direction in this area means the direction to attenuation of the affection. The deer feel unsafe near the tiger, so their move directions are reverse to the tiger's location. Thirdly, the free area means staying in this area won't be affected by other factors.

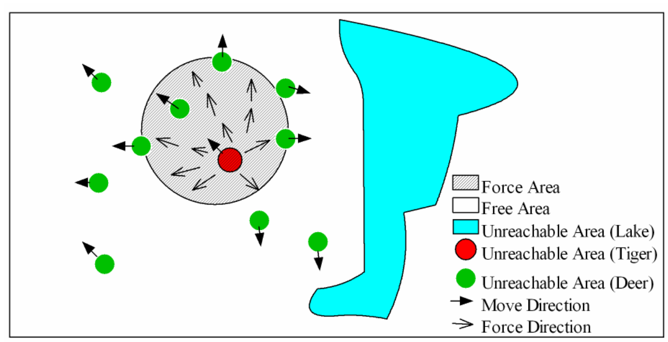


Figure 3. Three Types of Area in the Dynamic Potential Field

The key work to construct the dynamical potential field is building a reasonable force area. Every location in the force area has two characteristics: direction and weight. So we adopt a vector to indicate the force in an individual's position. We ought to know the parameters which include tiger's position $\mathbf{P}_T^i\ (i=1,2,3,\cdots,n)$ and move direction $\mathbf{M}_T^i\ (i=1,2,3,\cdots,n)$, deer's position $\mathbf{P}_D$ and the radius of one force area R. We calculate the force $\mathbf{F}_D$ for every deer in the following mathematical model. First, we must denote a district as the force area. The force area is circle whose radius is R and the centre is $\mathbf{C}^i$ calculated by the equation (1).

$$\mathbf{C}^i = \mathbf{P}_T^i + \frac{R}{3} \cdot \frac{\mathbf{M}_T^i}{\left\|\mathbf{M}_T^i\right\|} \tag{1}$$

The $\|\cdot\|$ means the Euclid distance. Because of the move direction of every Tiger, we don't put the tiger in the centre of the circle simply.

Then we need to calculate the force in a deer's position which is in one or more force area. If $\mathbf{P}_D$ in one force area A^i, we can calculate $\mathbf{F}_D^i$ by the equation (2).

$$\mathbf{F}_D^i = \frac{\mathbf{P}_D - \mathbf{P}_T^i}{\left\|\mathbf{P}_D - \mathbf{P}_T^i\right\|} \cdot \frac{1}{e}\int_0^t e^x dx, \quad t = 1 - \frac{\left\|\mathbf{P}_D - \mathbf{P}_T^i\right\|}{l_D} \tag{2}$$

The symbol e is Euler number and l_D is the distance from the tiger's position to the bound of its force area through the deer's position of the calculated by equation (3).

$$l_D = \frac{R}{\sin\theta}\left[\pi - \theta - \arcsin\left(\frac{1}{3\sin\theta}\right)\right], \quad \theta = \arccos\left(\frac{\left(\mathbf{P}_D - \mathbf{P}_T^i\right)\mathbf{M}_T^i}{\left\|\mathbf{P}_D - \mathbf{P}_T^i\right\|\left\|\mathbf{M}_T^i\right\|}\right) \tag{3}$$

Now we calculated the $\mathbf{F}_D$ with single force area. If the deer in the overlap force areas from many tiger, we just have to add the forces from these areas as equation (4). The symbol $\mathbf{F}_D^i$ denotes the force from the number i tiger.

$$\mathbf{F}_D = \sum_{i=1}^{n} \mathbf{F}_D^i \quad \left(if \quad \mathbf{P}_D \notin A^i, \quad then \quad \mathbf{F}_D^i = 0\right) \tag{4}$$

B. Improvement of Leader-Follower Model

There is a simple leader-follower model mentioned in the paper wrote by Niederberger et al. [16]. However, the simple model yielded the stiff and monotonous group behavior. We make a little breakthrough at the point of only one leader in a group in traditional leader-follower model. If the number of individuals in one group is more than three, we choose three individuals as leaders in our model. The basic barycentric coordinates is composed of the three leaders in the group. There is a constraint D_H represents the maximum distance value between the leaders. If the distance between two leaders is too long, we can't take them as a group. The constraint D_L represents minimum distance between the leaders. We can't endure that the individuals in one group hustle into one small area.

We need to adopt the barycentric coordinates in our model to calculate the followers' position they should be. We assume the number i follower's position $\mathbf{P}_F^i$ and the three weights W_j^i, $(j = 1,2,3)$. The three leaders' positions $\mathbf{P}_L^j$, $(j = 1,2,3)$ are computed by own intelligent mechanism in the dynamical potential field respectively. We must consider the inequation (5) of distance constraint on the leaders' positions.

$$D_L \le \left\|\mathbf{P}_L^i - \mathbf{P}_L^j\right\| \le D_H, \quad (i, j = 1,2,3 \quad and \quad i \ne j) \tag{5}$$

The inequation (6) describes a constraint condition of all weights. We don't want to find a follower is far from the group or close to just one leader. The inequation (7) is an important function in barycentric coordinates which could denote any point on the leaders' plane uniquely if the three leaders are not in line. The number of all followers in the group is n.

$$-3 \le W_j^i \le \frac{3\min_{k \ne l}\left\|P_L^k - P_L^l\right\|}{\sum_{k \ne l}\left\|P_L^k - P_L^l\right\|}, \quad (i = 1,2,\cdots,n \quad j = 1,2,3) \tag{6}$$

$$D_L \le \left\|\mathbf{P}_L^i - \mathbf{P}_L^j\right\| \le D_H, \quad (i, j = 1,2,3 \quad and \quad i \ne j) \tag{7}$$

The most important constraint equation (8) is the key point of affine combination in our model. We can generate the weights at random, but the weights of one follower must satisfy the equation (8). At last, we can compute the destination $\mathbf{P}_F^i$ of every follower easily according to the equation (9).

$$\sum_{j=1,2,3} W_j^i = 1 \quad \left(i = 1,2,\cdots,n\right) \tag{8}$$

$$\mathbf{P}_F^i = \sum_{j=1,2,3} \mathbf{P}_L^j W_j^i \quad \left(i = 1,2,\cdots,n\right) \tag{9}$$

We can choose more leaders in a group if needed. The model could be constructed as the upper methods and equations. However, we can't say the equation (8) is a simple triangle barycentric coordinates but a polygon barycentric coordinates and replace equation (8) with equation (10). The number of all leaders in the group is m.

$$\sum_{j=1}^{m} W_j^i = 1 \quad \left(i = 1,2,\cdots,n\right) \tag{10}$$

V. Global Planning and Local Collision Avoidance

There is paradox between global planning and local collision avoidance as we mentioned in Section Ⅰ. There is model with physically-based particles referred in the paper wrote by HEÏGEAS et al. [17]. Our model is based on the dynamical potential field so adopted the force resistance model naturally. In this way, we could consider the global planning and local collision avoidance simultaneously and just need to compute the resistance when an individual in the resistance area. We simply describe our model in "Fig 4" which is like the force area in the "Fig 3". However, the resistance can't push the individuals out of it but only stop the individual who want to advance in the reverse direction of resistance. The target area in it means the global goal for the individuals.

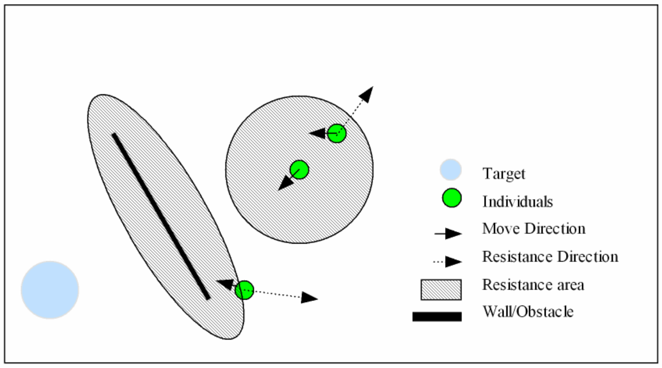


Figure 4. The Effects of Resistance Areas

Our model about resistance area uses the elasticity model in physics for reference. In order to prevent the overlap of two objects, we divide two distances in the resistance firstly. The minimum distance D_M ensure no real collision happen in the animation and the resistance distance D_R confirms the resistance area around one object. So the resistance area is region composed of the points $\mathbf{P}_R$ satisfied the inequation (11). The discrete points $\mathbf{P}_{Bj}^i$ are the n boundary points around the j obstacle.

$$D_M \le \min_{i=1,2,\cdots,n} \left\| \mathbf{P}_R - \mathbf{P}_{Bj}^i \right\| \le D_R \quad (11)$$

Then we could construct the force resistance model based on the individual's position $\mathbf{P}_I$ and velocity $\mathbf{V}_I$ .We define the resistance from one obstacle in the one point $\mathbf{P}_I$ is the vector $\mathbf{R}_I^i,\ (i=1,2,\cdots,n)$ .The number n means how many obstacles affect the individual. We can compute the vector $\mathbf{R}_I^i$ singly by the equation (12). If the inner product between direction of resistance and velocity $\mathbf{V}_I$ is bigger than zero, the vector $\mathbf{R}_I^i$ is evaluated to zero.

$$\mathbf{R}_I^i = \begin{cases} \mathbf{U}\dfrac{D_R - \min\limits_{j=1,2,\cdots,n}\left\|\mathbf{P}_I - \mathbf{P}_{Bi}^j\right\|}{D_R - D_M}, (if \quad \mathbf{U}\cdot\mathbf{V}_I < 0) \\ 0, \quad (if \quad \mathbf{U}\cdot\mathbf{V}_I \ge 0) \end{cases}, \mathbf{U} = \frac{\mathbf{P}_I - \mathbf{P}_{Bi}^j}{\min\limits_{j=1,2,\cdots,n}\left\|\mathbf{P}_I - \mathbf{P}_{Bi}^j\right\|} \quad (12)$$

The length range of single vector is from zero to one computed in the equation (12). The resistance vector $\mathbf{R}_I$ is a combination of the effects yielded by all resistance areas. We use the equation (13) to calculate the final resistance.

$$\mathbf{R}_I = \begin{cases} \sum\limits_{i=1}^{n} \mathbf{R}_I^i, & \left(if \quad \left\|\sum\limits_{i=1}^{n}\mathbf{R}_I^i\right\| \le 1\right) \\ \sum\limits_{i=1}^{n} \mathbf{R}_I^i \Big/ \left\|\sum\limits_{i=1}^{n}\mathbf{R}_I^i\right\|, & \left(if \quad \left\|\sum\limits_{i=1}^{n}\mathbf{R}_I^i\right\| > 1\right) \end{cases} \quad (13)$$

At last, the final resistance must act on the velocity of one individual and generate the update velocity $\mathbf{V}_I^U$ .We adopt a very simple way to countervail the head-on velocity as equation (14). So the problem of local collision avoidance is settled in our model.

$$\mathbf{V}_I^U = \mathbf{V}_I - \mathbf{V}_I \cdot \mathbf{R}_I \quad (14)$$

The global planning is driven by global goal in our model. Set the goal point $\mathbf{P}_G$ for a group, the leaders produce the maximum speed S_I^m to the goal directly and immediately as the equation (15). Although they need to pass through some force areas or resistance areas in their way to goal, the group will achieve the goal generally.

$$\mathbf{V}_I^U = S_I^m \frac{\mathbf{P}_G - \mathbf{P}_I}{\left\|\mathbf{P}_G - \mathbf{P}_I\right\|} \quad (15)$$

VI. Implementation and Result

The FSM (Finite State Machine) was an important control technology in AI. To finish implementations of our group behavior model, we added the concrete FSM to every individual in the animation as "Fig 5" described. All kinds of animals will change their states according to different states they had and various context. The place neglected easily is that the resistance area yielded by deer must be of no effect on tiger forever. Otherwise we will see the strange circumstance that the tiger couldn't approach the deer. The tiger has good acceleration but can't keep on the high speed which is faster than deer of course for a long time. So it must have a transitional "Trace" state and wait for the optimum occasion of hunting.

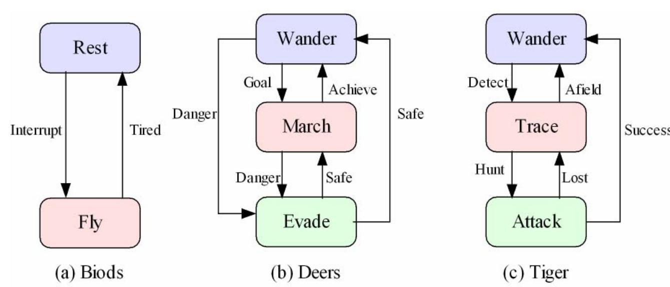
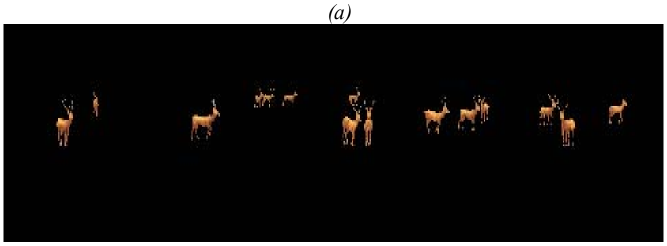


Figure 5. The Finite state machines of Three kinds of Animals

We implemented our 3D game engine in a mixture of C++ and OpenGL. All simulations ran on a 3.0 GHz Pentium computer with a NVIDIA GeForce 7600 GT graphics card. We abandoned all the environmental render to get the most reliable real-time test data as "Fig 6" showed. We regarded the tigers as independent animals and didn't organize them in any group. The birds in picture (a) from "Fig 6" weren't managed by MGL but just by a single group level. Because of its simple structure and internal FSM, simulation of more than 1000 birds about updates took between about 70 frames per second (fps).

(a)



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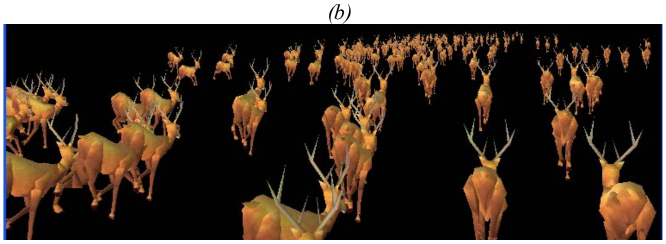

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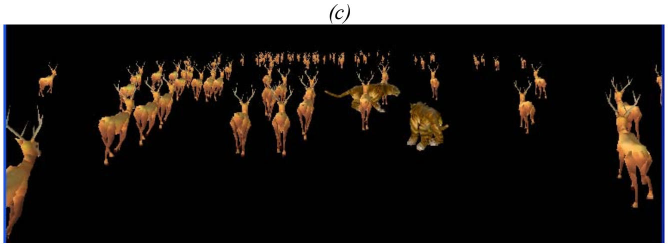

(d)

Figure 6. Four Pictures of Group Behavior in Our 3D Vitual Environment. (a): A simple model of about 1000 birds. (b): A group of 15 deer is in the wander state. (c): More than 1000 deer march to the same goal. (d): Two tigers attack the deer at the same time.

The group of deer in picture (b) from "Fig 6" had three leaders and adopted the barycentric coordinates mentioned in Section Ⅳ. We couldn't find the explicit leaders in them who at the "Wander" state. There is better intelligent scene than only choose one leader.

The picture (c) and picture (d) from "Fig 6" showed the situation of large group of deer or tigers. We implemented these deer by framework of all the models presented in this paper. In order to avoid the complex operations, we just used two group levels in the program. The big difference between picture (c) and picture (d) is the tigers. We can see that the deer is sparse around the tigers' areas and the deer on the left of picture (d) stopped the advances for goal.

We tested the performances of different sizes of the deer 13 times as the "Fig 7" illuminated. Because of huge scale of computation between two individuals, it is clearly that the frames per second decreased quickly along the exponential curve by increase the size of individuals. If considering the 24 fps standard, our framework was suit for the construction of real-time group behavior model whose size less than 3500 individuals.

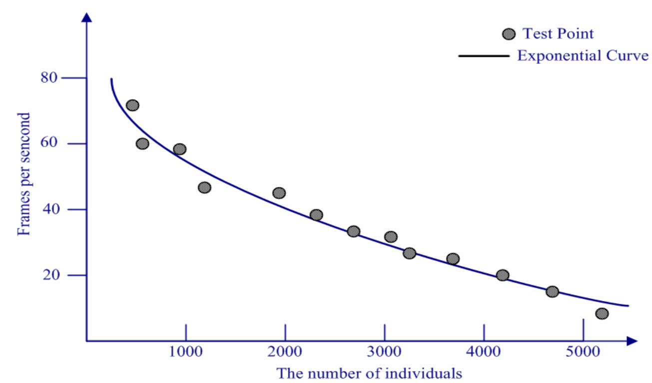

Figure 7. The 13 Tests with Different Sizes of Individuals (Deer)

VII. Discussion and Future Work

Our framework has numerous advantages over previous systems in graphics. Firstly, we used the hierarchical structure and MGL in the groups. This structure brought better management of individuals and more convenient operations for manipulators. Secondly, we improved the simple leader-follower model by introduce the barycentric coordinates into our model. The implicit leader-follower organization gave us more realistic group behavior. Thirdly, we made a combination of dynamic potential field and simple FSM in the implementation stage. It gave the deer more dubious factors to demonstrate the behavior by itself and brought more interesting or vivid scenarios in animation.

The research in group behavior in virtual environment is a fresh field in AI and Computer Graphics (CG) developed in recent years. The framework and models we proposed is not appropriate for all the group behavior. It is simple model we present and for the medium or large size of individuals. We didn't consider long distance path planning or emotional computation etc. in our framework but paid attention to the real-time performance of large size of group behaviors. We encouraged our framework or model to be revised or enhanced by other researchers. For example, you can extend the leader-follower model by choose more leaders and let one follower be controlled from different leaders. Along with the development of computer science and emergence of more fast computer chips, the more intelligent and autonomous real-time group behavior will appear in the future.

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