A Microscopic Swarm Model Simulation and Fractal Approach towards Swarm Agent Behaviour

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Summary

This research presents a simulation of a microscopic swarm model. The model represents detailed interaction of agents to control their movement in any agent arena. A physical based microscopic agent simulation model has been developed. The developed microscopic agent simulation model is a physical force based model similar to the social force model with forward and repulsion forces as the main force driver. However, the detail of the model is somewhat customized with inputs of the model. The repulsive force is added to guarantee collision avoidance. The developed model also uses the physical based variables that can be measured. The collision avoidance algorithm is influenced by existing algorithm flock which uses the steering behaviour to animate birds. It was revealed that the microscopic swarm model studies have been successfully applied to explore to the behaviour of microscopic agents flow by showing influenced three forces. The research was extended to fractal characteristics that share the characteristics of the fractal formation and agent paths. It is clearly shown that fractal could be used to approach the emerging swarm behaviour as we have produced the result that has sharing characteristics with crowd microscopic model.

Key words:

Microscopic swarm model, agent path characteristics, physical force, collision avoidance, fractal formation.

Introduction

Swarm in respects of human movement could be synonym with crowd. Microscopic swarm model represents detailed interaction of agents to control their movement in any agent arena. An agent may represent a robot in swarm agents movement. The microscopic agent flow characteristics need to be explored in controlling their movement. This paper investigates a physical based microscopic agent simulation model and identifies the features of agents' paths resulted. For this purposes, a microscopic swarm model and simulation has been developed to determine the microscopic characteristics of agent flow.

The microscopic swarm model and simulation is a computer simulation model of agent movement where every agent member in the model is treated as an individual agent. The model is restricted to three variables of force types.

The developed microscopic swarm model and simulation is a physical force based model similar to the social force model with forward and repulsion forces as the main force driver [10]. However, the detail of inputs and outputs is customised to trace agents' paths. Bruzzone [4] presented a model able to reproduce the behaviour of a crowd allowing collision in case to be happened. Our modelled does not allow any collisions by giving additional radius of the agents and a repulsive force assignment when two the radii collide. The developed model also uses the mass parameter besides force variables that can be measured. The collision avoidance algorithm is influenced by Reynolds the steering behaviour model [18, 19]. Thus, the developed microscopic agent simulation keeps the existing models' advantages. is made based on the existing models to improve the deficiency of the existing models.

Agents in the microscopic simulation model are modelled as Non-Player Characters (NPCs). NPCs are the autonomous characters that are free from the user's control but initial conditions are keyed by the users. NPCs are seen from above of the facilities (top view). An agent is modelled as a circle with a certain radius. Each agent's initial conditions include initial location, initial time, and initial, velocity, and predetermined target location (opposite to the initial location). These inputs can be determined by the user as a design experiment and be specified randomly.

NPCs will interpret an action and this interpretation process is important for this view in behavioural animation. This will lead to further autonomous actions in the virtual environment as well as intelligent responses to the action being carried out. Thus motion or path planning becomes much more complicated when an animation for large swarms must be made. The development in motion planning and in global techniques for improving the approach has been discussed [16] but it concentrated on the probabilistic roadmap (PRM). Whereas the improvement for path planning techniques used for large swarms is very few.

The main objective of this study is to boost different view of swarm path planning analysis by demonstrating the result of fractal experiments related to swarm path yielded from the microscopic swarm model. Furthermore, it is aimed to magnify that crowd may behave like fractal.

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2. The Research Method

Briefly, the method used is depicted in Fig. 1. The microscopic swarm model is a mathematical model that every agent has three variables of forces. The overall model is a mathematical model that is heavily influenced by escape panic model [8-13], bird flocking behavioural model [17] and pedestrian traffic model [24]. The development of the model and simulation is designed to capture the individual swarm member and able to record the its movements characteristics. The calibration of the simulation is concerned with the determination of the numerical value of the parameters and the results of the simulation. Whereas, validation and verification does not mean validating with real-life movement but it is rather an exposure that the model does work. However, this paper has extended the method with comparison between the characteristics microscopic model and fractal experiment result.

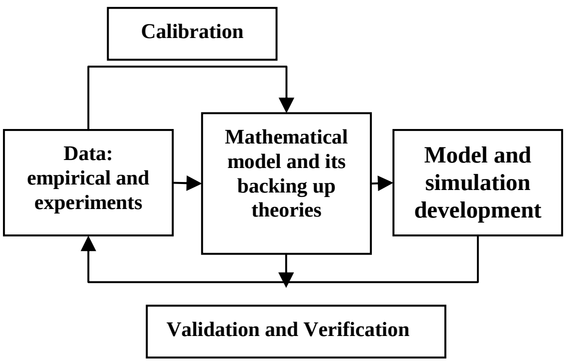

Fig 1. The method used.

2.1 Collision Free Multi Agents (Swarm) Motion Planning

Still [27] has developed his own breed of fractal - the "orchid" - which can be used to model the way in which crowds leave confined spaces such as sporting events. Basic orchid fractals behave like a well-ordered, rational crowd - one without the inherent confusion caused by people moving at different speeds, walking in the wrong direction or simply standing about. Because crowds are hardly models of good behaviour, Still added random elements, to simulate human characteristics.

Aparecido [1] used density estimation based on Minkowski fractal dimension. Fractal dimension has been widely used to characterize data texture in a large number of physical and biological sciences. The results of their experiments show that fractal dimension can also be used to characterize levels of people congestion in images of crowds.

Provided a situation that involves large number of agents, for example an egress during an emergency, an agent may have to act and produce movement. Every single robot in a swarm is expected to move away from the threat but there must not be any movement that causes jam, obstruction or other non-adaptive direction. Canter [5], and Still [19-21] modelled the problem by producing movement either predictable directions: towards the threat or away from the threat or no movement. This problem was reduced to three variables that interact - Objective, Motility and Constraint - and one parameter which represents the reaction time; Assimilation. The Objective is to reach the expected point. The Motility is the speed of each agent. The Constraint is the geometric size of each agent. The interaction between these three variables were plotted against each other the results are fractal in nature [20].

Tzafestas [27] studied collision avoidance for motion planning and control of mobile robots but it does not involve swarm robots. Bruzzone [4] used repulsion among the entities to avoid collision with other entities as explained in the following equations (Eq. 1a, b, c).

$$FEC(i) = \sum_{j=1, j\neq i}^{n} -kec(P_j, P_i)\frac{P_j - P_i}{\left|P_j - P\right|} + V\_rand(P_j - P_i) \quad (1a)$$

$$kec(C1,C2) = \begin{cases} \left|C1_x - C2_x\right| + \left|C1_y - C2_y\right| > d0 & \text{kec} = 0 \\ d1 < \left|C1_x - C2_x\right| + \left|C1_y - C2_y\right| \le d0 & \text{kec} = \text{k0} \\ 2\cdot d2^2 < \left(C1_x - C2_x\right)^2 + \left(C1_y - C2_y\right)^2 \le d1^2 & \text{kec} = \text{k1} \\ \left(C1_x - C2_x\right)^2 + \left(C1_y - C2_y\right)^2 \le 2\cdot d2^2 & \text{kec} = \text{k2} \end{cases} \quad (1b)$$

$$V\_rand(D) = \begin{cases} \text{D} > \text{d2} & \text{V\_rand} = (0,0) \\ \text{D} \le \text{d2} & \text{V\_rand} = k\_coll\left(\frac{\text{v\_randx}}{\sqrt{\text{v\_randx}^2 + \text{v\_randy}^2}}, \frac{\text{v\_randy}}{\sqrt{\text{v\_randx}^2 + \text{v\_randy}^2}}\right) \end{cases} \quad (1c)$$

Where:

- FEC is the Repulsion among the entities (used to avoid collisions),
- n is the number of entities,
- kec (Pi,Pj) module of the force vector due to repulsion interaction between i-th and j-th entities,
- d0,d1,d2 reference distances (collision distance between two entities),
- k1,k2,k3 repulsion forces,
- V_rand(D) random force in case of collision,
- v_randx, v_randy are random values for collision reaction, and
- k_coll force in case of collision.

Helbing [12] was able to model the collective phenomenon of escape panic in the frame of possessing self-reaction. The model assumes a mixture of socio-psychological and physical forces influencing the behaviour in, say a crowd in matrices I, with N_i agents where each agent of i has mass m_i, with vector certain desired speed v_i^0 and direction e_i^0 and therefore tends to correspondingly adapt its velocity v_i, within a certain characteristic time τ_i.

At the same time, it tries to keep a velocity-dependent distance from other agent j and walls W in order to avoid neither collision nor deadlock. This effort of collision free motion can be modelled by 'interaction force' f_{ij} and f_{iW}, respectively. Derivation of velocity in time t results the acceleration equation (Eq. 2)

$$m_i \frac{dv_i}{dt} = m_i \frac{v_i^0(t)e_i^0(t) - v_i(t)}{t_i} + \sum_{j(\neq i)} f_{ij} + \sum_W f_{iW} \qquad (2)$$

Meanwhile, the velocity is resulted from the derivation of position $r_i(t)$ in time t, $v_i(t) = \frac{dv}{dt}$. In order to get a collision free motion, an agent i decides at time t_i (i.e. before deadlock) to avoid another agent j (i.e. to keep a certain distance). However the agent j has both an attractive effect and repulsive effects which can be described by quantities $\vec{f}_{ij}^a, \vec{f}_{ij}^r$ respectively. They are a measure for direction and strength of psychic motivation of i to approach or avoid j and they are not forces yet.

2.2 Modelling Agent Movements

We have observed available video materials and we share related summary that the characteristic features of bio-creatures crowd movement as follows: (1) Crowd flow is further slowed by fallen or injured or stopped agent acting as `obstacles'. (2) The physical interactions in the jammed swarm add up (3) People in special show a tendency towards mass behaviour, that is, to do what other people do [14]. (4) Alternative exits are often overlooked or not efficiently used in escape situations [6].

These observations have encouraged us to model the collective phenomenon of swarm flow in the framework of emerging swarm behaviour, NPCs. The developed computer simulations of the swarm dynamics of agents are modelled as physical based with explicit visual interaction. The explicit visual interaction might represent a generalized force model [13] inside the collective behaviour of the agents.

We assume a mixture of socio psychological [8] and physical forces influencing the behaviour in a crowd. It is assumed that each agent is subject to "mixed forces" that represent motivation to move ahead toward the target location. The force here is not meant the real physical force that has dimension of Newton (kg m/second2) but only the analogy of the force that characterizes the internal driving force or motivation of the pedestrian.

Modelling the agents movement starts with assumption that each agent is subject to the force analogy that characterizes the internal moving force or motivation of the agents to move ahead toward the target location.

The force is assumed proportional with the discrepancy between the summation of expected velocities, $\hat{v}(t)$ and the actual current velocity, $v(t)$. Therefore, the force (in meter/second2) becomes (Eq. 3).

$$f(t) = m'a(t) = m'\frac{dv(t)}{dt} \qquad (3a)$$

$$m'\frac{dv(t)}{dt} = \frac{\sum \hat{v}(t) - v(t)}{\phi} \qquad (3b)$$

$$m\frac{dv(t)}{dt} = \sum \hat{v}(t) - v(t) \qquad (3c)$$

The expected velocity is a kind of predicted velocity on which way the agent is going to move in the next time ahead. The expected velocity directs the acceleration and the forward force toward the target point. The direction of the expected velocity must be the same as the force and the acceleration. Based on the Newton law, the acceleration is proportional to the force with a constant proportion called mass, m. Since the acceleration has the same direction as the force, it is also the direction of the acceleration. When the expected velocity is equal to the current velocity, the force (and the acceleration) has zero value and the pedestrian may be stopped or walking with constant velocity.

To simplify the model $m'\frac{dv(t)}{dt} = \frac{\sum \hat{v}(t) - v(t)}{\phi}$, the parameter mass, m, contains a time dimension and measured in time unit, where the constant ϕ has the time dimension while the mass, m', is dimensionless. However since both m' and ϕ are constant, they can be put together as one parameter $m = m'\phi$. The parameter mass relates the speed and the acceleration. That means mass has no real physical dimension but obeying the nature of Newton law.

Each agent in the system is influenced by the three forces [23]. Four parameters of the model are the mass, m, alpha, α , beta, β and chi, χ. Alpha influences the force to move ahead, Beta for collision avoidance and Chi for move away. The mass is applied toward the three forces together (global parameter) while the other three parameters are applied only for the particular force. The three forces are (Eq. 4)

$$ma_f = \frac{\hat{v}_f}{\alpha} - \frac{\alpha'}{\alpha}v$$
$$ma_a = \frac{\hat{v}_a}{\chi} - \frac{\chi'}{\chi}v \qquad (4a, b, c)$$
$$ma_r = \frac{\hat{v}_r}{\beta} - \frac{\beta'}{\beta}v$$

Resultant of the three forces (addition of vectors) yields (Eq. 5)

$$m\left(a_f + a_a + a_r\right) = \frac{\hat{v}_f}{\alpha} + \frac{\hat{v}_a}{\chi} + \frac{\hat{v}_r}{\beta} - \left(\frac{\alpha'}{\alpha} + \frac{\chi'}{\chi} + \frac{\beta'}{\beta}\right)v \qquad (5)$$

Say $a = a_f + a_a + a_r$ and $c = \frac{\alpha'}{\alpha} + \frac{\chi'}{\chi} + \frac{\beta'}{\beta}$, then Eq. 5 becomes Eq. 6

$$ma + cv = \frac{\hat{v}_f}{\alpha} + \frac{\hat{v}_a}{\chi} + \frac{\hat{v}_r}{\beta} \qquad (6)$$

Generally, the movement of a agent is from the current location, $\mathbf{p}(t)$ toward the destination point, $\mathbf{e}(t)$. Alpha is applied as the force to move ahead that directs the agent to move. The alpha force makes the agent path almost in a straight line during absence of the other two forces. On the other hand, the absence of alpha force will make an agent immobilized in sense of no destination. The direction of the alpha force is from the current location toward the destination. The gradient (direction) of the alpha force is given by $\mathbf{g}(t)$ as written in Eq.7 ,

$$\mathbf{g}(t) = \frac{\mathbf{e}(t) - \mathbf{p}(t)}{\left\|\mathbf{e}(t) - \mathbf{p}(t)\right\|} \qquad (7)$$

If there is no obstruction, the agent's expected velocity reaches the maximum moving speed, $\mu_{\max}$ or smaller $\left(0 \le \hat{v}(t) \le \mu_{\max}\right)$. The existence of other agents or obstructions will give other forces reduce the moving speed. Thus, the expected velocity for the alpha force is given by Eq. 8.

$$\hat{v}_f(t) = \frac{\mu_{\max}}{\alpha}\mathbf{g}(t) = \frac{\mu_{\max}}{\alpha}\frac{\mathbf{e}(t) - \mathbf{p}(t)}{\left\|\mathbf{e}(t) - \mathbf{p}(t)\right\|} \qquad (8)$$

The norm in the denominator of equation above represents the distance between the current position and the destination.

When two agents nearly collide, they usually move [repulse] away from each other within a certain distance [Fig. 2]. They may not wait until their distance becomes too close to move away unless there are no space surrounding them. A similar behaviour happens when an agent is following another slower agent. They have to adjust their velocity speed so that any proper alignment can be reached matching velocity with nearby agent. Align an actor's velocity vector with that of the local flock. This move [repulse] away direction causes the path bend and the overall swarm path also may create emerging behaviour of curve path.

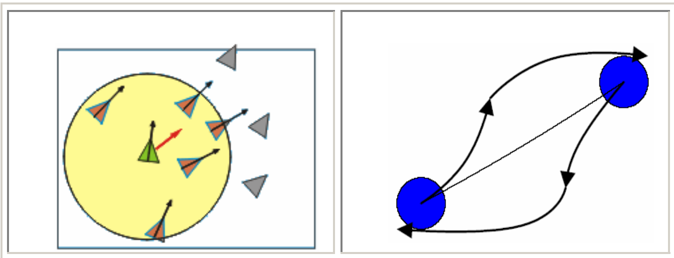

Fig. 2. Alignment of Reynold's flock rules and move away [18, 23].

If $d(t)$, y and r are, respectively, representing the distance between the agents, interference of the closest agent in the area in front of the actor and the influence radius of agent, the expected velocity of agent i^{th} , $\hat{v}_a^{\,i}(t)$ due to Chi force to move away, is given by Eq. 9.

$$\hat{v}_a^{\,i}(t) = \frac{\mu_{\max}\left(2r - y(t)\right)}{\chi\, d(t)} = \frac{\mu_{\max}\left(2r - y(t)\right)}{\chi\left\|\mathbf{p}_k(t) - \mathbf{p}_i(t)\right\|} \qquad (9)$$

By the alpha and chi forces, the agents can adjust the distance between two agents and are able move away from each other. However, those two forces may not be able to prevent a collision when there are many agents in the arena. To more prevent a collision, a force that considers all surrounding agents is needed. For this purpose, it is assumed that each agent has an influence radius that represents his or her security awareness. By giving influence radius they are able to keep a certain distance away from nearest agent and to avoid collisions with nearby agent. The force must be generated when at least two agents' influencing radii partly cover each other as shown in Fig. 3.

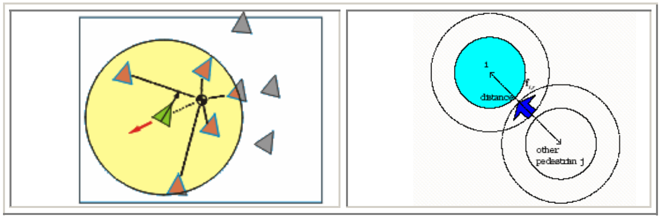

Fig. 3. Separation of Reynold's flock rules and expected velocity to avoid collision by applying beta force [18, 23]

No repulsive force is generated if the influence radius does not overlap each other. Instead of considering the closest pedestrian as the first repulsive force, the second repulsive force considers all surrounding pedestrians and the forces are summed up linearly.

Similar to the first repulsive force, the second repulsive force depends on the distance between the actor and other pedestrians surrounding it. The beta force is given

Since $v(t)=\frac{d\mathbf{p}(t)}{dt}$ and $a(t)=\frac{dv(t)}{dt}=\frac{d^2\mathbf{p}(t)}{dt^2}$, the formulation can be put together in terms of the current position of pedestrian i, $\mathbf{p}(t)$ as a second order differential equation

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$$m\frac{d^2\mathbf{p}_i(t)}{dt^2}+\frac{d\mathbf{p}_i(t)}{dt}=\mu_{\max}\left\{\frac{\mathbf{e}(t)-\mathbf{p}_i(t)}{\alpha\|\mathbf{e}(t)-\mathbf{p}_i(t)\|}+\frac{2r-y(t)}{\chi\|\mathbf{p}_\chi(t)-\mathbf{p}_i(t)\|}+\sum_j\left[\frac{2r}{\|\mathbf{p}_i(t)-\mathbf{p}_i(t)\|}-1\right]\left[\frac{\mathbf{p}_j(t)-\mathbf{p}_i(t)}{\beta\|\mathbf{p}_j(t)-\mathbf{p}_i(t)\|}\right]\right\} \quad (10)$$

Equation (10) is a non-linear second order differential equation of pedestrian positions that depend on each pedestrian's positions, speeds and accelerations. The analytical solution of the differential equation is very difficult and not practical since it is also dependent on the number of pedestrians and the sight distance. Numerical method through simulation is more favourable and it has the benefit to visualize the movement of each pedestrian in a plan as an animation.

3. Principal of the Model Simulation and Its Results Discussion

The differential equation (8) is solved numerically by divide and conquer algorithm using Euler method, which provides adequate results while keeping the computational speed reasonable. Each equation is computed one by one, as each pedestrian is assumed an autonomous agent. A pedestrian has his own internal forces and influence other pedestrians only through his position. The pedestrian movement is based on the resultant forces that act upon him. Other numerical method to solve the differential equation such as Runge Kutta may produce a better approach to the differential equation but it decreases the computational speed significantly if the number of pedestrian is more than 100, thus, it is recommended for further study.

3.1 Characteristics of the Agent Microscopic Model Developed

In case of microscopic characteristics of agents' movement, the effects of forces applied are explained from the Figures 4. It could be seen that forward force causes the paths are linear line and repulse away forces direct the overtaking behaviour.

In all cases of the experiment results [Fig 4], it would be said that the paths have same pattern but they are not self-similar. However, each figure has the same rules for every member of swarm i.e. they move based on force[s] applied. In other words it is up repetition of the rules but they are not literally sequential. Therefore, the paths formed do not construct a tree as a fractal does.

Somewhat, the procedure of making a rule be applied in itself innumerable times, which is called recursion or recursive process, is iterated indeed. That means, each time this rule is applied we get a new result, or a new path. The difference between the swarms model and fractal path results would happens because of random generation inclusion. Further discussion of path resulted from fractal will be discussed in the following subsection.

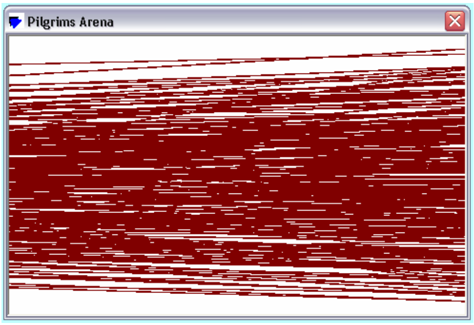

Fig. 4a. Forward [equation 2a applied]

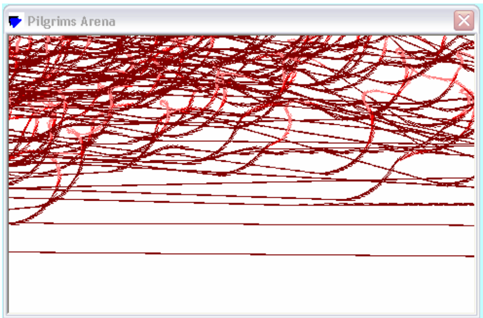

Fig. 4b. Forward, and move away [equation 2a, 2b]

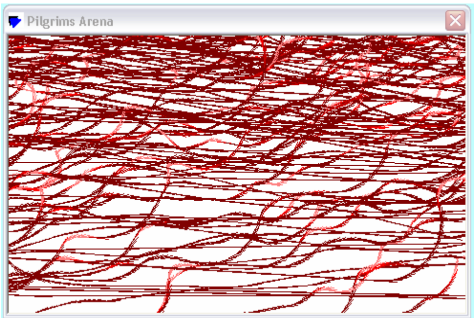

Fig. 4c. Forward, repulse away and avoid collision [equation 2a, b, c]

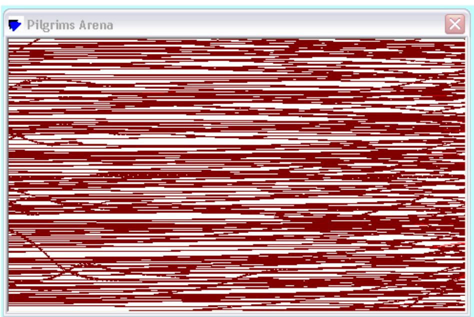

Fig. 4d. Forward and avoid collision [equation 2a, c]. The effects of forces to agents' paths

The relationship between speed and density is common to be observed in many traffic and pedestrian model and it is linear. Interestingly, the swarm microscopic simulation model also produces linear graphs but the slope is not consistently negative [Fig. 5]. The data are resulted with one various maximum speed and all three forces applied.

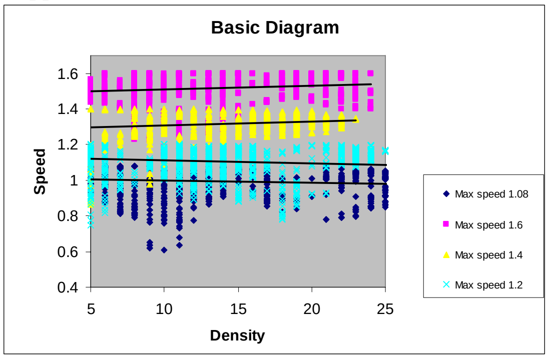

Figure5. The relationship between speed and density

Other experiments vary in forces applied and speeds are distributed normally clearly depict positive relationship but will achieve a flat line [Fig. 6]. It is interesting to note that the gradient and the intercept of the graph in swarm are different from the traffic [Fig. 7].

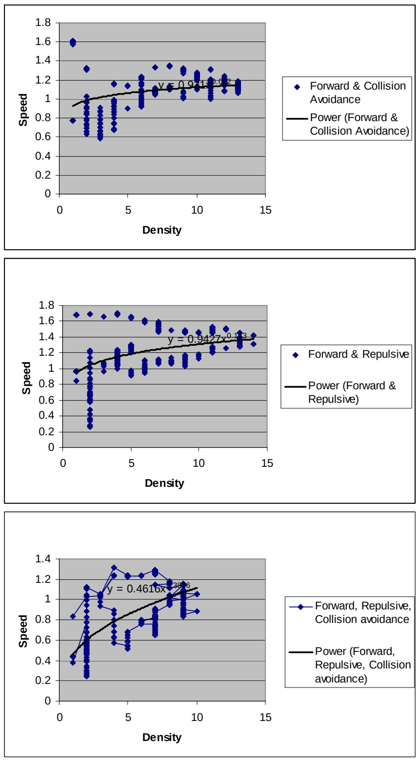

Fig. 6a, b, c. The relationship between speed and density vary in forces applied and speeds are distributed normally

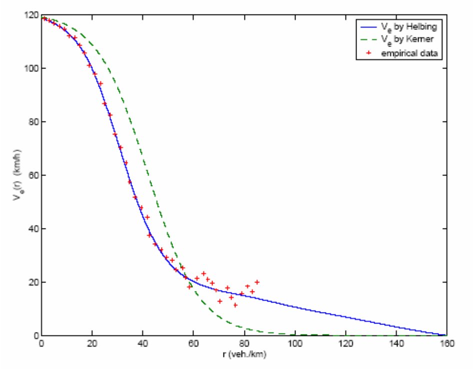

Fig. 7. The relationship between speed and density by Helbing, Kerne , traffic data the Dutch highway A9

Compared to similar graph [Fig. 8], the speed-density relationship is linear with higher maximum speed on the top of the lower one. The simulation results share this feature.

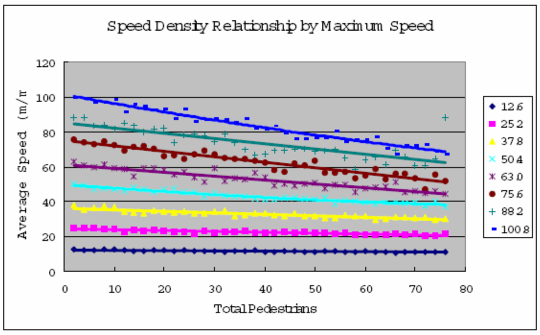

Fig. 8. The relationship between speed and density [Teknomo, 2002]

3.2 Fractal Characteristics of the Agent Microscopic Model Developed

Some experiments of a fractal pattern i.e. **one arm generated symmetrical toward left and right** as shown in Fig. 9 have been conducted. Fig. 10 and Fig. 11 show some result with the variant of symmetrical and asymmetrical length and angle of arms. Furthermore, Fig. 12 and Fig. 13 produce a very significant pattern of fractal that can contribute toward a very complicated structure of swarm research.

The most important advantage of fractal usage to model swarm is that the whole members are relatively more uniform distributed than any other models. Uniform distribution will achieve uniform swarm density. The occupied density is an influenced characteristic to control any swarm, crowd, flock or other large massive group of agents.

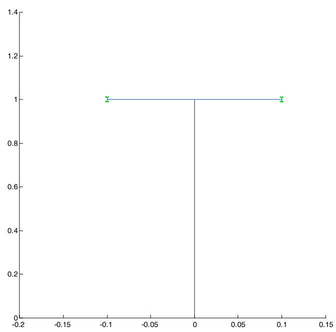

Fig. 9. A fractal pattern used in experiment

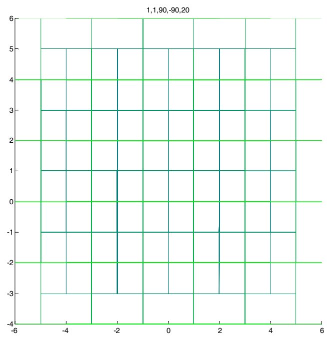

Fig. 10. Result with symmetric length and symmetric angle of arm

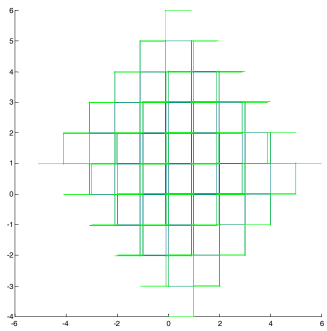

Fig. 11. Result with asymmetric length but symmetric angle of arm

From the both above figures [Fig 9 and 10], we can see that any curve path has not been formed yet if the fractal has symmetric angle of arm. Analogically, any scalar parameters [e.g. mass] in physical based model may not significantly influence the path direction but any vector parameters [e.g. velocity] may cause bending of path direction.

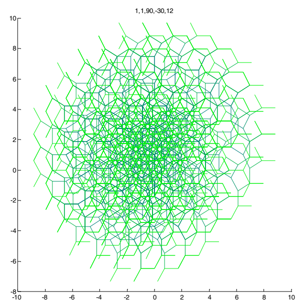

Fig. 12. Result with symmetric length but asymmetric angle of arm

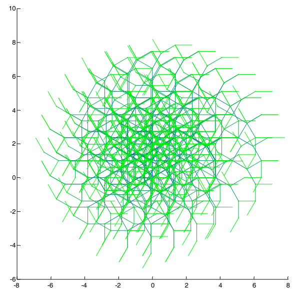

Fig 13. Result with asymmetric length and asymmetric angle of arm

The two above experiment results [Fig. 12 and 13] with asymmetric angle of arm whereas the arm length both symmetric and asymmetric have sharing characteristics of curve emerging behaviour with characteristics of the agent microscopic model developed that applied repulse away forces [Fig. 4b and 4c]. However, these sharing characteristics have not been mathematically proven except from curve paths seen.

Amazingly, the experiment results with equal arm's length and 60 degrees equal arm's angle will emerge a bee hive like formation [Fig. 14]. It is common knowledge that a bee is a grouping creature. Are there any relationships between group behaviour and fractal characteristics? This question needs further research.

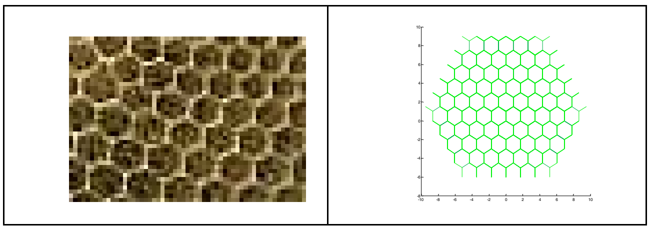

Fig. 14. Result with equal arm's length i.e.1 and 60 degrees equal arm's angle

Predictably, a straight line formation can be built by equal arm's length and zero degree [Fig. 15]. As we focus on the formula with the basic shape and form of a fractal, the fractal images created were not further processed by transformations that transform and warp the shape of a fractal and combine various transformations to create complex effects. We also do not involve colouring algorithms to give beautiful and complex images.

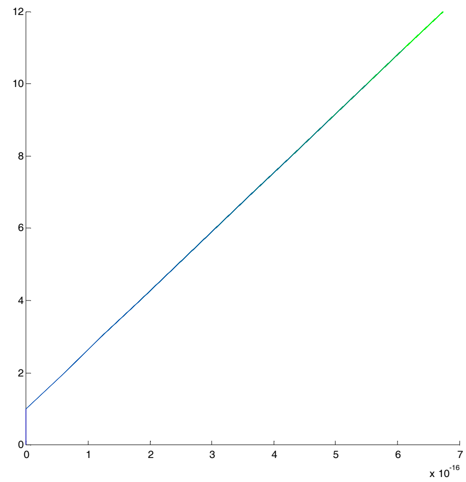

Fig. 15. Result with equal arm's length and zero degree

A fundamental challenge for computer scientists over swarm model is to develop methods for predicting overall behavior of its individual computing units emerged during programs execution. Like most of swarm programs must deal with uncertain environments and mobile nodes, the scientific challenges of fractal swarm computing are also to understand how to create programs for individual units based on the desired behavior. However, the fractal swarm computing needs to predict the total behavior in such based on the fractal equation that must be initially discovered.

A common type of fractal dimension is the Hausdorff-Besicovich Dimension, by which fractal dimension can be calculated by taking the limit of the quotient of the log change in object size and the log change in measurement scale, as the measurement scale approaches zero, for example the Sierpinski triangle [Fig.16] . The advent of defiant interpretation is not avoidable due to what is exactly meant by "object size" and "measurement scale". It happens when we need to get an average number out of many different parts of a geometrical object.

Height of the Sierpinski triangle = 2 Fractal dimension = 0	Height of the Sierpinski triangle = 4 Fractal dimension = 0.4703
Height of the Sierpinski triangle = 8 Fractal dimension = 0.9203	Height of the Sierpinski triangle = 16 Fractal dimension = 1.3147

Fig. 16. The Sierpinski triangle fractal

If a fractal is exactly self-similar, the fractal measurement can be defined by how often functions systems are iterated. Indeed, fractal dimension and iteration are not adequate enough to describe the fractal complexity except the bigger figure numbers mean more complex [Fig. 16 and 17]. In relation with swarm behaviour, bigger fractal dimension and iteration would be interpreted as higher swarm density.

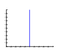	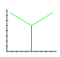	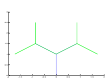	
Iteration =			
1	**2**	**3**	**4**

Fig. 17. Sequential result with equal arm's length i.e.1 and 60 degrees equal arm's angle

Paths resulted in experiment of crowd microscopic model with forward forces applied [Fig. 4a and 4d] in swarm has sharing characteristics with paths resulted in the fractal experiment with equal arm's length and a small degree [e.g. 5 degree] of arm's angle [Fig. 18].

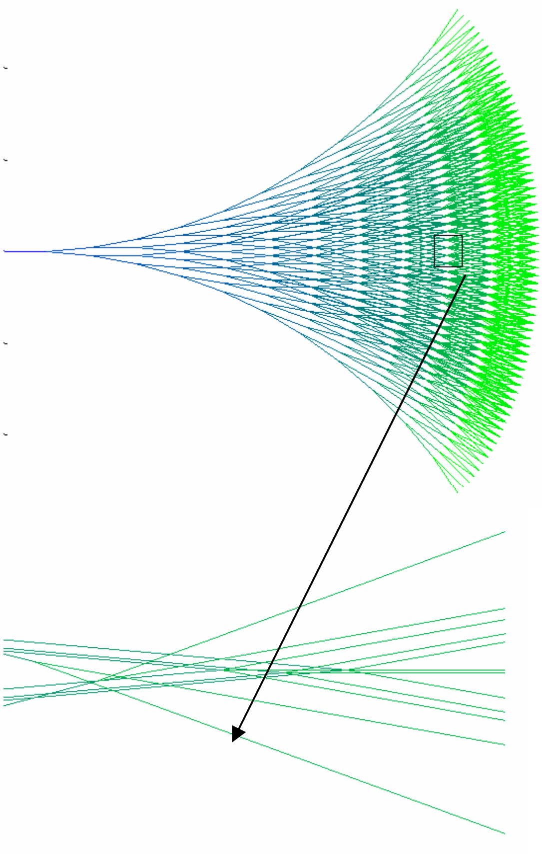

Fig. 18. Result with equal arm's length and a small degree [e.g. 5 degree] of arm's angle

The case of crowd exit [Fig 19 and 20] may well describe that group behaviour is fractal, so does swarm.

Fig. 19. Crowd in exit

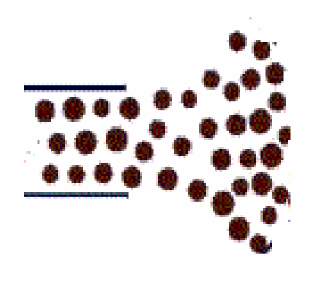

Fig. 19. Snapshot from re-simulation of Helbing model

Regarding the validation and verification, crowd compiler can be used to visually compare between real world [Fig. 20] and simulation snapshots.

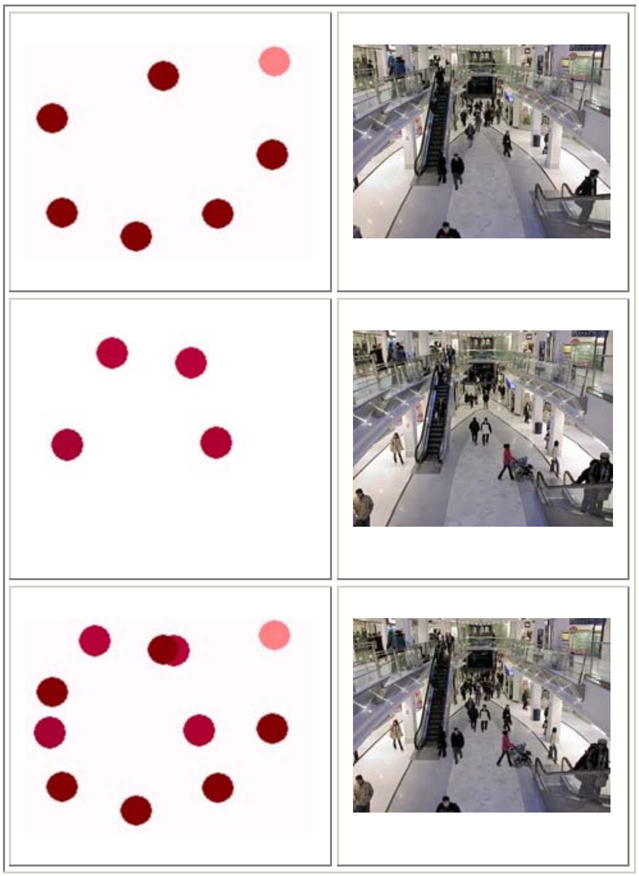

Figure20. Crowd compiler

4. Conclusions

The microscopic agent simulation model has been developed to determine the microscopic characteristics of swarm. From the simulation results, there is relationship between density and agent speed. The relationship is influenced by maximum speed and velocity distributions.

The agent paths resulted are studied and compared to paths that are created from the fractal. We have demonstrated that fractal could be used to approach the emerging swarm behaviour. As we have produced the result that has sharing characteristics with crowd microscopic model, modelling swarm with fractal equation would be potentially conducted in the future.

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