Boids and Crowd Behaviour

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Figure 1: Crowd at Knebworth House - Rolling Stones 1976

ABSTRACT

With an increasing need to portray the real world in the realm of computer graphics, the need to efficiently simulate complex natural behaviour became more and more apparent. In this paper the state of the art of flocking, swarming and crowd simulation will be explored.

CCS CONCEPTS

• **General and reference** → *General literature*; • **Computing methodologies** → **Procedural animation**.

KEYWORDS

Boids, Crowd Behaviour, Crowd Simulation, Artificial Intelligence, State-of-the-art

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1 INTRODUCTION

At first it was taught that nature was truly random and chaotic therefore making it near impossible to accurately simulate and predict. However, with the rise of scientific discovery and analysis, sets of rules were discovered that describe the behaviours of nature. This proves that nature, as complex as it appears at a first glance, is actually a set of smaller rules interacting with each other to create a bigger and more complex reality.

In the search to simulate complex structures and behaviours observed in reality, the world of computer graphics also started to search for simple rules that closely mimic reality. The main difference when compared with the scientific rules is that there is a need for them to consume as little computational resources as possible. Thus, for the most part, the main goal of the rules created for computer graphics is to generate believable and visually pleasing results that appear reality-like while consuming as little computational resources as possible.

One of the most relevant cases of this is the simulation of large groups of animals or people. In this paper the evolution of the simulation of entities will be explored, making brief references to the most relevant authors, leading into the creation of entities capable of learning during a simulation. Then the most recent algorithms for crowd simulation will be discussed and compared and their use cases presented. Finally, what the future holds in this field will be discussed.

2 THE DAWN OF BOIDS

The appearance of a large flock of birds might be mesmerising and appear truly random at first as waves and direction changes propagate over the flock seemingly without a origin or end. However, a flock is not a truly random system. Even tough the position of each individual bird might not be predictable in the far future, there is a high probability that, in the immediate future, any given bird will most likely still be steering towards the same direction. Therefore, any attempt to simulate how them behave cant be based on a random algorithm that arbitrary changes the direction any given bird is flying.

After analyzing the behaviour of flocks and reaching this conclusions, Craig Reynolds created the first instance of a boid in 1986[15]. The term originates from the contraction of the term "bird-oid object" meaning bird-like object and was used to describe

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a artificial life program that simulates the natural flight path of a flock of birds. This type of program is generally called artificial life program due to the fact that it seeks to recreate and simulate the interactions between animals and the interaction of animals with the environment.

The creation of this program was considered a turning point in computer graphics since up to that point the behaviour of a flock of birds was recreated by manually defining the path of each bird one by one. This old method was extremely time consuming and often produced sub-par results. The new method however, aimed to solve this problems by instead defining the behaviour of each boid as a small set of rules that defined steering behaviours in relation to the environment and the boids in the immediate surrounding. This gave birth to procedurally generated animations that were faster to implement and resulted in more realistic results.

Even tough the program has access to all the boid's position at any given time, the information to process each rule is limited to only the nearby boids. This reduces the area of influence of each boid resulting in a more realistic result. Additionally this method greatly reduces computation load since each boid only looks at his vicinity and other boids inside of it.

Thus, based on the information they can collect each boid follows a set of three different rules (Image 2).

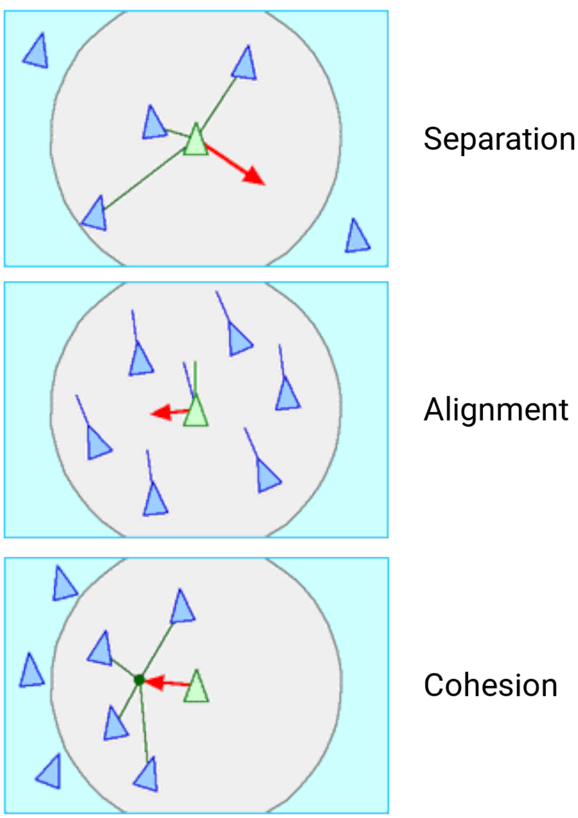

Figure 2: Three original rules for flock behaviour (https://www.red3d.com/cwr/boids/).

Firstly, each boid steers to avoid local flock-mates in order to avoid collisions mid-air and ceate separation from nearby boids. Then the boid aligns itself with the average heading of local flock-mates in order to follow the general direction in which the flock is moving. Finally, so that the flock does not dissipate, the boid steers towards the average position of local flock-mates.

This already creates realistic flocks with seemingly random waves that propagate over time (Image 3). However the flock does not interact with the environment yet. In the original 1987 paper it is explored the possibility to add rules for object avoidance and simple goal seeking. The later results in all the boids following a small set of paths destroying the chaotic nature of a flock of birds.

Figure 3: Boid simulation using Tabletop Simulator (https://steamcommunity.com/sharedfiles/filedetails/?id=743303969)

Ultimately this new development in computer graphics culminated in the creation of a short film called "Stanley and Stella in: Breaking the Ice"[7]. In this short, a micro ecosystem exists inside a semi-transparent glass sphere half filled with water. Under the water a school of fish swim around in a natural way avoiding rectangular objects and above the water a flock of birds flies avoiding cylindrical objects (Image 4). The short follows the story of Stanley the bird and Stella the fish falling in love but being unable to meet face to face due to a tick sheet of ice that formed on the water[11]. The first version of the film did not gain much traction outside of the computer graphics field. Nevertheless, after a tonal shift provided by a new, less somber, Jazz soundtrack and a renaming to "Love Found" this film actually gained a certain cult following amongst certain film enthusiasts that enjoy the aesthetic of computer generated graphics of this era and was even aired several times on television. Now it is available on several video sharing platforms like youtube.

Even tough the graphics do not hold up today this short film came as a turning point in computer graphics and computer animation and represents one of the first instances of realistic procedurelly generated animation since both the fish and the birds use the revolutionary technology developed by Craig Reynolds to streamline the creation of this complex animations for the time.

Figure 4: Stanley and Stella in: Breaking the ice[7] scene

3 CREATION OF BOID INDIVIDUALITY

After the breakthrough created by Craig Reynolds the study of boids gained great traction amongst the computer graphics field. This is due to the fact that one of the goals of computer engineering that is transversal to all of it's fields is the search of simplicity and efficiency. Thus, it is far better for a task to be performed automatically by a computer than to be painstakingly created by a artist, programmer or designer. This goal perfectly fits the concept of the simulation of schools of fish or flocks of birds with the use of Boids.

Even tough initially the work of Craig Reynolds was targeted towards simply representing in a way that seems credible the real world without necessarily having scientific accuracy, the scientific community quickly realised that the possibility of running simulations over the behaviour of animals could lead to scientific breakthroughs. For example, it could become possible to study the reaction of animals to the introduction of an invasive species.

After realizing that there were several applications for the ability to simulate the behaviour of large groups of animals outside of simply graphically representing them in a believable way, a need to simulate the behaviours of more complex entities started to appear. However the boids created by Craig Reynolds are simply to restrictive to recreate the real world realistically.

In order to overcome the hurdle posed by the simplicity of the boid algorithm a incessant search for different paradigms for the simulation of large number of entities started.

The work of Craig Reynolds regarding the simulation of school of fish was greatly built upon in 1994 by Xiaoyuan Tu, Demetri Terzopoulos and Radek Grzeszczuk [12]. This team was most notably able to greatly increase the complexity of each boid and how it interacts with the environment. Each boid was previously simply a three dimensional model with a default swim animation attached to a point that followed a predetermined set of rules. This basic system was changed into a structure of muscle and actuators controlled by a larger set of behaviour routines that can be optimized overtime by an artificial intelligence algorithm. To further add to the individuality of each boid a set of habits of each individual are taken into account when interacting with the environment. To further improve the realism, the number of sensors and data available to the boid was increased. Finally, physical properties were added to the environment so that, for example, the movement of a fish under water interacts following the hydrodynamic principles (Image 5).

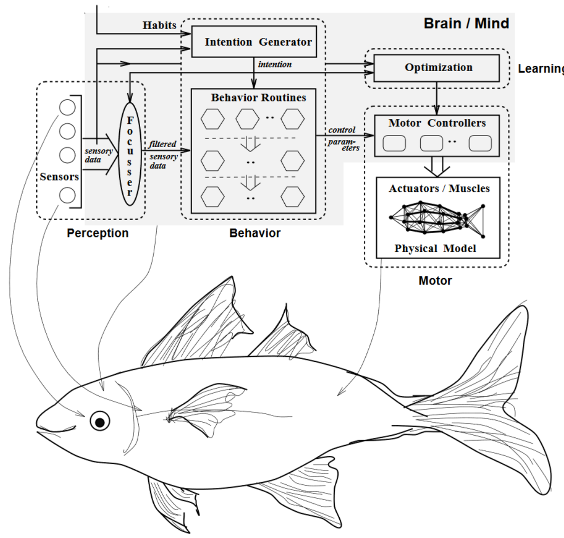

Figure 5: Control and information flow in artificial fish(from the original article[12])

Furthermore, the demonstration used to visually represent the new theory also showed the great development in computing power and graphical fidelity (Image 6).

Figure 6: Artificial fishes in their physics-based world (taken from the original paper[12])

4 CATEGORIZATION OF ALGORITHMS

Even tough this algorithm represented a massive breakthrough in the realistic representation of large groups of varied entities, the underlying logic is still similar: Each entity's interaction with the environment and other entities is individually computed.

With the development of new algorithms that, for example, focused more on the global flow of the crowd, the need to classify them surfaced. Thus, a set of three categories where created to define the possible approaches to the problem of Crowd simulation : Agent-based Approach, Flow-based Approach and Entity-based Approach [18].

All the algorithms that fall under the category of Agent-based approach are described as a set of autonomous interacting individuals with a certain level of intelligence that react to the environment and each other based on a set of rules. This rules can change during the simulation based on the interaction of the entities with the environment giving them the ability to learn during the simulation. This gives complete control to the researcher making this type of simulation possibly the most realistic in modeling the behaviour albeit the most computationally expensive. The boid algorithm after being improved in 1994 is an example of a Agent-based approach.

By contrast, Flow-based Approach focuses on simulating a crowd as a whole. Thus, when this type of simulation is used, the focus is usually on how the crowd reacts and interacts with the environment and flows through it in the general sense. For example, this simulation is often used to simulate how a large crowd flows through a small opening like a door (Image 7). Interestingly this algorithm often borrows elements from the study of fluid dynamics[17]. Since this method mimics the flow of a crowd the individuality of each entity is mostly nonexistent leading to the lowest cost per entity of all of the three approaches. This model is mainly used to simulate large sets of elements in a small time frame.

Figure 7: Crowd Flow during Black Friday in 2011 (https://www.youtube.com/watch?v=DigiWS1YhxI)

Finally, the entity-based approach can be considered a middle ground between the previous approaches. A set of immutable global laws are created that rule the way the entities behave. This rules cannot be changed during the simulation making the entities unable to learn and improve during the simulation. This type of algorithm is ideal to simulate small to medium crowds in short time frames. Also, the increased simplicity when compared with the Agent-based approach greatly reduces the computational cost per entity making it a middle ground in terms of computing power between the previous methods.

5 REAL WORLD APPLICATIONS

Surprisingly, even tough there have been many breakthroughs in the research of crowd simulation, in many areas, the original algorithm crated by Craig Reynolds is still used to this day mostly unchanged. This approach still shines in cases where there is a need for simple and fast computations to create a scene. The two most prominent use cases of this technology to this day are video games and background CGI in movies. In recent years there has been a shift towards more complex algorithms in the movie industry mainly in blockbuster movies.

Apart from leisure activities, there are some real world applications that have direct impact in the quality of life of the human population. For example, there are many areas in the design of modern cities that require the simulation of large crowds to ensure that it is up to the required standards. Urban planning, Evacuation Handling and Law Enforcement are great examples of this.

5.1 Video Games

One of the most well know examples of Boids in a video game is present in Half-Life released in 1998. In this game, flocks of green and orange flying monsters (Image 8) can be seen near the end of the game when the player enters a region known as Xen. This flocking behaviour uses a simple algorithm very similar to the one developed in 1987 by Craig Reynolds[6]. After analysing the code of the game it was discovered that there were plans to add a second yellow variant of this entity capable of more advanced interactions with each other, including the creation of a small ecosystem with predators and prey. However this was considered unnecessarily advanced and too computationally expensive in a performance critical program such as a video game and eventually the concept was scrapped.

Figure 8: Flocking Behaviour in Half-Life

The limits of the hardware at the time was also one of the factors that made many developer choose to use procedurelly generated flight paths instead of having a large set of pre-generated flight paths for the birds: it is actually more space efficient to save the code that creates animations rather than the flight paths themselves

5.2 Film, Cinema and Movies

Boids are often used in the case of swarm or flock simulation in movies[3]. A great example of this is the 1992 film "Batman Returns" directed by Tim Burton. In this movie swarms of bats that use the boid algorithm were used in several scenes (Image 9). Since at this time there had been a great jump in computation power and investment from the movie studios into computer generated graphics, the bats in this movie appear much more life like when compared with the movie created with the help of Craig Reynolds.

Figure 9: A swarm of bats using boid algorithms in 1992 "Batman Return's"

However, sometimes such simple algorithms are not enough to simulate the more complex scenes. Usually in the simulation of armies clashing in a fierce battle, it is not enough to have them simply avoid each other and their surroundings. Each entity has to have a goal and a varied set of actions they can take to create the maximum variety possible in a scene containing thousand of entities[5]. One of the most well know example of such grandiose battles containing upwards of fifty thousand soldiers were "The Lord Of the Rings" trilogy (Image 10. The production of this movies used an already existing program to develop the animations. Yet, what made it stand from the rest was the much larger number of individual animations each entity could perform based with it's interaction with the environment.

Figure 10: Battle of Helm's Deep in "Lord of the Ring: The Two Towers"

5.3 Drone Swarms

Recently there have been many examples of shows and popular sports events were the fireworks are changed to a more ecofriendly solution based on swarms of drones with a multi-color light source attached to the base. This allows to create extreme complex animations in the night sky that would be otherwise utterly impossible to recreate with traditional means (Image 11).

Figure 11: Swarm of drones creating a running animation

To create each figure a drone has a target destination where he has to go to without entering in a collision route with any of the thousands of other drones that are also trying to reach their respective destinies. To achieve this swarm simulation algorithms similar to the one developed for boids are used.

This area of robotics is called Swarm Robotics and there are many uses outside of simple entertainment for this revolutionary technology. For example, there are currently many teams dedicated to the study of swarms of flying or ground drones capable of finding victims in a catastrophe[14], returning to base when there is a need for repairs or recharging (Image 12) and entering hostile environments.

Figure 12: Swarm of open-source Jasmine micro-robots recharging themselves [CC BY-SA 3.0]

5.4 Urban Planing

Urban planing of a large city covers a wide area of topics. There is a need to define how the land is to be divided and used in the long term and decide how all the infrastructures in the city will be built accounting for future changes in population density and technologies.

Infrastructure planing can be divided in two broad topics: Areas that directly influence how people navigate through a city and areas that do not. Examples of areas that do not influence how people navigate a city include water, gas and electrical grid. Examples of areas that do influence how people navigate a city are transportation and roads[13].

Since crowd simulation is better suited to areas that directly influence how people move people, the later is the area that mostly benefits from crowd simulation.

When compared with mathematically calculating the maximum possible flow in a given intersection or roundabout, the ability to simulate different flows, road designs and time frames with the press of a button paints a much more realistic representation of the impact of a given alteration on the real world. Thus, when applied in a large scale, urban planing allied with crowd simulation can represent a great improvement on the quality of life.

One of the greatest example of a city wide optimization of infrastructures comes from from the "prototype city of the future" that is being created by Toyota in Japan[16]. Toyota is calling the city "Woven city", a reference to how different types of roads dedicated to different type of traffic where optimized as much as possible to create a woven network of roads, parks and buildings that maximise safety, flow and well-being of the citizens (Image 13). The company expects that the city will house over two thousand people by the end of 2021.

Figure 13: Woven City Concept presented bu Toyota at CES 2020

Toyota's claims are not unfounded, most experts believe that the city of the future is in fact an interconnected mesh of sustainable services and resources powered by constant developments in the capability to simulate human behaviour and cater to it.

5.5 Evacuation Handling

If Urban Planing is Crowd simulation applied in the macro scale, then Evacuation Handling is the micro scale. Instead of simulating how an entire city behaves during the day or rush-hour, evacuation handling powered by crowd simulation focuses how a subset of a city, usually a building or road section, reacts during a catastrophe in a small time frame[1].

This simulations have to be often altered to accurately represent how a human behaves during stressful events[9]. Firstly, when scared, people tend to behave as a herd following the person immediately in front of them. Secondly, not everyone knows the space they are navigating in the case of an emergency. Thus, they do not know what kind of hazards and obstacles can be on the way. This leads to situations in which a crowd is trying to rush to the same exit while another exit a couple of meters away is completely deserted (Image 14).

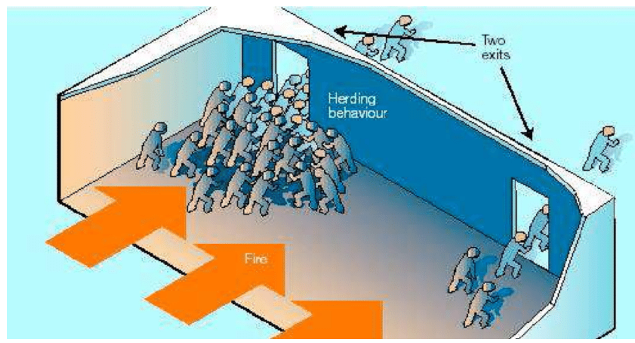

Figure 14: Crowd Simulation trying to escape a smoke filled room

If this stampeding behaviour of humans in panic can be precisely replicated in a simulation, parameters can be changed in order to create better evacuation plans for a building and save lives in a catastrophe. Thus, there has been a lot of research effort put into this area resulting in many programs capable of simulating and optimizing evacuation routes in a building (Image 15).

Figure 15: Simulation of an Emergency Evacuation due to a fire

5.6 Law enforcement

Law enforcement often has to deal with crowds in panic and herd behaviour similar in many ways with the one present in Evacuation Handling. Examples of such parallels are protests and catastrophe relief were in both a herd mentality can be observed in the movement of people. In a protest people tend to follow the person they perceive as a leader, such as the one holding the placards or the megaphone. On the other hand, in catastrophe relief people tend to be disoriented and follow the person immediately in front of them.

To better train police officers, firefighters and military to deal with mobs and crowds, simulations can be used to train how each group can help calm and direct people to act as effectively as possible.

Figure 16: Firefighters after a 6.2-magnitude earthquake in Chile (https://i.dailymail.co.uk/i/pix/2016/08/24/22/378E249600000578-3755722-image-a-3_1472075559182.jpg)

In fact, there are already examples of this in the real world[10]. For example, Rotterdam's Police and the Dutch Government have developed a real time simulation of riots and protests in conjugation with VSTEP called "VSTEP Crowd Control Trainer"[4](Image 17) that accurately represents how a agglomerate of people reacts to police intervention.

Figure 17: Crowd Control Trainer example17

Nowadays this tool is used to train more efficient police brigades in three different fields. The ability to manage a crowd by creating order, the ability to control a crowd and maintain order and the ability to deescalate rising tensions in order to prevent riots and violence, allowing very varied simulations including the simulation of opposing groups that have to be guided in order to avoid each other (e.g. football supporters).

6 CONCLUSION AND THE NEXT STEP

The study of boids and crowd behaviour and subsequent simulation of them is a field of real time computer graphics with many real life applications. From leisure activities,like movies and video games, to critical activities that can save lives or help save the planet by reducing pollution, like evacuation handling or urban planning. Thus, making this an area that directly impacts human's quality of life.

This rise in interest from many areas will surely will surely not stop in the foreseeable future creating a snowball effect that will result in a complete revolution of how it is implemented and created in a near future.

One of the hot topics is the ability to have each entity behave based on a complex neural network effectively increasing the autonomy and learning abilities. Currently this technology is far from being wide spread and capable of being computed in real time. However, with a heavy investment from GPU manufacturers into graphics cards with an increased neural network computing capacity[2, 8] it is not difficult to imagine that crowd simulations in the near future will be powered solely by complex neural networks.

This performance boost comes mainly from the implementation of tensor cores. These are dedicated areas of memory for matrix operations that support the most common operations, such as matrix multiplication, that are common in both computer graphics and AI leading to an increase in throughput up to 32 times (Image 18).

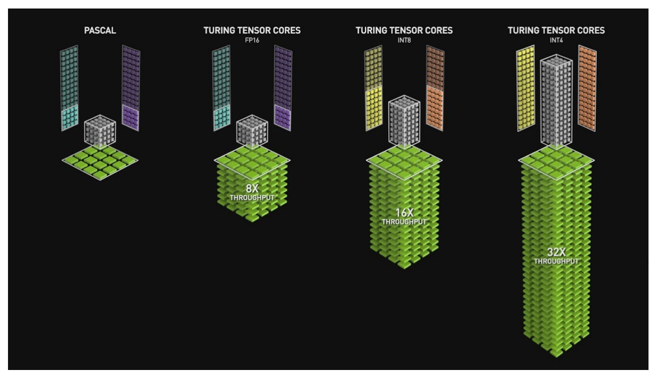

Figure 18: Nvidia Tensor core performance comparison for dotprod

Although neural networks can lead to a more realistic simulation to be used in critical areas, this bleeding-edge technology will surely make its way into leisure activities to also improve the quality of movies and video games and create more immersive experiences were the world fells truly alive when observed.

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