**Multi Agent Bat Behavioral Simulations**

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**Abstract**

This paper details relevant research on bat behavior patterns and echolocation abilities and uses it to create models for simulation. That research highlights the key aspects and motivations for simulating bat colonies and prey such as combating White-Nose-Syndrome or studying the positive effects of bat colonies on crop health. The created models include bat and insect flocking behavior, echolocation abilities, hunting patterns, roosting behavior, and energetics. Each model is built from mathematical equations or computer algorithms and founded in the bat research. These behaviors are combined in a multi agent simulation run in the Unity Engine in real time. Each individual agent controls its actions for any time step based on these behaviors and the emergent patterns are studied and discussed throughout this paper with suggestions on where future research on bat simulations should focus.

**Background of Bat Behaviors**

**General Information:**

Bats are complex creatures with amazing capabilities. They are the only flying mammal and one of the most evolved echolocators on the planet (Kolli 2007). There are over one-thousand four-hundred species of bats worldwide and they can be found in almost all climates, save arctic and desert regions (Bat Conservation International 2022). Only 70% of bats use echolocation and each species has unique echolocation calls (Stroffregen & Pittenger 1995). Many bats are hibernators and will periodically roost in trees or building overhangs while foraging for food in a night, especially when hunting conditions are poor (Kolli 2007). This roosting habit is an important factor that will be discussed more in the simulation section. Bats have much in common with other well-known animals, they clean themselves similarly to cats and feed their pups breast milk instead of insects (Bat Conservation International 2022). The longest living bat is 41 years old, and most bats live an average life span of 20 years in the wild (Bat Conservation International 2022). Bats have few natural predators such as Owls, Hawks and Snakes although many bats have been dying from a fungal virus known as White-Nose-Syndrome (Bat Conservation International 2022).



(Fig 1: White-Nose Syndrome fungus)

White-Nose-Syndrome is one of the most dangerous threats to bat populations and can have a mortality rate of over 90% in colonies (B.C. Bat Action 2020). Bats will often have a home colony and roost, they will either hibernate through winter or migrate to a warmer climate (Bat Conservation International 2022). Depending on the species, bat colonies can range from fewer than twenty-five to over one-thousand bats (B.C. Ministry of Environment 2019). In British Colombia there are species of bat such as Hoary and Red Bats that roost as single-family units and the Yuma and Little Brown bat species can reach colonies of over a thousand individuals (B.C. Ministry of Environment 2019).

**Hunting and Flocking:**

Bats are nocturnal hunters and forage for food over an 80-kilometer radius from their home roost (Kolli 2007). The ability to hunt at night protects bats from many species that would try to hunt them and often allows them to hunt without being detected. Bats almost exclusively consume flying insects, but some species are known to hunt land or tree dwelling prey (Kolli 2007). The Mexican free tailed bat hunts as high as 1200 meters as insectoid prey can be found migrating at high altitudes (Kolli 2007). Many of the insects a bat consumes forage for food below 400 meters; these factors have been considered in creating the simulation parameters. Bats flock when leaving their home caves or roosts and will fly upwards in a column until they reach their hunting destinations (Kolli 2007). Bats flock this way for safety and bats on the outer parts of the column will steer the flock away from any predators or threats they perceive. The bats will then break off from the main flock into subgroups in search of prey. Most species of bat hunt individually and their perceptions range from 2 to 10 meters when echolocating (University of Southern Denmark 2013). Throughout the night bats will roost in safe locations to rest and conserve energy (Kolli 2007). When facing unfavorable hunting conditions due to weather or lack of insect prey, bats will favor roosting and try again later that night. Nursing mothers require more food than the average bat and will find periods throughout the night to return to the home roost and feed their pups (Kolli 2007). Different species of bats need varied amounts of food, many can consume up to their body weight in prey each night (Kolli 2007, Bat Conservation International 2022). The hunting behaviors and energetics of roosting are important factors in bat behavior and have been considered for this simulation.

**Echolocation:**

Bat echolocation calls are unique for each species but there are many similarities between them. Bat echolocation calls can range from 11 kHz to 212 kHz with the majority of echolocation falling within 20 kHz – 70 kHz (Stroffregen & Pittenger 1995). The range of human hearing only extends to 20 kHz, as such most bat calls are imperceptible to humans. These high frequency calls are very useful for detecting minute details in echoed signals. Echolocation relies on an emitted call from the echolocating animal and the reflection of that waveform convolved with objects in the immediate environment (Huang et al. 2013, Kolli 2007, Aihara et al. 2013, Grunwald et al. 2004). Every physical object has an impulse response (IR) that characterizes how sound interacts with its surfaces. All materials have absorption properties and coefficients that categorize how much sound energy they reflect for various frequencies (Grunwald et al. 2004). These material properties and the orientation of surfaces convolve with a bat’s call waveform and reflect echoes that can be interpreted by the bat. The time from pulse to echo allows bats to determine distance to objects and minute time differences between ears give positional information relative to the bat (Kolli 2007, Aihara et al. 2013, Grunwald et al. 2004). Sound interactions are very complex, and the frequencies of a bat call are modulated when interacting with moving objects because of the relative speeds, surface interactions, and waveform spectrum (Huang et al. 2013, Grunwald et al. 2004). This effect is known as doppler shift and allows bats to gain information on the relative speeds and headings of moving objects like insectoid prey (Huang et al. 2013, Aihara et al. 2013, Grunwald et al. 2004, Stroffregen & Pittenger 1995). For example, if an insect is moving away from an echolocating bat, it will receive lower frequency echoes or higher frequency echoes when insects are moving toward the bat. It is commonly theorized that bats can recreate highly detailed virtual images of objects through echolocation almost instantaneously (Kolli 2007, Aihara et al. 2013, Stroffregen & Pittenger 1995). The complex interactions of bat echolocation are not the focus of this paper and has been simplified in the model.

Bats vary the amplitude and frequency bandwidth of their calls depending on the situation (Kolli 2007, Aihara et al. 2013, Stroffregen & Pittenger 1995). Bats use constant frequency calls when detecting objects in their surroundings or trying to broadly locate prey (Kolli 2007, Aihara et al. 2013). These calls are often emitted in a lower frequency range around 30 kHz and give bats generalized details of their environment while frequency modulated calls determine more exact information on distance, direction, size, and texture of detected objects (Kolli 2007, Aihara et al. 2013). When hunting bats use relative low frequency calls of around 30 kHz to broadly detect prey during their search phase. These calls are then modified with shortened intervals between bursts, increased intensity, and bandwidth to gain more accurate information during the approach phase. This increases into even shorter intervals between pulses and greater intensity immediately prior to catching prey to give an incredibly accurate sound image of prey on interception (Kolli 2007).

The distance for prey to be perceivable depends on the intensity of a bats call, the distance between bat and prey and the angles of reflection. Bats emit very loud calls averaging around 109 dB and can increase intensity to as high as 137 dB (Forschungsverbund 2020). Due to the inverse square law sound loses energy proportional to one over the distance squared.

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(Fig 2. Inverse square law of sound propagation)

When the environmental noise floor is high bats need to adjust their calls volume to be able to perceive sounds at a similar distance and can require significantly more energy (8).

**Echolocation Field of View:**

A Bats echolocation perspective is based on their individual calls, ears, speed, and the detected objects. In the (Aihara et al. 2013) study *Rhinolphus derrumequinum nippon* bat calls were shown to decay at greater speeds off-centre of the call. When angled +/- 25π/180 radians from the pulse direction the sound pressure levels dropped by 50% (Aihara et al. 2013). This is an important characteristic that has been used to model the perception range of bat echolocation. Different bat species can have different perspective characteristics and this field of vision can be parameterized accordingly. The size and textures of the detected object are quite relevant to the distance they can be echolocated from. Larger and more reflective objects will return more echoes with higher energy toward a bat and can thus be detected from further away. Smaller objects often require closer proximity for detection (Aihara et al. 2013, Grunwald et al. 2004, University of Southern Denmark 2013).

**Bat Behavioral Simulation**

**Why Do We Simulate?**

Appropriate simulation for bats could help us identify a solution to the White-Nose-Syndrome without risk or harm to animals. They could also be used to model a farming system where bats help control insectoid pests increasing crop yields and quality, continuing the work done by (Kolli 2007). The closer a simulation can match reality the more we will understand about the mathematical and physical forces that govern bats echolocation and behavior.

**Simulation Overview**

This simulation was done in unity and takes advantage of many of its built-in functionalities such as space partitioning and fixed time updates. The simulation encompasses bats hunting, roosting, energetics, and behavioral patterns over multiple days and can be adjusted to study specific goals. The simulations main objects are a home colony cave, temporary roost spots, and insect clusters that migrate with an adjustable wind vector to match real world insect behaviors. The simulation space can be modelled to mimic real world environments.

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Using unities time functionality, a day and night system was created to help model the bats behavior patterns. This system allows for modifiable day/night lengths and can accommodate seasonal changes in day length from the physical world. Using to represent the night length, to represent the day length and (with index base 1) to represent how many days have passed the following equations keep track of night and day:

(9)

(10)

The simulation starts on the first night and equation nine will be satisfied during the entire night length where equation 10 will be satisfied during the entire day length.

**Bat Flocking, Based on the Boid Model:**

This bat flocking model is based on the Boids rules developed by Craig Reynolds (Reynolds 1987, Reynolds 1999). The boid model is based on individual agent perception and a desire to remain in the flock. The agent’s position is represented as a 3-dimensional point and is updated at each simulation step by a velocity direction vector. The velocity vector is a weighted summation of 4 vectors based on the boid’s perception: Cohesion, Alignment, Separation and Objective.

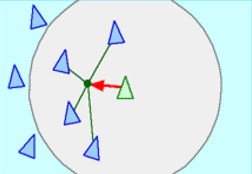
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(Fig 4. Individual Boid perception with radius and angle of visibility)

Cohesion refers to the desire to move toward nearby agents and remain in the flock. This rule is made through a summation of vectors from the boid to each perceptible agent and dividing that vector by the number of perceived agents.

(1)



(Fig 5. Boid cohesion)

Alignment averages the direction of nearby agents and keeps the flock moving in the same direction. This is done through a summation of the perceivable agent’s velocity vectors divided by the number of perceived agents. The velocity vectors for all agents are then updated separately to ensure all agents are working with information from the same fixed time step. {fig 4}

(2)

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(Fig 6. Boid alignment)

Separation refers to the desire to avoid collisions and helps steer away from very close flock mates. The radius check for collision risk scales with proximity which makes objects that are close by have a much larger impact on the vector than objects further away. {fig 5}

(3)

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(Fig 7. Boid separation)

Objective allows the agents to be moved toward goals within the simulation such as perceptible insect groups, temporary roosts, and a home roost. At each time step a vector is made by subtracting the bats’ goal point from their current point in simulated space.

(4)

The velocity is then calculated using a weighted summation of these four vectors. The and are the weighting coefficients for separation, cohesion, alignment, and objective respectively.

(5)

This velocity summation could have a magnitude greater than the maximum speed of a given bat. In this case velocity vectors are truncated to the maximum speed by normalizing them and multiplying by the max speed (Reynolds 1987). Adjusting these weighting coefficients can give priority to behavioral goals such as avoiding imminent collision or steering towards prey.

The speed of agents and weighting coefficients can be parameterized for different species to better match their flight patterns. This boid model does not account for physical aspects such as wind, drag, lift and gravity. It is a simplification to fit the purposes of this research project.

A computer agent could have access to all information within the simulation. This is unrealistic for real bats and as such, the first 3 rules are given a localized field of view (Reynolds 1987, Reynolds 1999, Jonsson & Ljungberg 2017) as shown in Fig 4. This boid model is used for both the simulated bats and their insect prey. The insects simulated within clustered groups without a defined objective. These groups can be perceived by a bat in accordance with their echolocation model.

**Echolocation Model:**

From the previous studies on echolocation this model uses a perception field of view for hunting as a 25π/180 radian angle from the bats current velocity heading which represents their head’s angle. This creates a cone of detection for prey within the 2–10-meter echolocation range.

Diagram

Description automatically generated

(Fig 8. Vector A represents the distance from a bat to the nearest insect. B represents the bats current velocity and head angle. Objects within this cone are detectable according to the echolocation equation 6)

For this simulation insects are assumed to be detectable if their distance from the bat is within 8 meters and they lie withing this detection cone. As such prey are detectible if they satisfy the following equation where **A** represents a vector from the bat to a nearby insect and **B** represents the velocity vector of that bat:

, (6)

This equality is based on the dot product of two vectors which gives the angle between them. Rearranging gives equation 6 and a quick perception check from unities space partitioning. The magnitude of **A** (the vector from bat to insect) also needs to be less than 8 meters for it to return strong enough echoes to be perceivable.

The echolocation is not modelled through sound but rather based on the known perceivable field of view. Further studies could add a sound particle-based echolocation model, however that was computationally too expensive and not the intention of this paper.

A group of birds flying in the sky

Description automatically generated with low confidence

(Fig 10. Bat boid flocking implementation)

**Bat Hunting Model:**

Based on what we know of physical bats the simulated bats fly around to find their nearest detectable insect clusters and will split off into smaller subgroups to hunt. These subgroup sizes and the number of insects per cluster can be easily adjustable to reflect a real-world environment more accurately. The bats that don’t split off to hunt will flock towards the next nearest insect cluster.

Chart, scatter chart

Description automatically generated

(Fig 11. Bat boids splitting into subgroups for hunting based on their individual behavioral rules)

We know that echolocating bats have access to the size, relative position, and relative velocity of objects that they detect. As such these simulated bats can also gain access to these variables when they detect a potential prey through the echolocation model. The bats can update their velocity heading based on the current position and current velocity of a detected insect to chart an intercept course. This is represented by the following equation where **V** and **P** represent the velocities and positions respectively:

(7)

This allows the bats to better intercept prey because they know where it is and where its going at any given time step. Bats that get within 10 cm of a prey are considered close enough to catch it and a cooldown timeframe stops them from eating multiple prey in quick succession and simulates their need to consume their insect before hunting another. Most insects are unable to hear at the frequencies bats use for echolocation which gives bats a stealth advantage when hunting.

A picture containing light, traffic

Description automatically generated

(Fig 12. Bat hunting implementation. The black cubes represent the bats, and the red capsules represent insects)

The simulation keeps track of the last insect eaten time and bats who are unsuccessful in catching prey over a specified threshold will roost temporarily and try again later in the night. The bats have an energetics model that is updated at each time step and those who are very successful in catching prey will roost once they exceed a satiated energy threshold.

**Energetics Model:**

The bat energetic model was built from the work of (Guy et al. 2010) and is loosely based on human energetic principles. Bats have a maximum caloric level of 2200 calories and are considered satiated or full above 2000 calories.

The bats consume energy at a constant metabolic rate to stay alive with greater energy expenditure during flight and hunting based on their speed. Many species of bats are hibernators and can have low energy expenditure while roosting but their energy costs for flight are quite expensive. This is represented by the following equation showing the energy expended (E) over a given time frame:

(8)

Where represents the metabolic rate for static energy consumption and is a multiplier that scales energy expenditure based on or flight speed squared. and are constants set to 1.0 and 0.05 respectively and the bats replenish 200 calories whenever they capture and consume an insect. These values were determined heuristically through testing and have low basis in physicality. These values and this model are meant as a representation of bat energy consumption and are used in determining their behavior patterns.

**Behavioral Model:**

Diagram, venn diagram

Description automatically generated

(Fig 13. Finite state machine for bat behavior. Each state involves energy consumption based on static metabolic rate and flight speed. If the time-of-day switches into day or night the bats will behave accordingly. The transitions are labeled with a brief description of what happens to trigger a state change)

The behavior model is represented by a finite state machine with four different states that govern a bats behavior. Each state has its own subset of rules for bats to follow. While in each state bats will update their current energy levels based on the energetics model and will travel back to the home cave location if the time moves into day. When at the home roost bats will hibernate until night then transition to their hunting state.

The Hunting state employs the bats hunting and echolocation models as well as boid rules while in flight between insect clusters. These behaviours can be seen in figures 10, 11, and 12. Bats travel to detected insect clusters and split off into subgroups once they are close enough. Then they hunt using equations 6 and 7 until their behavior state changes. Bats who capture and consume insects will replenish their energy level by the specified amount (currently 200 calories) then continue hunting after their prey is consumed. This energy gain could be modelled with a steady energy gain over time, but the one-time burst is sufficient for the purposes of this paper.

Once a bat has exceeded its satiation threshold it will transition to the roosting state until its energy levels drop below that threshold or the sun rises on a new simulated day. Bats who are unsuccessful in catching prey for the last (time hunting since last capture) seconds will transition to the timed roosting state and find a nearby roost to conserve energy for (time for recouperation) seconds. When in the roosting state if a bats energy level drops below its satiation threshold it will return to hunting. When in the timed roosting state, a bat will wait for an adjustable length of time before returning to the hunting state.

This behavioral model can be further extended to include even more behavior patterns such as nursing mothers returning home to feed their young during the night.

**Results and Discussion**

**What worked well:**

The bat behavioral models as implemented capture many known aspects of bat behavior and perception. Many aspects of this simulation can be customized to model specific species of bats, such as colony size, maximum subgroup number for hunting, and maximum speed. The simulation can be scaled with proper consideration to best fit research goals. With very low effort bat energetics and proximity could be monitored over several days to calculate the spread of White-Nose-Syndrome through a colony.

This simulation runs in real time for fewer than 140 bats and with more optimizations could accommodate even larger colonies. Simulations with over 140 bats will run in real time once the groups split up into smaller subgroups because the boid rule checks then require fewer neighbors. The insects are spawned only spawned when bats are in close enough proximity (within 20 meters), but the groups could still be detected from further away. This saves computations and further improves run time speed. The bats can be further individualized with slight variations in maximum speed and more behavior patterns for nursing mothers and differently aged bats who require different lengths of roost time.

**What needs improvement:**

The energetics model is heuristic and needs more research and adjustment to better fit with reality. Many of the concepts work well for this simulation but further research and improvement is strongly recommended.

The insects currently react very little to bat boids and their behavior should be extended to include more accurate responses to their neighbors being captured. The bats have inconsistencies in their velocities and can change without C1 continuity. This should be adjusted to better represent realistic motion.

The bats move from one insect cluster to the next by accessing their locations directly from unity. Hunting bats could have intuition for the best hunting areas around their home roost to reflect this, but the model should be adjusted to allow bats to search for insect clusters with flight patterns or memory assumptions instead.

**Conclusion**

While there are many aspects that need further consideration for simulating bats, there is great potential in its uses and understanding the effects have on an ecosystem. Combating White-Nose-Syndrome and understanding effects on crop health are just a few of the benefits of bat simulations. With a bat model these simulation rules could be used in animations for Television, Movies or Video Games. Research into echolocation has already led to the development of Radar and further research could provide new technologies that could augment virtual reality or even help people with visual impairments in the physical world.

**Future Research**

Studies on White-Nose-Syndrome and how it spreads would be an important next step to see if there is anything we can do to help bats overcome this threat. This could be done by studying how close bats need to get before the fungus spreads and checking any infected bats coming within this distance to non infected bats. When roosting many bats will group very tightly and this behavior would need to be implemented accurately to help in a White-Nose-Syndrome study.

Incorporating aspects from other research about bats and their positive affects on crop yield could create a system that would help predict these effects. Studies from (Kolli 2007) have shown that introducing a small bat colony helps control insect pests in farming.

Combining research on bat species into a database could greatly improve simulation capabilities. This would allow for simulations to be specified for a given species and would decrease research time to find the appropriate parameters for simulating them.

Incorporating aerodynamics and sound particle energetics would greatly improve the accuracy of bat simulations but would likely trade off with run time efficiency. Optimization and realism of bat echolocation would be an important next step in this research. Adding a physically based bat model with kinematic chains and flight movement would also increase the realism of these simulations.

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