Braitenberg Vehicles : Modelling and Analyzing Competing Prey-Predator Behaviour

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***Abstract*— Braitenberg vehicles are autonomous agents with a simple control architecture. Biologically inspired Braitenberg vehicle models have been adopted in artificial life and robotics research to imitate animal behaviors. This paper presents a Braitenberg Vehicle-based model to simulate and analyze competing prey-predator behavior. The project focuses primarily on the impact of maximum speed and the field of view on prey-predator characteristics and survivability (ability to escape and hunt respectively) in a single agent, and emergent behavior in a multi-agent setup. The results of the experiments indicate prey-predator path-planning, hunting and escape strategies. The hope is for this study to pave the way for future work in the area of ethology, phylogeny, evolution, and other similar biological domains using Braitenberg Vehicles.**

Keywords*— *Prey, Predator, Braitenberg Vehicle

I. INTRODUCTION

Prey-predator interaction plays a vital role in understanding the evolution of organisms in their environment. Behavioural ecology, physiology, phylogeny, evolutionary biology, and robotics are among the various scientific fields that hold relevance in understanding the dynamics of these interactions. The major limitation in studying prey-predator interactions are their rare occurrence, and difficulty in observation of the animals in wild. Also, some intended studies may not be ethically possible. A solution is to simulate the characteristics in artificial agents, and observe and analyse the resultant behaviours. There have been many works in robotics and artificial life in this direction.

Braitenberg vehicles [1] with their simple control architectures have been used extensively to model animal behaviour and characteristics in artificial autonomous agents. These vehicles with different sensor-motor translations can be modelled to mimic various psychological animal behaviours like “aggression”, “fear”, “love” etc. towards or away from a stimulus source [1]. Insect models based on Braitenberg vehicles have been developed to investigate chemotaxis behaviour in fruit flies using chemical sensors [2], and phonotaxis behaviour in lizards employing microphones [3]. Braitenberg vehicles with ultrasonic sensors have been used to mimic and analyse obstacle avoidance behaviour in bats [4]. In underwater aquatic environments, rheotaxis behaviour has been implemented in fish robots with pressure sensors, to orient to the flow of incoming current [5]. Further, Braitenberg’s bottom-up approach [1] has been applied to understand neural basis of navigation behaviour in animals, using animal models based on Braitenberg vehicles [6].

In this paper, a Braitenberg-vehicle based prey-predator model is implemented. The experiments and results are relevant considering terrestrial vertebrate prey-predator systems which hunt and escape in a run and chase manner. The impact of increase in maximum speed , and the position of the eyes i.e. field of view, on the respective ability to escape and hunt in a single prey and predator system, and the emergent behavior of the prey-predator agents in a multi- agent environment are observed and analyzed.

II. BIOLOGICAL BACKGROUND AND MODEL FORMULATION

A. Prey-Predator behaviour and characteristics

All the animals are either a predator or a prey. Prey-predator interactions are crucial in the formation of ecological ecosystems. A behavioural response race controls prey-predator environments, wherein the predator develops adaptations that improve its hunting performance while the prey develops anti-predator strategies [7]. Based on the “arms race” analogy [8], considering the speed of a terrestrial prey-predator system, relative speed rather than absolute speed determines the result of any race [9]. This implies that if a predator increases speed to overcome prey defence, the prey should increase its speed to further improve its defence, and vice versa.

Similarly, predator and prey have different adaptations for position of their eyes. Predators often have their eyes placed in front of their head offering a frontal view. This allows predators to have a focused vision and depth perception of their target prey, increasing their chances of hunting. On the other hand, prey animals commonly have their eyes situated on either sides of their head offering a peripheral view. This offers a wider field of vision to the prey helping it efficiently spot an approaching predator and escape.

In a group environment, animals show emergent behaviour of cooperative hunting, and adopt different formations and strategies for hunting as seen in lions [10], wild dogs [11], chimpanzees [12], and wolves [13]. This collaborative approach increases the hunting success rate with increasing group size of predators [11], and decreases the distance travelled during chasing [11]. Similarly, prey animals display unpredictable trajectories as an anti-predatory behaviour [14]. A more protean prey's escape trajectory will lead to enhanced confusion and difficulty for the predators in targeting the prey [15].

B. Braitenberg Vehicles

In their most basic form, Braitenberg vehicles [1] consist of one or more sensor(s) such as light, distance, chemical, sound etc., with two separate motorized wheels abstracting the locomotion mechanism. They can be used to model animal behaviors with motion towards, or away from a particular stimulus, biologically referred as taxis behavior [16]. The nature and mechanism of the sensor motor couplings determine the behavior of the vehicle. A direct coupling is achieved by an ipsilateral connection wherein the sensors and motors on the same side are connected together, whereas a cross coupling is achieved by contralateral connection, where the sensors and motors on opposite sides of the vehicle are connected together [6]. The coupling can either be positive or negative. A positive coupling is excitatory, where strong stimulus perceived by the sensor translates to a strong connected motor excitation, whereas a negative coupling is inhibitory, wherein strong stimulus perceived by the sensor translates to a weak excitation of the connected motor. Considering a light source, Braitenberg vehicles exhibit positive and negative photo taxis towards the light source which can be interpreted as "aggression" and "fear" respectively [1].

A vehicle with two sensors and two wheels, with positive and cross sensorimotor coupling exhibits positive phototaxis. Considering the light source on the left of the vehicle as in Fig.1 (b), the left sensor will be excited to an extent greater than the right sensor causing the right wheel to rotate faster than the left due to the cross connection. This makes the vehicle turn left, towards the light source. As the vehicle approaches closer to the source, with a greater sensor stimulus, the wheels rotate faster and the vehicle accelerates towards the light source and ultimately collides with it. This can be interpreted as "Aggression" towards light source [1] as the vehicle moves and accelerates towards the source.

Similarly, a vehicle with two sensors and two wheels, with positive and direct sensorimotor coupling exhibits negative phototaxis. Considering the light source on the right of the vehicle as in Fig.1 (a), the right sensor will be excited to an extent greater than the left sensor causing the right wheel to rotate faster than the left due to the direct connection. This makes the vehicle turn left, in a direction away from the light source. As the vehicle moves further away from the source, with a weaker sensor stimulus, the wheels rotate slower and the vehicle decelerates and ultimately stops. This can be interpreted as "Fear" from the light source [1] as the vehicle moves away from the source.

The above described Braitenberg vehicles can be used as basis to formulate prey-predator behavior. The

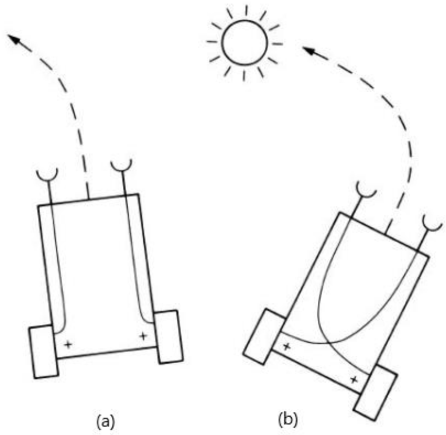


Fig. 1: (a) Fear and (b) Aggression behaviours in Braitenberg Vehicles [1]

aggression model can be used to imitate predatory behavior towards a light source, and the fear model can be used to mimic prey behavior away from the light source.

C. Modelling the prey-predator agents using Braitenberg Vehicles

The prey and predator agents are custom simulated robots with 2 light sensors and 2 motorized wheels. The prey agent is made to mimic the "fear" behavior by positive direct connection of light sensors to motors. The predator agent is made to mimic the "aggression" behavior by positive cross- connection of light sensors to motors. The prey agent is incorporated with a green color point light of intensity 2 Watt per meter square (W/m^2) and the predator agent is incorporated with a red color point light of intensity 2 Watt per meter square (W/m^2). The light sensors of the prey agent are made sensitive to only red colored light, whereas the light sensors of the predator agent are made sensitive to only green colored light. Thus, the prey agent will show "fear" from the predator agent with mounted red point light, and the predator agent will show "aggression" towards the prey with mounted green point light.

The frontal sensor position is achieved by placing the left and right sensors 0.04 meters apart in front of the agent with an angle of rotation of 1.27 and 1.87 radians respectively from the x axis (red arrow) of the robot as shown in Fig. 2 (a). The peripheral sensor position is achieved by placing the left and right sensors 0.1 meters

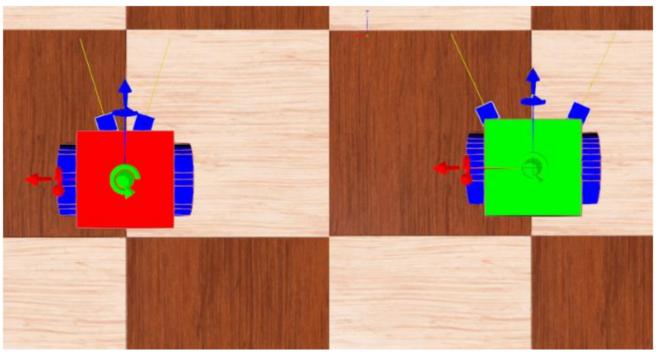


Fig.2 (a) frontal vision in predator and (b) peripheral vision in prey agent apart in front of the agent with an angle of rotation of 1.14 and 2 radians respectively from the x axis (red arrow) of the robot as shown in Fig. 2 (b).

Predator's "aggression" behavior is modelled by making a positive cross translation of light sensor readings (L_{left} and L_{right}) to the wheel speed (S_{left} and S_{right}). Additionally, a coefficient of aggression K_a is introduced to imitate the acceleration of the predator upon spotting a prey. K_a is an increasing function which has a constant initial value until a threshold of the light sensor reading is reached, and starts increasing linearly once the light sensor reading exceeds the threshold. The wheel speeds are capped at a maximum speed (S_{max}). By this method, the equation for right and left wheel speeds S_{right} and S_{left} for the predator Braitenberg vehicle can be formulated as in (1) and (2).

$$S_{right} = \begin{cases} L_{left} * K_a & , \text{if } L_{left} * K_a < S_{max} \\ S_{max} & , \text{if } L_{left} * K_a > S_{max} \end{cases} \quad (1)$$

$$S_{left} = \begin{cases} L_{right} * K_a & , \text{if } L_{right} * K_a < S_{max} \\ S_{max} & , \text{if } L_{right} * K_a > S_{max} \end{cases} \quad (2)$$

Similarly, prey's "fear" behavior is modelled by making a positive direct translation of light sensor readings (L_{left} and L_{right}) to the wheel speed (S_{left} and S_{right}). A coefficient of fear K_f is introduced to mimic the acceleration of the prey upon spotting a predator. K_f is an increasing function which has a constant value until a threshold of the light sensor reading is reached, and starts increasing linearly once the light sensor reading exceeds the threshold. The wheel speeds are capped at a maximum speed (S_{max}). By this method, the equation for right and left wheel speeds S_{right} and S_{left} for the prey Braitenberg vehicle can be formulated as in (3) and (4).

$$S_{right} = \begin{cases} L_{right} * K_f & , \text{if } L_{right} * K_f < S_{max} \\ S_{max} & , \text{if } L_{right} * K_f > S_{max} \end{cases} \quad (3)$$

$$S_{left} = \begin{cases} L_{left} * K_f & , \text{if } L_{left} * K_f < S_{max} \\ S_{max} & , \text{if } L_{leftt} * K_f > S_{max} \end{cases} \quad (4)$$

D. *Hypothesis*

Based on the above discussed prey-predator behavior characteristics and the formulated model and equations, the following hypothesis are proposed and tested for the model in a single and multiple prey-predator agent setups.

H1: A peripheral view in the prey will make the agent reach farther distance from the predator after a specific experiment time step.
H2: A frontal view in the predator will make the agent take less time and travel less distance in reaching the prey.
H3: An increase in the predator's maximum speed will make the agent take less time and travel less distance to reach the prey.
H4: An increase in the prey's maximum speed will make the agent reach farther distance from the predator after a specific experiment time step.
H5: In a multiple prey-predator agent environment, the predator agents tend to target and attack a single prey which is closest.
H6: In a multiple prey-predator agent environment, the prey agents tend to run away from each other (and from the predator) in different directions.

III. Experiments

Experiments are performed in a single and multiple prey-predator agent environment setup to test the proposed hypothesis for the prey-predator models.

A. *Simulation environment setup*

The simulations of the experiments have been done using Webots R2021a [17] software. Webots is a free open-source and multi-platform robot simulator that provides a virtual and realistic environment for quick prototyping, programming, and simulation of mobile robots. The application allows programming in multiple languages like C, C++, Java, Python etc. [17]. As shown in Fig. 3, to allow ample movement space for the simulated agents, a square arena of 20 meter (m) width and 20 meter (m) length is used. The reference coordinate system is also shown in the figure. The arena has a background ambient light of intensity 0.4 Watt per meter square (W/m^2). In the Webots simulation environment, individual custom controller code (over the templates available in Webots documentation [17]) running a script written in Python programming language controls the prey and predator agents (refer Appendix A).

B. *Experiment methodology*

1 *Single prey-predator agent experiments:*

Experiments were carried out to observe the behavior of the prey-predator agents for different values of maximum speed and different positions of light sensors. The initial values of coefficient of aggression K_a and coefficient of fear K_f were kept 1 meter cube per joule (m^3/J). As these are increasing functions after a threshold value of the light sensor reading (to mimic the acceleration upon spotting a prey/predator), the K_a and K_f values were incremented by 0.1 meter cube per joule

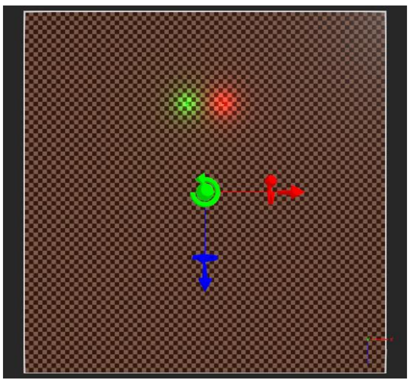


Fig. 3 Simulation Environment

(m^3/J) for every simulation time step after the threshold light sensor value of 0.4 Watt per meter square (W/m^2) is exceeded. The threshold of 0.4 Watt per meter square (W/m^2) was selected as the light sensors showed a default reading of 0.34 Watt per meter square (W/m^2) in the absence of any other nearby prey or predator agent. Thus, a light sensor reading of a value higher than 0.4 Watt per meter square (W/m^2) will indicate an approaching predator or nearby prey.

For all single prey-predator agent experiments, the agents were placed at a Euclidean distance of 5 meters (m) from the center of the arena, and Euclidean distance of 2 meters (m) apart from each other, with their forward z axis facing the center of the arena. The position was chosen to give both the agents a fair chance to hunt and to escape, avoiding complete visibility and also any potential blind spots.

For ease of experimentation and analysis, a decreasing counter "stamina" of 500 units was introduced for each agent, which will decrease by 1 unit for each simulation time step, after the light sensor threshold of 0.4 Watt per meter square (W/m^2) is reached. From the predator agents point of view, once the light sensor reading reaches the threshold 0.4 Watt per meter square (W/m^2), indicating a nearby prey, the K_a value begins to increase by 0.1 meter cube per joule (m^3/J) every simulation time step mimicking acceleration, and the "stamina" starts decreasing by 1 unit every simulation time step mimicking exhaustion, and once the stamina reaches 0, the agent stops.

a) Experiment A: Fixed maximum speed and sensor position of the predator, with variation in the sensor position of the prey with fixed maximum speed.

In this experiment, the sensor position of the prey agent is varied to imitate and analyze the behavior of prey with frontal and peripheral vision. The maximum speed and sensor position of the predator agent is kept constant at 10 meter per second (m/s) with a frontal view. Experiments are performed with prey agent with different sensor position (frontal and peripheral) for fixed maximum speed of 12 meter per second (m/s) (higher than predator's maximum speed to allow the prey to escape). Euclidean distance between the prey and predator agents after the stamina of both the agents approaches 0 units (the agents stop), and the trajectory of the agents are measured.

b) Experiment B: Fixed maximum speed and sensor position of the prey, with variation in the sensor position of the predator with fixed maximum speed.

Sensor position of the predator agent is varied to mimic and analyse the behaviour of predator with frontal and peripheral vision. The maximum speed and sensor position of the prey agent is kept constant at 10 meter per second (m/s) with a peripheral view. Experiments with predator agent with different sensor position (frontal and peripheral), and with fixed maximum speed, 12 metre per second (m/s) (higher than prey's maximum speed to allow the predator to hunt) are carried out. Time taken and distance travelled by the predator to reach the prey (initial contact is made), and the path taken by the agents are measured and analysed.

c) Experiment C: Fixed maximum speed and sensor position of the prey, with variation in the maximum speed of the predator with fixed sensor position.

In this experiment, to understand how maximum speed impacts the ability of the predator to hunt, for a prey with fixed maximum speed 10 metre per second (m/s) and peripheral vision, experiments of predator agent with frontal vision, and with different maximum speed (12 , 14 , 16, 18 , 20 metre per second (m/s)) are carried out. The time taken and distance travelled by the predator to reach the prey (initial contact) is noted for each experiment and the results analysed. The experiments are repeated for different values of K_a (1 (default) and 2 meter cube per joule (m^3/J)) to see how increasing the aggression of the predator impacts its ability to hunt.

c) Experiment D: Fixed maximum speed and sensor position of the predator, with variation in the maximum speed of the prey with fixed sensor position

To understand how maximum speed impacts the ability of the prey to escape, for a predator with fixed maximum speed 10 meter per second (m/s) and frontal vision, experiments of prey agent with peripheral vision, and with different maximum speed (12, 14, 16, 18, 20 metre per second (m/s)) are carried out. The Euclidean distance between the prey and predator agents after the stamina of both the agents approaches 0 units (the agents stop) is measured and analysed. The experiments are repeated for different values of K_f (1 (default) and 2 meter cube per joule (m^3/J)) to see how increasing the fear of the prey impacts its ability to escape.

2 Multiple prey-predator agent experiments:

Experiments were carried out to observe the behavior of the prey-predator agents with variation in group size of the prey and predator agents. The closest prey-predator agents (base agents) are placed at a Euclidean distance of 5 metre (m) from the centre of the arena, and 1.5 metre (m) from each other, with their forward axis (z axis) perpendicular to each other. The subsequent predator and prey agents are placed at a Euclidean distance of 0.5 metre (m) maintained along the positive x and negative x axis of the adjacent predator and prey agent respectively, with their forward axis parallel to the base agent.

a) Experiment E: Fixed maximum speed and sensor position of the prey and predator, with variation in the number of prey and predator agents

Prey and predator agents with frontal and peripheral view respectively, and with fixed maximum speed of 10 metre per second (m/s), constant K_a and K_f of 1 meter cube per joule (m^3/J) for predator and prey are used. As already discussed, the K_a and K_f are increasing function with 0.1 meter cube per joule (m^3/J) increase for every simulation time step after the light sensor reading threshold of 0.4 Watt per meter square (W/m^2) is reached. Experiments are carried out for different group size of prey and predator (N_{prey}, $N_{predator}$) = (2, 2), (3, 3) and (4, 4). The least time taken by the predator to reach the prey (if multiple predators hunt), and the trajectories of all the agents are measured and analysed.

IV. RESULTS AND DISCUSSION

Experimental results and analysis, and their relevance to the prey-predator behaviour are discussed below.

A. *Experimental results and their relevance to biological prey-predator behaviour*

Table 1 shows the Euclidean distance between the prey and predator agents after their respective stamina reaches 0 units i.e. the agents reach exhaustion, from the observation of experiment A. We see the prey with a fixed maximum speed (12 m/s) is able to reach a farther distance when having a peripheral view of its environment, than with a frontal view. Also from Fig.4 (a) and (b) which shows the path taken by the prey-predator agents in experiment A, we see that a prey with a peripheral view is able to detect the approaching predator quickly and make a sharp turn in a direction away from the predator and flee successfully as shown in Fig.4 (b), whereas the prey with a frontal view rather makes a slow narrow turn away from the predator in order to flee as shown in Fig.4 (a). These observations effectively prove hypothesis H1 which can be claimed as true. It can be inferred that in physical world, prey with a peripheral view have a wider field of vision with fewer blind spots, allowing them to detect an approaching predator quickly, and make an effective escape plan.

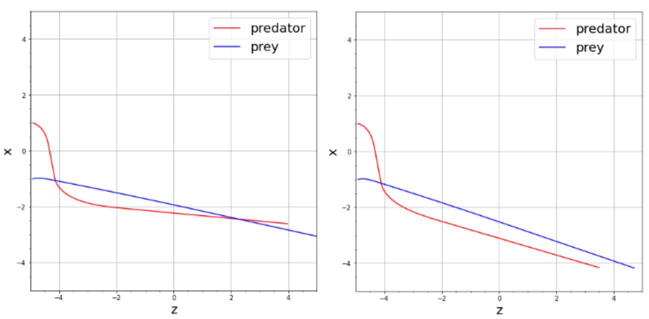
Table II shows the time taken and distance travelled by the predator to reach the prey (make initial contact), from the observations of experiment B. It can be observed that contrary to the hypothesis H2, the predator with a frontal vision takes more time to reach the prey when compared to a predator with a peripheral vision. Also by observing the path taken by the predator in experiment B, we see that the predator with a peripheral view is able to detect the prey quickly making a sharp turn towards it as shown in Fig.5 (b), when compared to the predator with a frontal view which makes a wider turn towards the prey as in Fig.5 (a). Therefore, the experimental results do not prove the hypothesis H2. Experimentally, this behavior of the agent can be explained as the light sensor readings depend on the position and orientation of the sensors with respect to the light source (see Webots light sensor documentation [17]), thus with the peripheral sensor positions, as the prey was to the side of the predator, the light sensors were able to detect the light source with a high light sensor reading, which is proportionally translated to wheel speed (as in equation (1) and (2)), thus giving a higher acceleration enabling the predator agent reach the prey quickly, whereas with a frontal sensor positions, the light sensor readings are comparatively low, translating to a lower wheel acceleration. Biologically, a frontal view allows depth perception and binocular vision in predators. Using simple light sensors might not effectively mimic this characteristic and will require complex perception mechanisms in artificial agents.

TABLE I. OBSERVATIONS FROM EXPERIMENT A

Predator max speed= 10 m/s , Predator sensor position = Frontal, Prey max speed = 12 m/s	
Prey sensor position	***Euclidean distance between prey-predator after stamina (m)***
Frontal	1.135
Peripheral	1.225

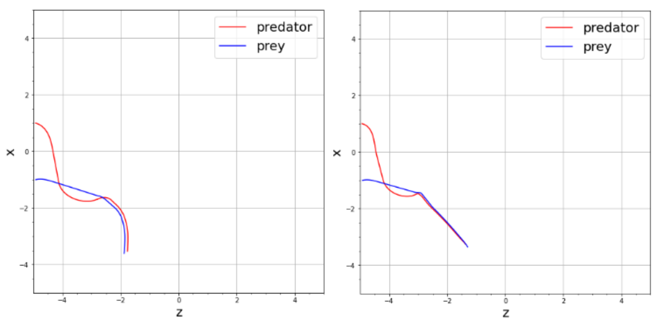
TABLE II. OBSERVATIONS FROM EXPERIMENT B

Prey max speed= 10 m/s , Prey sensor position = Peripheral, Predator max speed = 12 m/s		
Predator sensor position	***Time taken by predator to reach the prey (s)***	***Distance travelled by predator to reach the prey (m)***
Frontal	13.952	3.959
Peripheral	12.864	3.483



Prey with (a) frontal sensor position (b) peripheral sensor position

Fig. 4 Path taken by prey-predator agents for a fixed predator speed (10 m/s) and sensor position (frontal), with different sensor position for prey of maximum speed 12 m/s, from observations of experiment A. (plotted on a 10 m x 10 m grid (centre of 20 m x 20 m square arena) for better visibility)



Predator with (a) frontal sensor position (b) peripheral sensor position

Fig. 5 Path taken by prey-predator agents for a fixed prey speed (10 m/s) and sensor position (peripheral), with different sensor position for predator of maximum speed 12 m/s, from observations of experiment B. (plotted on a 10 m x 10 m grid (centre of 20 m x 20 m square arena) for better visibility)

Fig. 6 and Fig. 7 show the plot of time taken and distance travelled respectively, by the predator with a frontal view to reach the prey vs. maximum speed of the predator, for different coefficient of aggression K_a, as per the observations of experiment C. It can be observed that with increasing maximum speed of the predator, the time taken by the predator to reach the prey decreases, consequently causing a decrease in the distance travelled by the predator to reach the prey. Thus a higher maximum speed allows the predator to reach the prey quickly increasing its chances to hunt. This confirms the proposed hypothesis H3. The increase in maximum speed can be interpreted as different stages of a predator's growth lifecycle from child to adult. The maximum speed can also be different for different predator species, gender etc.

Further, for a higher aggression coefficient K_a = 2 meter cube per joule (m^3/J), it can be observed that the time taken and distance travelled by the predator to reach the prey reduces further with increasing maximum speed when compared to K_a = 1 meter cube per joule (m^3/J). A higher aggression can be interpreted as the desperation of the predator to hunt the prey. Varying aggression can be even attributed to potential injuries and diseases in a predator which may weaken it [18].

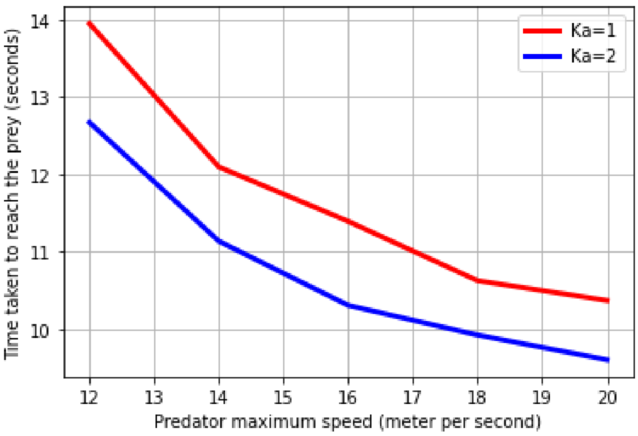


Fig. 6 Plot for time taken by predator to reach the prey vs. maximum speed of the predator for different K_a values, from observations of experiment C

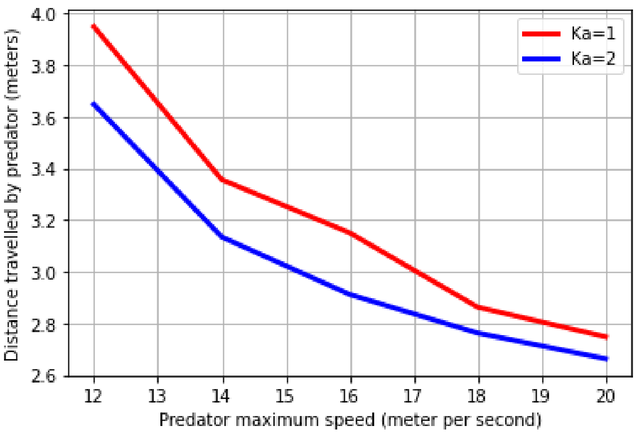


Fig. 7 Plot for distance travelled by predator to reach the prey vs. maximum speed of the predator for different K_a values, from observations of experiment C

Fig. 8 shows the plot of Euclidean distance between the prey and predator agents after the agents approach their respective stamina of 0 units vs. the maximum speed of the prey, for different coefficient of fear K_f, from the observation of experiment D. We can see that the distance between the prey and predator increases linearly with an increase in the maximum speed of the prey until a threshold, beyond which the stamina reaches 0 i.e. the agent gets exhausted before it can achieve maximum speed. Thus with increasing maximum speed, the prey is able to reach a farther distance from the predator before the agent gets exhausted, increasing the chances of the prey to escape successfully. Hypothesis H4 can be considered true based on these observations. The different maximum speed of the prey can be attributed to different stages of development (from infant to an adult), gender, or species of prey animals.

From the experiments with an increased fear coefficient of K_f = 2 meter cube per joule (m^3/J), it is seen that the distance between the prey and predator after exhaustion further increases when compared to K_f = 1 meter cube per joule (m^3/J). A higher coefficient of fear can indicate a higher sensitivity or alertness of the prey animal. An alert agent will react to slightest level of threat and try to flee quickly reaching farther distance from the approaching predator. Varying fear can be even attributed to potential injuries and diseases in a prey which may weaken it [18].

Fig. 9 shows the path taken by prey-predator agents for different group sizes of prey and predators, as per the observations of experiment E. For a 2 prey - 2 predator system as shown in Fig. 9 (a), it can be observed that the predators isolate and target a single prey, while one predator agent actively attacking the prey and the other parallelly following it. Fig. 9 (b) shows a 3 prey - 3 predator system where the predator initially isolate and target a single prey making contact, but further while one predator agent pursues the isolated prey, the other predator agent goes on to chase another prey moving away. In a 4 predator - 4 prey system as shown in Fig. 9 (c), while all the predators initially attack the nearest

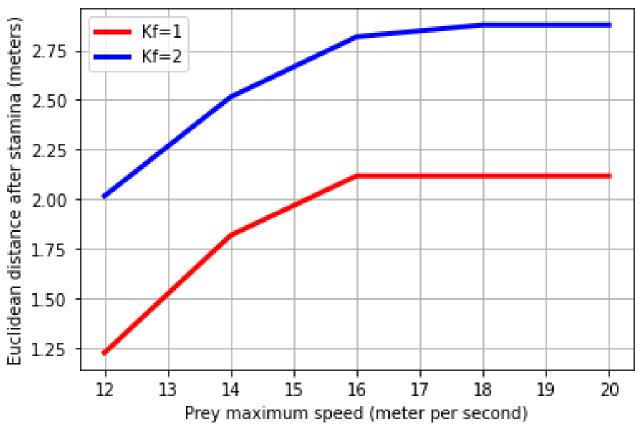
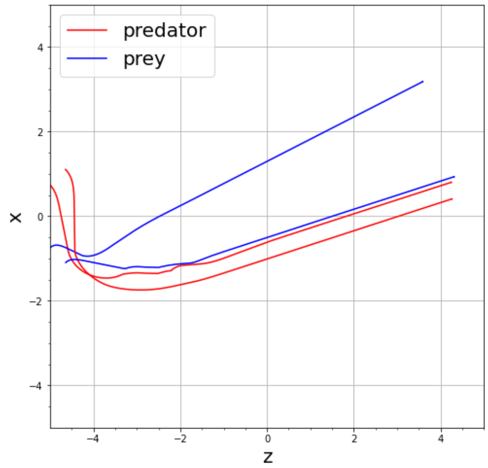
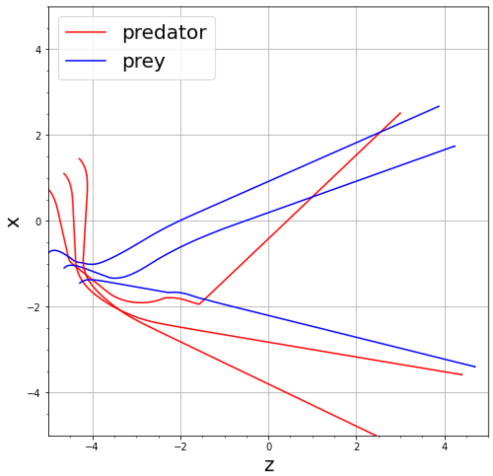


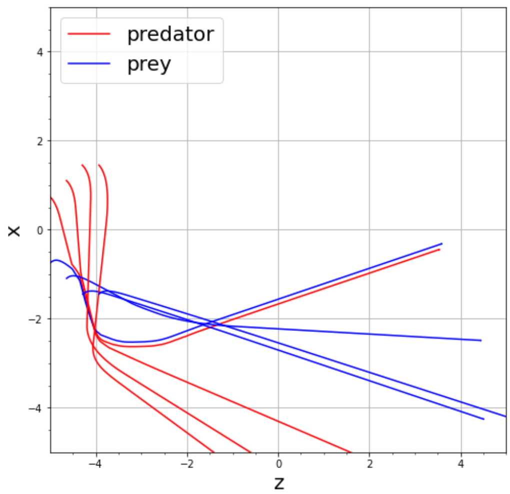
Fig.8 Plot for Euclidean distance between prey-predator after the agents approach stamina of 0 vs. maximum speed of the prey for different K_f values, from the observations of experiment D



(a) group size of 2 prey – 2 predator



(b) group size of 3 prey – 3 predator



(c) group size of 4 prey – 4 predator

Fig. 9 Path taken by the prey-predator agents for different group size of prey and predators, from observations of experiment E. (plotted on a 10 m x 10 m grid (centre of 20 m x 20 m square arena) for better visibility)

prey, only one agent goes on to pursue it, while the others diverge in directions parallel to the other fleeing prey agents.

In all the discussed group-sizes, the common pattern observed is the predators primarily identify, isolate and attack a single prey agent. There is not enough experimental evidence to conclude that the predators target the closest prey. The criterion for selection of the target prey could be dependent on various factors like size, age, potential injuries or weakness etc. Thus, hypothesis H5 can only be considered partially correct. Also, from the path taken by the prey agents, it can be seen that the prey agents move in different directions away from each other (and from the predator) while escaping. This can be interpreted as an anti-predatory strategy which increases their chances of survival, as it confuses the predator making it difficult to target the prey. Therefore hypothesis H6 can be considered true.

Further, from the observed behavior of predator agents in the experiment, it can be said that when hunting in a group, predators follow role based hunting strategies, where a single leader predator initiates the attack on the identified isolated prey, whereas the other predators play supporting role by running in parallel, to hunt in case the prey tries to escape in other directions.

Table III shows the least time taken by the predator to reach the prey for different group sizes of prey-predator agents, as per the observations of experiment E. It is seen that the time taken by the predator to reach the prey decreases as the prey-predator group sizes increase. A higher density of prey agents makes it easier for the predator to find and reach a prey, increasing the probability of predator hunting. Also with increasing predator group size, collaborative hunting helps increase predator hunting success, and reduces the time taken to hunt, consequently reducing distance travelled in chasing [11].

TABLE III. OBSERVATIONS FROM EXPERIMENT E

Prey max speed= 10 m/s , Prey sensor position = Peripheral, Predator max speed = 10 m/s, Predator sensor position = Frontal	
Group sizes of prey – predator agents	***Least time taken by predator to reach the prey (s)***
2 prey – 2 predator	10.688
3 prey – 3 predator	6.08
4 prey – 4 predator	5.952

The calculation methodology for Euclidean distance, time taken, path taken, and distance travelled by the agents for the experiments discussed above are explained in Appendix B, C, and D. Also, the time and distance data from the experiments are available in Appendix E.

V. CRITICAL EVALUATION AND FUTURE WORK

This study, mostly due to lack of similar research in the area of Braitenberg Vehicles, has had a more explorative approach. The observation from the experiment E can provide useful information in the field of behavioral ecology regarding prey-predator behavior in a multi-agent environment with respect to their predator avoidance and prey hunting strategies. The observations from experiment A, B C and D can be looked upon together to make comparisons between different prey and predator species based on their speed and field of view. These can also be useful to study indirect interaction between predator species that share a common prey, or prey species that share a common predator [19] [20]. Further, observations from experiments C and D can provide insights regarding selective pressure and adaptive behavior in prey-predator systems which can be useful in the area of phylogeny. The models of prey-predator Braitenberg vehicles formulated can be used to simulate and analyze similar concepts in evolutionary biology.

This project is limited to the study of competing prey-predator behavior to the scope of speed and field of view. Considering other adaptations in prey predator systems like size, stealth etc. can improve the biological relevance of the project. Moreover, the formulated model did not mimic effectively the depth perception and binocular vision in predators with frontal vision. An improved perception mechanism can be implemented to effectively formulate and test the frontal view hypothesis. Also, introducing other types of sensory perceptions (olfactory, auditory etc.) will provide better imitation of a real world prey-predator animal in their respective umwelt, which can lead to interesting observations and results, improving the relevance of the model.

Further, the formulated prey-predator artificial agent models can be extended with metaheuristic optimization algorithms like Genetic Algorithm (GA) or Prey-Predator Algorithm (PPA) [21] to simulate and study prey-predator coevolution.

VI. CONCLUSION

Biologically inspired Braitenberg vehicle based models can be formulated to understand the prey hunting and predator avoidance behavior in prey-predator system. The models described in the paper mimic the hunting and escape behaviors of predator and prey with different maximum speed and field of view. In single prey-predator environment, the observation from the experiments show the survivability of different prey-predator species depending on their speed and vision capabilities. In multiple prey-predator environments, the experimental observations showed interesting emergent behavior of various escape and hunting strategies in prey and predators exhibiting how predators target and isolate a prey and how preys tend to run in different directions to confuse the predator. Further, the formulated models can be extended to simulate prey-predator coevolution in artificial agents using optimization algorithms.

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