École Polytechnique Fédérale de Lausanne

BIOENG-456 - Controlling Behavior in Animals and Robots

COURTSHIP CHASING WHILE KEEPING A SPECIFIC DISTANCE USING VISUAL PROCESSING

Group 1

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Contents

1 Abstract

NeuroMechFly is a neuromechanical model that allows to simulate precisely Drosophila Melanogaster behavior. However, the model is still limited in the number of different behaviors it can reproduce. In this project, we aim to implement the courtship behavior between two flies. This includes the chasing of the female by the male, followed by the side walk and the wing extension that characterize the fly's courtship behavior and precede the mating. The chasing part was implemented by using the visual detection of the male to allow it to estimate the distance to the female, and catch her up. Then the crab walk was simulated by making the male turn around the female, and finally the wing extension was added when the male faces the side of the female. While the chasing part and wing extension seem to reproduce a natural behavior, a next step of the project would be to make the crab walk more realistic by creating a brand new sideway gait pattern.

2 Introduction

2.1 NeuroMechFly

NeuroMechFly in an open-source neuromechanical model of the adult Drosophila [1]. It enables the simulation of highly realistic models of the fruit fly, incorporating detailed morphological features for an accurate representation of the fly's exoskeleton, body segments and joint movements. The model analyses three-dimensional leg kinematics to identify degrees of freedom and study the coordination of leg movements during different types of behavior. Furthermore, it facilitates the computation of ground reaction forces, joint torques and tactile contacts during simulations, allowing to understand the forces and torques acting on the fly's body during different behaviors. Neuromechfly includes a central pattern generator-inspired coupled-oscillator network and muscle models, controlling specific behaviors such as fast and stable walking. It takes into account the neural dynamics, musculoskeletal biomechanics and environmental interactions to allow the understanding of how behaviors emerge from the interplay of these factors, thus providing insights into the complex interactions between them [1].

NeuroMechFly 2.0 represents a significant advancement in the study of motor control in Drosophila compared to previous models [2]. Among other things, it allows for the exploration of full hierarchical sensory-motor loops, thus enabling to understand how the fly's brain processes the environmental signals to regulate motor control. More specifically, NeuroMechFly 2.0 includes the simulation of sensing by the retinas, antennae and maxillary palps for vision and olfaction. This new version of the model enables full end-to-end modeling of multi-level sensorimotor control, including brain-level processing of sensory signals, leading to the emergence of more complex behaviors. These advancements thus provide insights into the complex interplay between sensory inputs, decision-making processes and motor outputs behind various types of behavior [2].

However, there are still some challenges and missing aspects in the current model. These include adding more information about specific body parts such as the wings or the abdomen, further refining and expanding the model to capture additional complexities in the neural and biomechanical control of behavior and adding more biological constraints and data from real experiments to enhance the accuracy and biological relevance of the simulations. In additions, specific behaviors such as egg-laying or courtship have not been implemented yet.

2.2 Courtship Behavior in Flies

Courtship is a natural behavior in every animal species, including flies. In drosophila, courtship behavior includes different phases: chasing, orientating toward the female fly, tapping, vibrating wings, singing and other elements [3]. Courtship is triggered by an internal arousal state, which shapes sensory processing and behavior.

In Drosophila, courtship behavior is triggered by the activation of P1 neurons and modulated by LC10a visual processing neurons [4]. More precisely, sexually dimorphic P1 neurons play a crucial role in triggering the courtship ritual in male Drosophila flies, as they regulate their internal arousal state and sensory processing. Indeed, these neurons are tuned to the pheromones of con-specific female mates and are activated upon mate recognition. This activation leads to a significant switch in male behavior, driving persistent courtship displays, which indicates that these neurons gate an enduring state of sexual arousal. Furthermore, P1 neuron activity highly correlates with the evolution of a male's pursuit during courtship on one hand, and with the activity of LC10a neurons on the other hand. This is due to the fact that P1 neuron activation adds gain to LC10a visual projection neurons, enhancing their sensitivity to moving targets. This dynamic modulation of visual signals in turn impacts the motor outputs of the fly and results in a vigorous tracking behavior [4]. During the chasing phase, the male maintains a constant distance with the female, most likely as a result of the continuous tuning of visual signalling through the visuo-motor circuit, mediated by P1 neuron activity. Indeed, this allows the male to keep the target at a close range within the center of his visual field during courtship pursuit. The dynamic modulation of visual signals ensures that the constant distance is maintained. By keeping the distance constant, the male also likely guarantees that he receives a consistent and optimal sensory input from the female, facilitates the communication and assessment of receptivity and reduces the likelihood of the female escaping of evading the courtship attempts, overall enhancing the courtship efficiency.

Next, after chasing the female, the male switches its gait to a "crab-walk" and orientates itself towards the side of the female, while extending its wings. The extended wings serve as cue to signal the male's courtship intentions to the female. Some studies have described how male Drosophila behave, often extending one wing to nearly 90 degrees from the long axis [5]. This extended wing position is important for the vibration and sound production that are integral parts of the courtship behavior in these insects. Indeed, the acoustic signals are part of the courtship song that, along with other behaviors, contribute to the communication between both flies during courtship [5]. Moreover, wing extension could also be a visual display that enhances the male's visibility and attractiveness to the female.

2.3 Implementing Courtship Behavior in NeuroMechFly

In Neuromechfly, courtship has not been implemented yet. However, the most recent version of the model provides considerable features such as sensory processing and hierarchical sensory-motor loops, that might allow for the simulation of such a complex behavior. This project aims to investigate whether it is possible to use visual processing to implement courtship chasing in males, more specifically using the distance to female flies to allow for the control of acceleration and deceleration and keeping a constant distance between both flies. Furthermore, this project tests the feasibility of implementing the "crab-walking", a specific type of gait that has not been studied yet, as well as the wing extension in male flies. Overall, this study aims to assess if it is possible to accurately replicate the first phase of the courtship behavior in flies using NeuroMechFly.

3 Methods

3.1 Courtship scenario

The goal was to design a multi-fly simulation with one female fly, called Target Fly, and one male fly, the Chasing Fly. The objective is to perform the three first steps of courtship behavior during the simulation: the chasing, the crab walking and the wing extension. At the beginning of the simulation, both flies are placed in the environment, with the Target Fly being postioned in front of the Chasing Fly. The distance between both flies is supposed to be initially too large to enable immediate chasing, allowing to observe the change in behavior. Immediately after, the female fly starts walking. The trajectory of the female fly was set to be a sinusoid in both x and y axis, leading to a zigzag motif. A speed adaptation component was added to vary the speed of the Target Fly randomly. By default, the male begins to move around randomly on the terrain, as the female is not yet detected. If by chance the male encounters the female at sufficiently small distance, it switches to an arousal state and starts chasing the female. At some point, the female fly stops walking to allow the male fly to undertake the next steps of its courtship sequence. When this stop in female walking is detected by the male, it switches its behavior to crab walking and wing extension. The state changes of the male fly are described more precisely in 3.2.1. In addition, other shorter scenarios were created allowing to study in more details each part of the implementation: the chasing, the crab walking and the wing extension.

To implement the courtship scenario and enable the observation of chasing, two new fly classes, Changing State Fly or Chasing Fly (section 3.2) and Target Fly (section 3.3) were implemented.

3.2 Changing State Fly (male)

3.2.1 Implementation of internal state

In order to implement the different sub-behaviors in the Chasing Fly, a new class of fly called ChangingStateFly was designed. This class inherits from the Fly class. It is a combination of the HybridTurningFly and the VisualTaxisFly classes provided, integrating in addition different new attributes that allow the change in behavior. The main addition was the implementation of internal states, set as class attributes, that define which action to take and that are updated at each step:

1. **Arousal State** : With arousal state of 0, the fly behaves like the normal HybridTurningFly, randomly walking around. When switched to arousal state of 1, it starts chasing and courting the other fly as described in the next sections. By default, the fly is initiated with an arousal state of 0. The switch of arousal state occurs when the fly randomly comes close the Target Fly. If the distance between the two flies, computed with the visual processing is close enough, then the internal state switches to 1 and the male fly starts the chasing behavior. The proximity threshold for switching to the chasing behavior is set to 2 times

the desired distance, that is one half of desired proximity.

From a biological point of view, the state of the male fly switching to "arousal" and leading to an active chasing behavior when it is close to a female, corresponds to the activation of sexually dimorphic P1 neurons, adding gain to LC10a visual projection neurons and driving chasing of a target.

2. **Crab-Walking State:** The crab-walking state controls the gait pattern of the fly. Initially set to 0, it allows either random walking if arousal state is 0 or chasing if arousal state is 1. When the Chasing Fly stops for a defined time, it transitions to the crab-walking behavior by switching the crab walking state to 1. This means that if the female fly remains stationary for a sufficient duration, the Crab-Walking state is activated. This enables the fly to change its gait and start turning around the female, thus orienting itself to the side of its mate. The crab state attributes takes more values than just 0 and 1, which will be described in 3.2.5.

3. **Wing-Extension State:** This attribute controls the state of wings extension. Initially set to 0, corresponding to rest position for both wings, it is switched to 1 after the male fly is oriented to the side of the female to allow unilateral wing extension, as described in section 3.2.6.

The value of each state is updated in the update_state() function at each timestep, by taking into account the visually determined distance between both flies and the criteria defined to switch behavior. This function updates the 3 new attributes, as well as the different counters used to define the behavior switch. A summary of the evolution of the different states is shown in Figure 1.

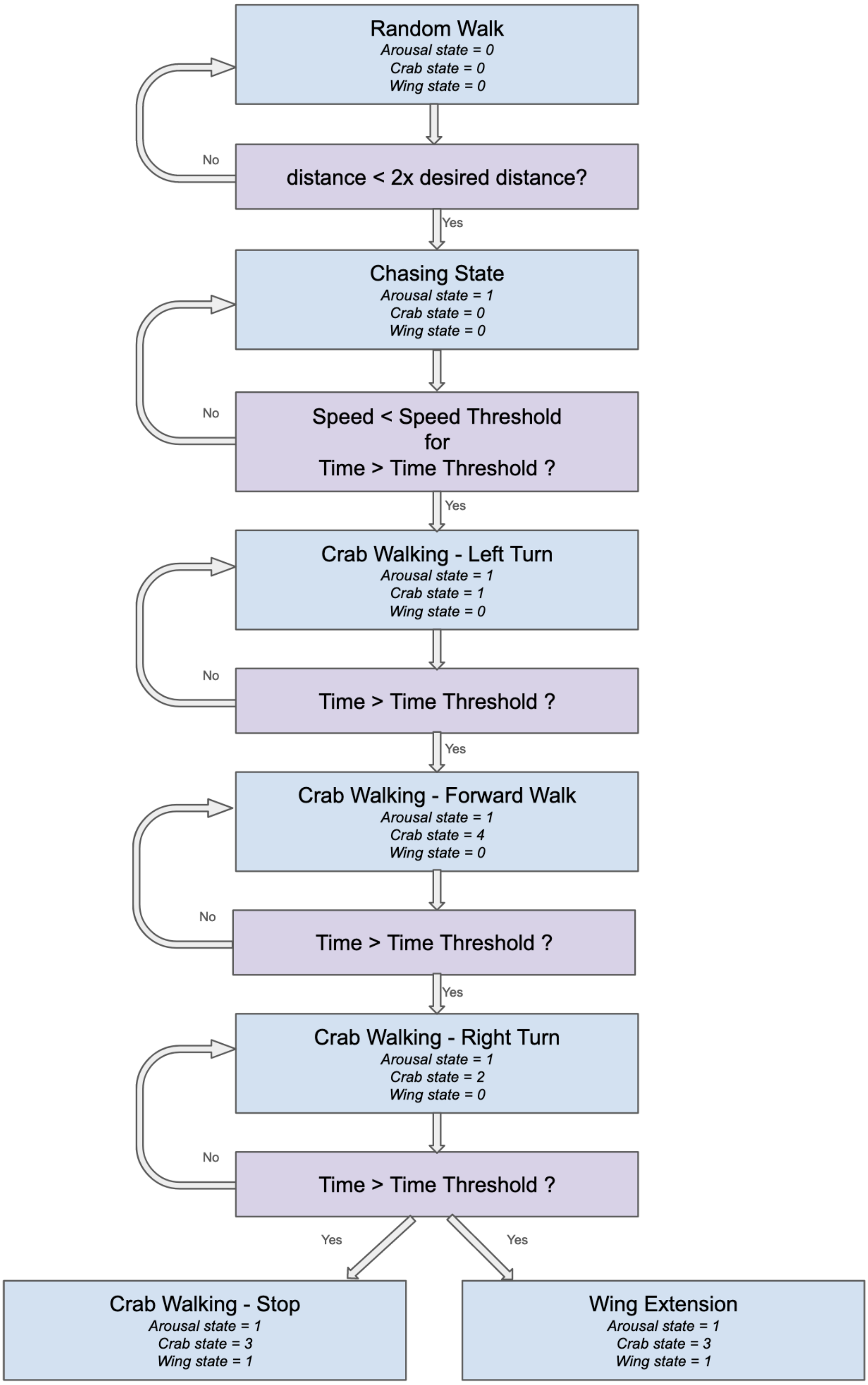


Figure 1: Diagram of the evolution of the three states for the Chasing Fly The blue boxes show the state of the Chasing Fly. The purple boxes show the conditions that are necessary to go to the next step.

3.2.2 Visual processing and distance evaluation

The ChangingStateFly() class was integrated with visual processing features as implemented in the VisualTaxisFly() to be able to chase the female fly. To allow the male fly to maintain a specific distance to the female fly, as well as to define the switch in behavior, it was necessary to also integrate a notion of distance to the target fly in the visual processing.

First, as defined in the VisualTaxisFly(), visual features extract coefficients for left and right speeds, defining the turning direction of the fly at next the step. These features are stored in the action variable. This corresponds to the interpretation of the direction of the chased fly from the information given by the ommatidia.

The distance is evaluated in the sense of proximity between flies, meaning that this value is in fact proportional to the inverse of the distance (the closer the flies, the higher the value of proximity). The visual processing function was thus adapted to compute this proximity based on the size (number of dark pixels in the visual field) of detected objects in the Chasing Fly's visual field. The larger the object is, the closer it is, and vice versa. Hence, the proximity value returned is equal to the sum of the "size" of the objects detected in the left and right eyes detected objects, normalized by the number of omatidia per eye.

More details about how the direction and distance informations are used to adapt the speed of the Chasing Fly are given in 3.2.4.

3.2.3 Random walking

Initially, the chasing fly moves randomly across the terrain by alternately turning right and left. This behavior was implemented using a function that returns left and right speeds to control the fly's turning. During this random walking, the fly turns right for a random number of timesteps, then turns left for another random number of timesteps, and so on.

3.2.4 Chasing

After the arousal state is set to 1, the male fly starts its chasing behavior. The VisualTaxisFly() is able to orientate itself towards the visual input using the direction part of the visual information (coefficients for left and right speeds). However, for the Chasing Fly to perform courtship chasing, a speed variation component was implemented taking into account the visually computed proximity to be able to accelerate or decelerate and to follow the female fly, keeping the desired distance constant between them. Thus, a desired distance attribute of the ChangingStateFly(), that defines the distance to keep in term of flies proximity was defined. Studying some videos of the fly's courtship allowed to estimate the distance kept constant between the female and the female during the chasing. Assuming the length of the fruit fly to be 2 mm, this distance would represent about 1 mm. The desired distance was experimentally fixed to a normalized proximity value of 0.009. As mentioned before, during the chasing behavior, the fly uses its visual processing function to extract both visual features (action), aiming at defining the fly's direction for chasing, and proximity, aiming at defining the fly's speed to keep the distance to the Target Fly constant. The proximity is used in the chasing behavior to define a factor multiplying the computed fly action to scale its forward speed. The factor is defined as a ratio of the desired proximity over the actual proximity of both flies. Thus, if the fly is far away from the target fly, the proximity will be lower than the desired proximity and the ratio will be high, leading to an acceleration. On the opposite, if the fly comes closer to the target fly, then the ratio will decrease until total stop of the chasing fly.

3.2.5 Crab walking

After the chasing phase, the male fly is positioned behind the female. The next step to be implemented involves the male performing a side walk around the female and extending its wings. This behavior makes the male more visible and enables it to sing and attempt to convince the female to mate.

Implementing the side walk, referred to as the "crab walk," presented a significant challenge due to the absence of documentation on the specific gait employed by the fly in this context. Consequently, an attempt was made to recreate a gait that would realistically simulate fly behavior, but it was unsuccessful. Adjustments were made to the gain on certain joints to observe the desired effects on the fly's gait. Despite several trials and the use of the MuJoCo interface to visualize each joint, it was realized that developing a novel gait would be very time-consuming. This process would require designing an entirely new pattern for the 42 degrees of freedom from the ground up.

Ultimately, an alternative solution was found to simulate the side walk. Instead of implementing a new gait, the existing forward tripod gait was utilized, and the fly was manipulated to turn left and then right, positioning it beside the female as desired. This was achieved by first setting the crab state attribute to 1, inducing a left turn. Next, setting the attribute to 2 induced a right turn. Finally, setting the crab state to 3 halted the chasing fly, allowing it to begin wing extension. The timing of each phase was carefully chosen to create an appropriate trajectory around the female. Setting the crab state to 4 between the left and right turn for a short time allowed the trajectory to be adjusted to be more realistic.

With this solution, the fly is turning around the female until it is oriented to its side and ready to start wing extension. This step is really important, so that the male can be beside the female to enable the latter to see the extended wings.

3.2.6 Wing extension

To add the wing extension behavior to the Chasing Fly, it was necessary to update the flygym repository with two elements:

- neuromechfly_courtship_kinorder_ypr.xml: the xml file that is used to build the neuromech-fly model, specifying each body part and joint. In this file, the 3 wings joints were added for the left and right wing, in order to be able to move them. This new file was added in the data folder of flygym-v1 along with the other defined models.

- config.yaml: the config file of flygym-v1 specifying the link to the different xml files available to build the model. The link to the new xml file was added to the original config file.

Once the physic model was ready, wing extension needed to be implemented. The transition to the wing extension state happens when the crab state is set to 3, meaning that the male fly has performed its turn and faces the side of the female fly. Wing extension was performed by updating the roll degree of freedom, toward negative angles values for the left wing and positive values for the right wing. Initially, wing joint angles are all set to 0. When the wing state is updated to 1 as explained in section 3.2.5, the joint angles of the wings are updated to perform unilateral wing extension. It was experimentally defined that left wing roll should be set to -1.2 and right wing roll to 1.2.

To know which wing to extend in unilateral extension, the selection method was based on the turning direction of the Chasing Fly: the wing to extend was defined to be the one closest to the Target Fly's head. Thus, if the Chasing Fly turned right before stopping at the side of the female, it has to show its left wing to be seen by the female and vice versa. Hence, the segregation was done taking into account the values of left and right deviation of the Chasing Fly (e.g., if right deviation < left deviation, the fly turned right and has to show its left wing). This was done to allow wing extension detection by the female, as discussed in 3.3.

As the extension lasts only for a short time, another counter was added in the fly attributes to count the number of timesteps during which wing extension is performed. After a defined time threshold, the extended wing goes back to its original position for a defined time of rest, and then if the wing extension conditions are still fulfilled (crab state value is 3), the wing extends again.

3.3 Target Fly (Female)

The Target Fly plays a key role in the development of the courtship scenarios in order to test the new abilities of the male that were implemented, as the behavior of the Chasing Fly fully depends on the behavior of the former.

In order to implement walking behavior and wing extension detection in the female fly, a class of fly called TargetFly was implemented. This class inherits from HybridTurningFly and integrates visual processing features. The Target Fly is black with a colored head, allowing vision. The visual processing function was defined to return the size of the object (in terms of number of dark pixels in the visual field) detected in left and right eyes. This allows to study if the Target Fly detects the wing extension of the male, by assessing if the number of dark pixels increases in the visual field of the female, on the side where the male waits during this behavior.

3.4 Robustness for colored flies and arena

As the visual processing is based on object detection, it was studies whether a non-black target fly as well as a colored floor would interfere with the performance of our simulation. It was first tested whether having a fully colored target fly still permits chasing using the implemented visual processing. To test the colored terrain, a new class ColoredTerrain() inheriting from FlatTerrain() was created, allowing to change the colors of the floor. This enables to study whether the visual processing of the ChasingStateFly() still works with a colored floor.

4 Results

4.1 Experimentally determined optimal parameters

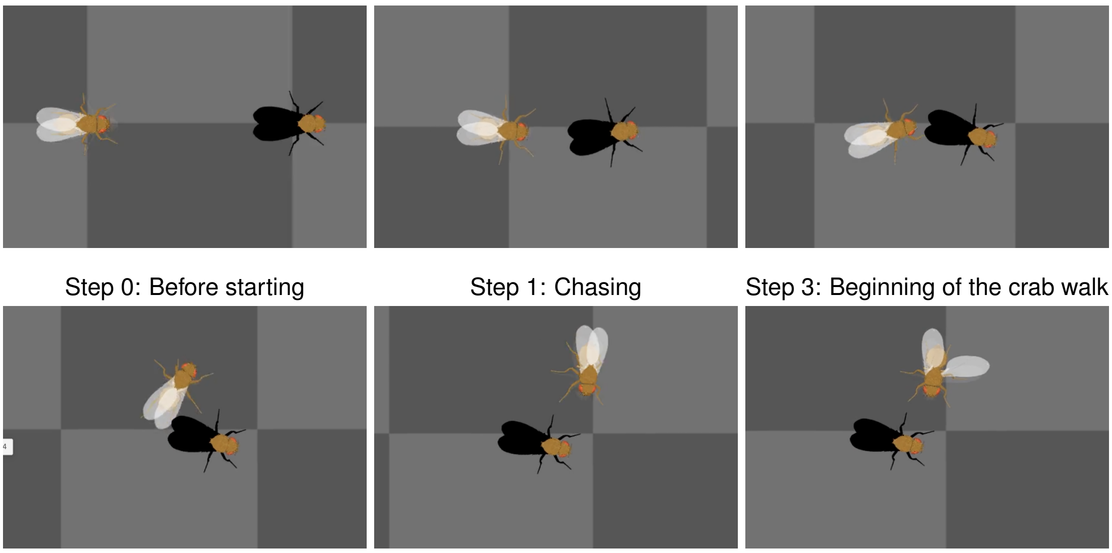
All attributes and parameters defined for the ChangingStateFly() were experimentally determined and summarized in Table 1.

Parameter	Value
Desired proximity	0.009
Timesteps at desired distance	1000
Speed threshold	0.2
Timesteps with wings open	5000
Timesteps with wings closed	2000
Duration of left turn (crab walk)	3000
Duration of forward walk (crab walk)	1500
Duration of right turn (crab walk)	4500

Table 1: ChangingStateFly() parameters

4.2 Simulation of the scenario

The videos of the simulation are available at this link. Overall, the simulation gives good results compared to the expected behavior of the fly. As shown in the video "1_scenario", the different phases of courtship can be observed, including the chasing at the beginning, followed by "crab walking" and wing extension. Figure 2 represents different frames of the scenario during the whole courtship behavior. It shows the male fly wandering, then chasing the target fly. The male then reaches the female and begins the crab walk, by turning left and then right to face the side of the female. Finally, the male fly extends its left wing in order to let the female see it.



Step 0: Before starting — Step 1: Chasing — Step 3: Beginning of the crab walk

Step 4: Left turn of crab walk — Step 4: Right turn of crab walk — Step 4: Wing extension

Figure 2: Screenshots of the behavior video at different steps of the entire courtship scenario

In the next sections, we will detail the results of the different parts of the simulation.

4.2.1 Chasing behavior

Figure 3 shows two frames of the chasing scenario video. On the first picture, we observe that the distance between both flies is quite large. This results in an increase of its speed and of the distance between the flies. The male fly detects the decrease in proximity and increases its speed: the second picture shows that the male caught the female up and that the distance between both decreased again.

Female moving away Male catching up

Figure 3: Screenshots of the behavior video at different steps of the chasing sequence

To observe the results of the chasing behavior, we plot the speed of both flies as well as the proximity between them, as depicted on Figure 4. The proximity is proportional to the proportion of dark pixels in the visual field of the chasing fly and thus inversely proportional to the distance between the two flies. As shown in Figure 4, each increase in Target Fly speed is followed by an increase in Chasing Fly speed to ensure keeping the distance constant. As a result, the proximity increases too.

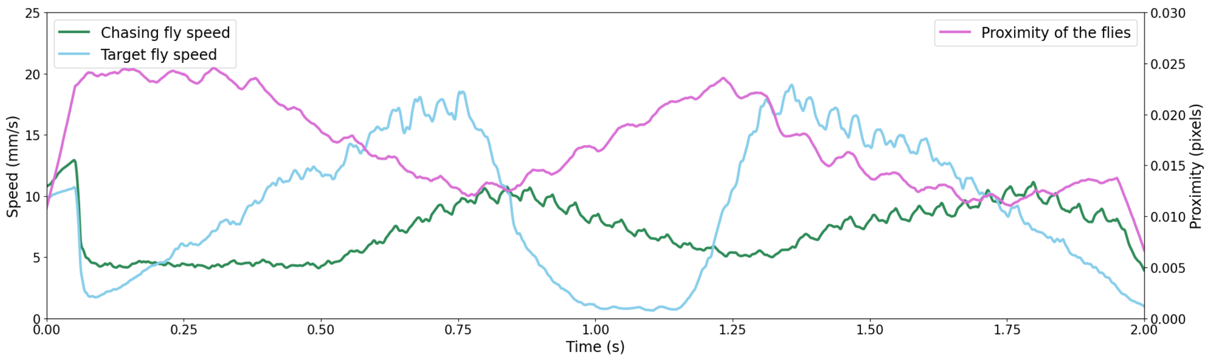
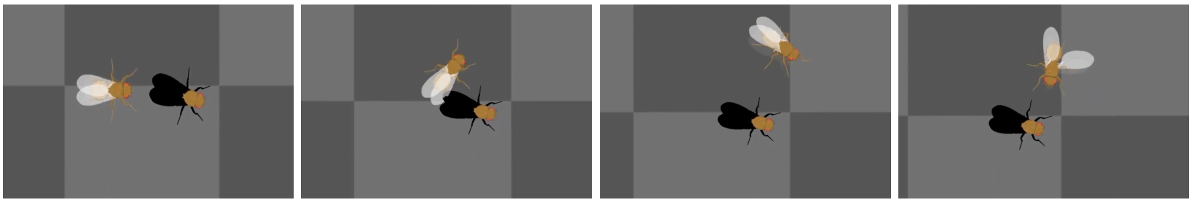


Figure 4: Evolution of speed and proximity during chasing. Blue curve is the smoothed speed of the female fly while green smoothed curve is the speed of the male fly, following the female. Proximity between both flies is shown in purple.

The chasing behavior is shown in video '2_chasing' on the drive. As seen in the video, speed adaptation and distance keeping in chasing behavior show good results. We observe that the speed of the chasing fly follows, with some delay, the one of the target fly until the desired proximity is reached.

4.2.2 Crab walking

The crab walking is divided into different phases that are shown on Figure 5. The first picture shows the end of the chasing phase which is also represented by the pink zone in the figure 6. After a timing threshold is reached, the Chasing Fly enters the crab walking phase. First, it turns around the female by turning left and then right, as we can observe on the pictures 2 and 3. Those turns are represented in the purple zone on the figure 6. The right turn has a higher factor as we want the fly to almost turn around to face the female after the left turn. Finally when the male faces the side of the female, it stops and begins the wing extension, as seen on the last picture. With this implementation, the "crab-walking" is always done to the same side of the female, i.e. to face its left side.



Step 0: Before starting   Step 1: Left turn   Step 3: Right turn   Step 4: Wing extension

Figure 5: Screenshots of the behavior video at different steps of the crab walking sequence

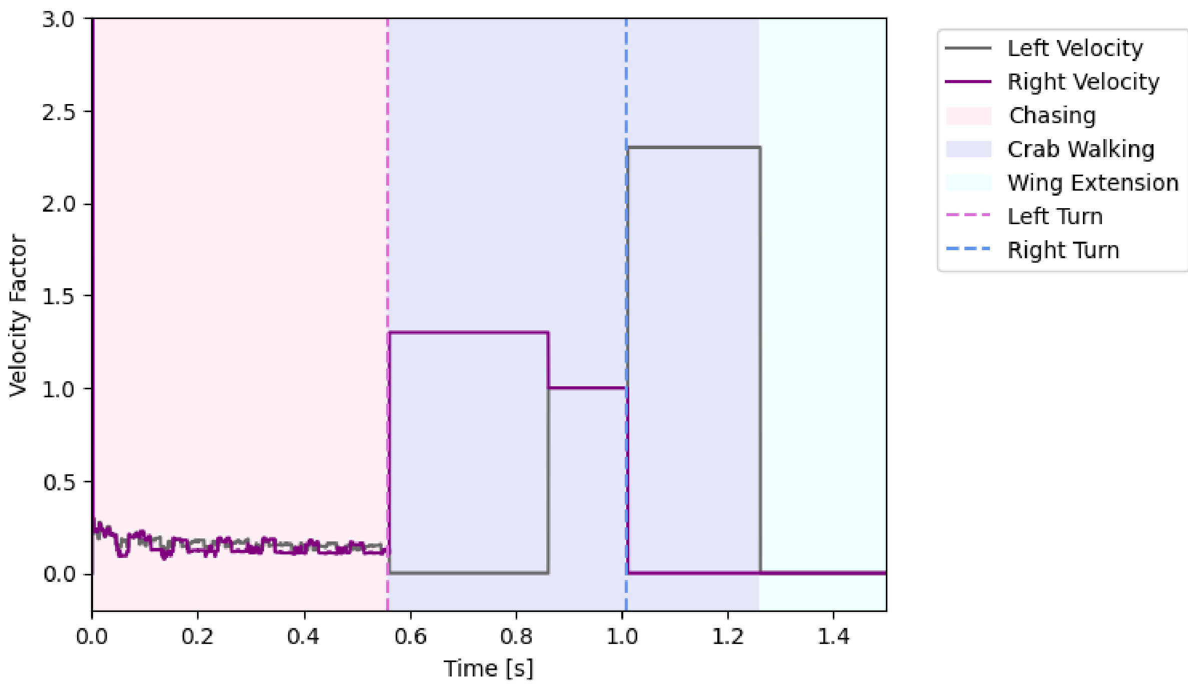


Figure 6: Evolution of left and right velocity during the different phases of Crab Walking. Dark violet curve is the right velocity and grey curve is the left velocity. Dashed lines represent the times where the fly turns to the left and to the right.

The crab walking behavior is shown in video '3_crab_and_wing' on the drive. As seen in the video, the male fly turns around the female fly in a quite "natural" way, but with a tripod gait.

4.2.3 Wings extension

Comparison between wings position during rest and unilateral wing extension is shown in Figure 7 along with an image from real drosophila courtship [6]. We can see that the wing opening looks biologically accurate when comparing the simulation to the photograph.

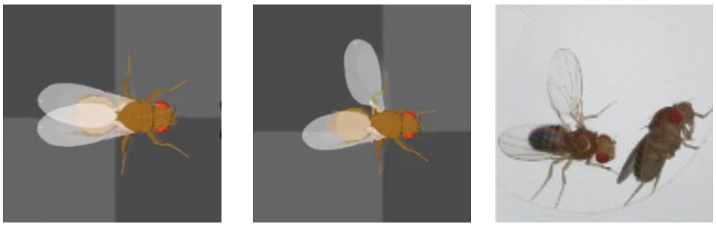


Figure 7: Wings position during rest (left) and wing extension (middle), compared to real drosophila wings extension (right) [6].

During the scenario, wings start to extend after the Chasing Fly faces the Target Fly. The changes in wing states are represented on Figure 8 in pink, the pink zones representing the times when the wings are extended.

The wing extension behavior is shown in the video 'crab_and_wing.mp4' on the drive. The video shows that the wing extension starts at the right timing, after the male is positionned to the side of the female.

Along with that, we studied whether the female fly perceives the wing extension. We plot the visual detection of left and right eyes of the female fly (Figure 8) and study whether there is a peak in visual information during wing extension. As we can see, there is a slight variation in visual detection on the side where the target fly is located. Indeed, during the simulation, the male turned around the female and faces her left side. We can see that the object detection values (that represent the number of pixels detected on both sides by the female in the simulation) were both equal at the beginning of the recording, meaning that the female could not see the male, as it was behind her. Then right before the wing extension begins, the male appears to the left side of the female, which results in a higher value for the left object detection, meaning the female fly sees its mate.

Unfortunately, even if the female is able to see the male at her side, it seems that she does not perceive the wing extension precisely, as the signal does not change between extended wing and normal wing states. This may be due to the thinness and color of the wings that do not provide enough contrast for pixel detection.

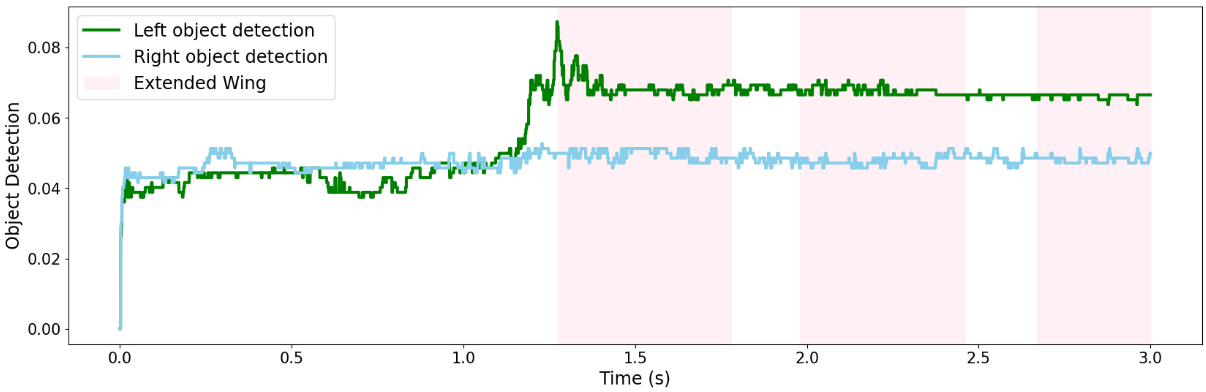


Figure 8: Wings extension detection by the female fly. Objects detected by left and right eye are shown in green and blue respectively. Wing state is shown in blue, being 0 at rest state and 1 when wings are open.

4.3 Robustness of visual processing

In the section we will discuss the results of chasing behavior with a colored target fly and terrain to assess the performance of visual detection in those conditions.

4.3.1 Robustness to fly color

When the Target Fly is not set to black as in the previous parts, the Chasing Fly has more difficulties to detect its target correctly, as shown in Figure 9 and video "4_colored_fly_original". Indeed, it performs chasing but very close to the Target Fly, almost superimposed, because object detection is based on black pixels which are less abundant in a colored fly. We can also see that the Chasing Fly starts a crab walking and wing extension behavior, which should not be the case. If we look at the fly speeds and proximity in Figure 10, we see indeed that the Chasing Fly's speed does not adapt to the target fly's speed, and that the proximity between both flies shows suddenly a peak. It may be due to the fact that the chasing fly sees much less black pixels at some distance, therefore it keeps moving forward, until they are almost at the same position, and with this close proximity the fly suddenly detects much more black pixels, as we can see on the left visual field in Figure 9. The change is too brutal to give the fly time to adapt its speed to keep a good distance, which lead to the condition of crab walking being fulfilled. Thus, the Chasing Fly does not perform very well in those conditions.

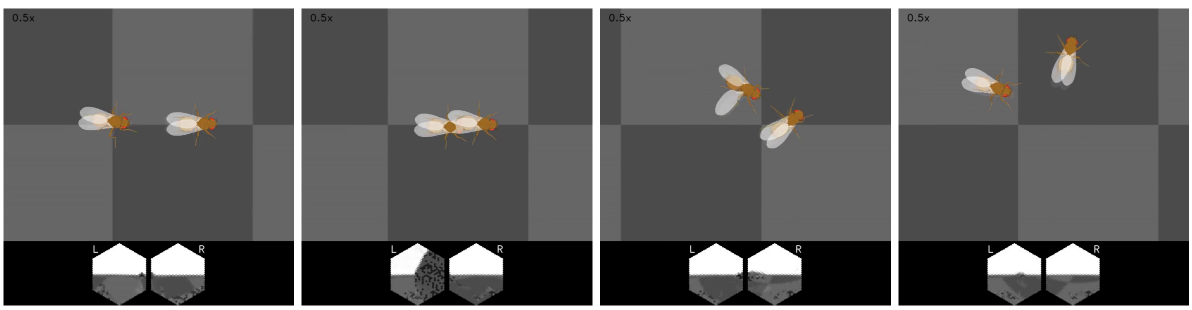


Figure 9: Screenshots of the behavior video at different steps of the original fly chasing with a colored target fly

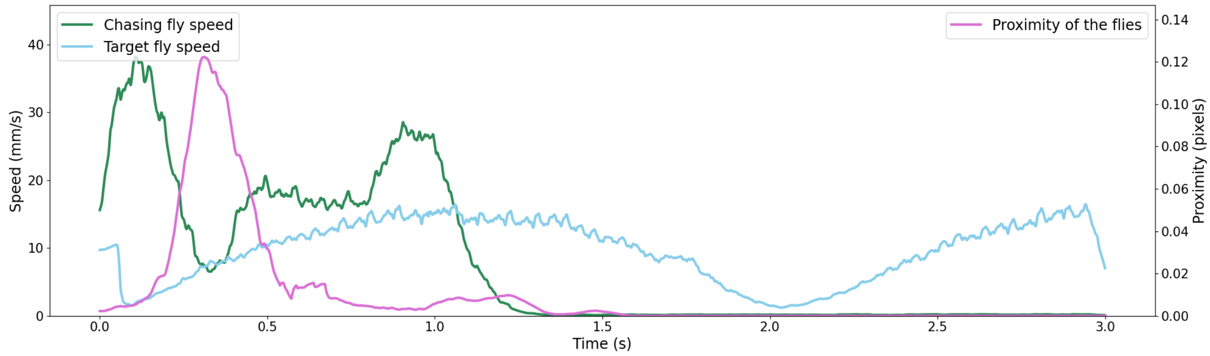


Figure 10: Chasing behavior with a colored fly with original parameters

The solution would be to adapt the desired_distance parameter to reduce the number of pixels required to start chasing. If the desired normalized proximity is fixed to half the original value, that is 0.005, much better results are obtained, as we can see in Figure 11 and in the video "4_colored_fly_updated". The chasing is much better, with the chasing fly keeping a reasonable distance to the target fly. However, at some point the chasing fly stops chasing. We can see in Figure 12 that the speed of the chasing fly starts to adapt to the speed of target fly, from 0.5s to 1.5s. Then, for an unknown reason the chasing fly stop chasing. To resolve this problem, more research should be done to update the class parameters further.

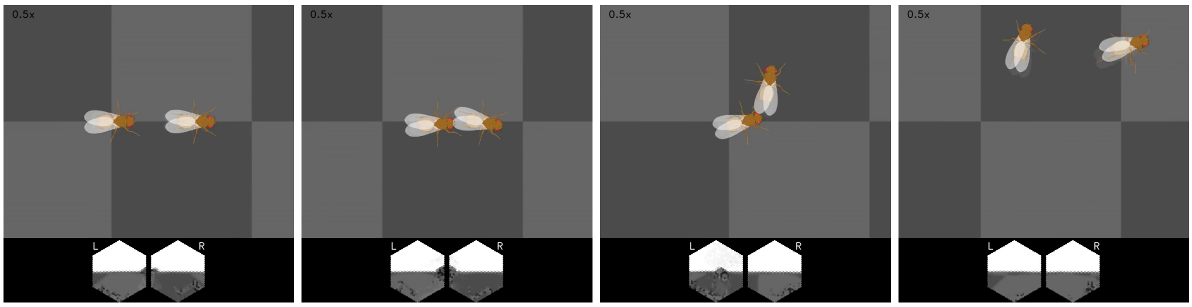


Figure 11: Screenshots of the behavior video at different steps of the original fly chasing with a colored target fly with updated distance

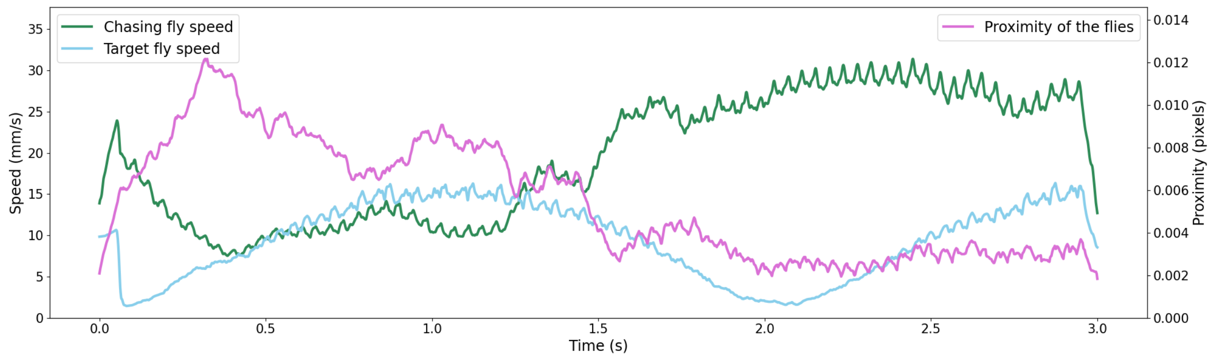


Figure 12: Chasing behavior with a colored fly with updated parameters

4.3.2 Robustness to terrain color

If we set the terrain color to red and yellow using the FlatColorTerrain() class, we observe that chasing using visual detection also fails, as depicted in Figure 13 and in the video "4_colored_terrain_original". We can observe that the fly speed does not adapt to keep the distance to the other fly, and that the wing extension behavior starts in the middle of the video. As before, it is due to the fly's vision being filled with black pixels due to the colored floor, as can be observed in the visual field of the fly. In addition, in Figure 14, we can see that the speeds of both fly are not adapted, and that proximity values are much larger than before, being between 0.2 and 1.4 instead of 0.002 and 0.01. Thus, it has been tried to adapt the desired distance parameter as in the previous section.

Figure 13: Screenshots of the behavior video at different steps of the fly chasing with a colored terrain with original parameters

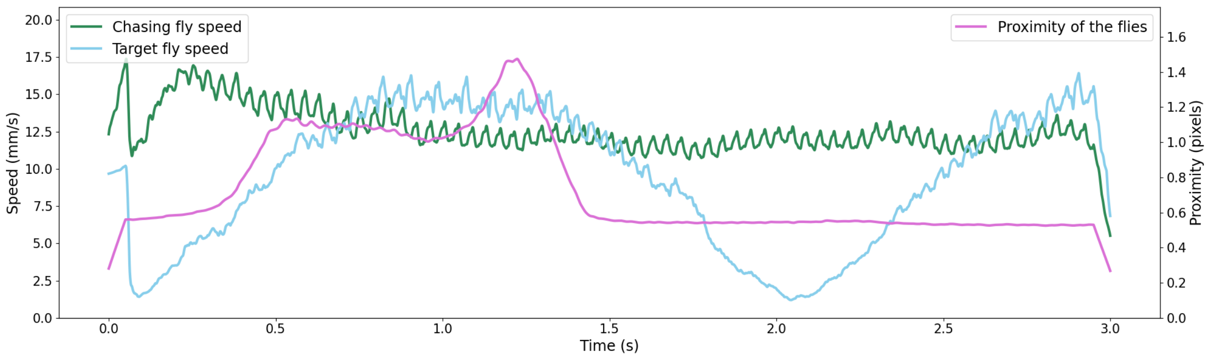


Figure 14: Chasing behavior with a colored terrain with original parameters

This time, more black pixels are detected in the visual field, so the desired proximity should increase to counteract the problem of the floor being to dark. If the desired distance is fixed to 0.7, slightly better results are obtained as shown in Figure 15, video "4_colored_terrain_updated" and Figure 16. Indeed, the wing extension behavior does not occur anymore. However, the speed adaptation of chasing is still not functioning correctly. We would need more research and experimentation to make the fly visual processing more robust.

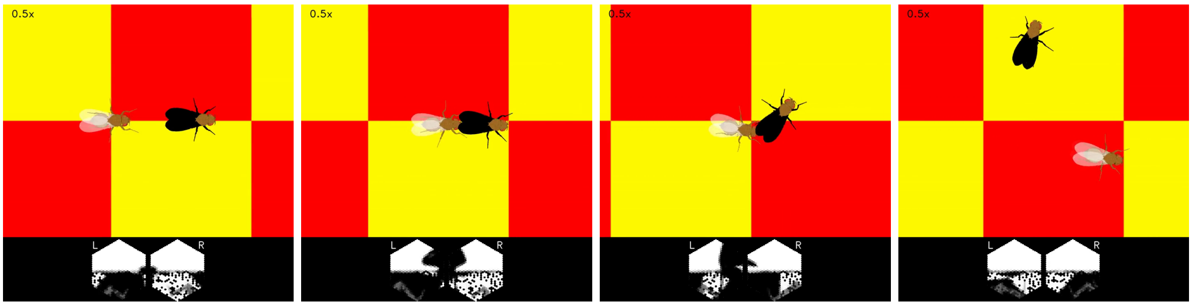


Figure 15: Screenshots of the behavior video at different steps of the fly chasing with a colored terrain with updated desired distance

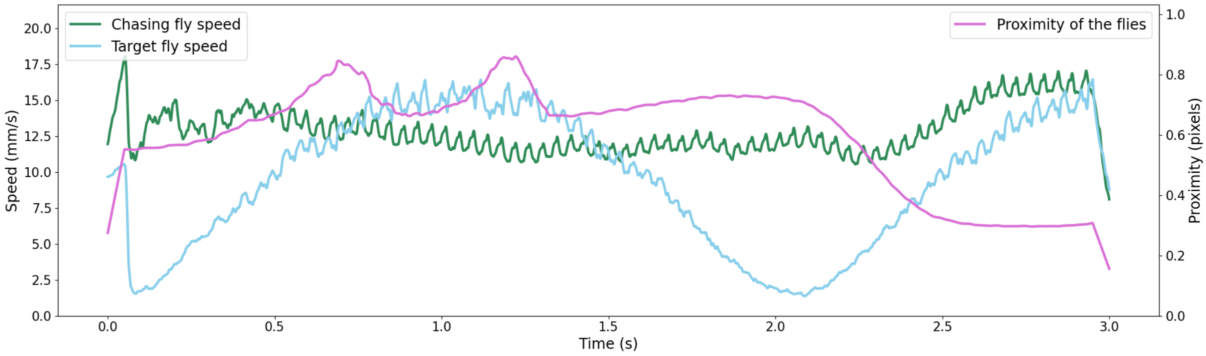


Figure 16: Chasing behavior with a colored terrain with updated desired distance

5 Discussion

Overall, the primary objective of the project was accomplished, as the chasing phase of the courtship behavior yielded promising results under simple conditions. Additionally, the male fly demonstrated the ability to execute subsequent courtship steps, including orienting itself to the side of the female and displaying its extended wings. However, several significant challenges were encountered, and there remains room for improvement.

One of the first challenges that was faced was the lack of data concerning the "crab walk" of the male around the female. Videos of that behavior were not precise enough to get a good idea of the type of gait that needed to be implemented. We thus chose to create scenario that looked as realistic as possible and allowed the fly to move around the female easily. The next step of the project would thus be to create a specific and more realistic new gait pattern that would allow the male to follow the same scenario, but walking sideways.

Another limitation of our project is our reliance on the visual system. We use the fly's vision for courtship, arousal state activation, and detecting wing extension in females. However, in reality, the arousal state is triggered by pheromones sensed by the olfactory system, which activates the P1 neurons. The wing extension, in turn, allows the male fly to sing, which the female hears rather than sees. Therefore, it would be interesting to implement multiple sensory signals, such as smell and sound, to create a more complete and realistic simulation of courtship behavior.

Future work on this project could include the adaptation of all the parameters fixed experimentally to be more accurate, and maybe adapt to the fly's environement. For example, it could be adapted according to the floor's color, or the target fly's color. It could also include the implementation of new colors and terrain textures to test the reliability of the vision system in more complex landscapes. This model also only allows the male Chasing Fly to turn around the female by her left side during the crab walk phase. It would be more realistic to implement a random variable that allows it to turn by both sides. Moreover, the current version of NeuroMechFly model only allows to work with female flies. Hence, it would be interesting to have another more adapted model allowing to implement male flies in the simulation, along with all their specific characteristics.

6 Appendix

Link for the drive to see the different videos : https://drive.google.com/drive/u/1/folders/1RxnbTyR-75OWsPtSnCLu-PBjjf7ijszE

Link of the GitHub of the project : https://github.com/ValentineDelevaux/COBAR_project.git

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