A Bio-inspired Collision Detector for Small Quadcopter

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Abstract—Sense and avoid capability enables insects to fly versatility and robustly in dynamic complex environment. Their biological principles are so practical and efficient that inspired we human imitating them in our flying machines. In this paper, we studied a novel bio-inspired collision detector and its application on a quadcopter. The detector is inspired from LGMD neurons in the locusts, and modeled into an STM32F407 MCU. Compared to other collision detecting methods applied on quadcopters, we focused on enhancing the collision selectivity in a bio-inspired way that can considerably increase the computing efficiency during an obstacle detecting task even in complex dynamic environment. We designed the quadcopter’s responding operation imminent collisions and tested this bio-inspired system in an indoor arena. The observed results from the experiments demonstrated that the LGMD collision detector is feasible to work as a vision module for the quadcopter’s collision avoidance task.

Index Terms—Bio-inspiration, Collision avoidance, Locusts vision, Quadcopter

I. INTRODUCTION

Quadcopter and its application has become ever more promising, this is because of their ability of agilely flying in real world and exploring extreme environment. Markets pursuing flying platform with more intelligence to accomplish robot tasks, the ability to sense and avoid surroundings is more and more vital for the quadcopter. Traditionally, quadcopters use GPS(outdoors) or optic flow(indoors)\[1][2] to navigate, and use ultra sonic, infrared, laser, SLAM\[3] algorithm or a combination system to avoid obstacles\[4]. However, it is still a challenge for quadcopters to fly automatically in an unfamiliar environment. The SLAM algorithm has made progress to address this problem to some degree, however, it requires too much computing power which constrict this technology to be applied to small quadcopters. Thus, we need to study more computing efficient methods for small or micro quadcopters. Nature demonstrates varieties of the successful mechanisms in collision avoidance situation, i.e. the locust is known to have professional fly skills and can fly in millions with out collision. There is a highly specialized neuron in the lobula plate that responds to imminent collision or approaching predators, which is so called: the lobula giant movement detector(LGMD)\[5]. This neural network has been modeled\[5][6] and promoted\[7] by previous researchers. The LGMD collision detector has been introduced to mobile robots\[8], embedded systems\[9][10], cars\[11][12], blimp\[13], and so on\[14]. But it hasn’t been challenged to any faster or more agile vehicles. Quadcopter has been introduced to this neuron network\[15] but few flight experiment has been achieved. Our work is the first time to achieve a quadcopter’s avoiding flight control in real flight and reflected its features confronting obstacle in a complex environment.

II. ALGORITHM DESCRIPTION

The LGMD algorithm used in this paper is inherited from our previous model described in Yue and Rind[7] and Cheng Hu[10][8] as Fig.2 shows, with some simplification and approximation. The model is composed of five groups of cells, which are P-cells (photoreceptor), I-cells(inhibitory), E-cells(excitatory), S-cells(summing) and G-cells(grouping) and also two individual cells, namely, the feed-forward inhibitory and LGMD.
The I layer can also be treated as a simplified convolution operation:

\[ [I_f] = [P] \ast [w] \]  

(4)

where \([w] \) is the convolution mask representing the local inhibiting weight distribution from the centre cell of P layer to neighbouring cells in S layer, a neighbouring cell's local weight is reciprocal to its distance from the centre cell:

\[
[w] = \begin{bmatrix}
\sqrt{5} & \sqrt{2} & 1 & \sqrt{5} & \sqrt{2} \\
\sqrt{2} & 2 & 1 & \sqrt{2} & 1 \\
1 & 1 & 2 & 1 & 1 \\
\sqrt{5} & \sqrt{2} & 1 & \sqrt{5} & \sqrt{2} \\
\sqrt{2} & 2 & 1 & \sqrt{2} & 1 \\
\end{bmatrix}
\]

(5)

The next layer is the Sum layer, where the excitation and inhibition from the E and I layer is combined by linear subtraction:

\[ S_f(x, y) = E_f(x, y) - I_f(x, y) \cdot W_I \]

(6)

Where \( W_I \) denotes the inhibition coefficient. However, the excitation would be falsely strengthened by the inhibition flow when using \( w \) if the inhibition has an opposite sign to the excitation. So an additional condition is significant to constrict the result:

\[ S_f(x, y) = \begin{cases} 
E_f(x, y), & \text{if } E_f(x, y) \cdot I_f(x, y) \leq 0 \\
S_f(x, y), & \text{otherwise}
\end{cases} \]

(7)

The G layer is introduced to this module in order to reduce the noise from the background. The expanded edges represented by clustered excitations are enhanced to extract colliding objects against complex backgrounds. This layer allows clusters of excitations in the S cells to easily pass to its corresponding G cells and provide a greater input to the membrane potential of the LGMD neuron compared with the excitation from a single S cell. This mechanism is implemented with a passing coefficient for each cell, which is defined by a convolution operation in the S layer. The passing coefficient is determined by its surrounding pixels, given by:

\[ |C(e)| = |S| \ast [w_e] \]

(8)

where \( w_e \) represents the influence of its neighbours and this operation can be simplified as a convolution mask:

\[ [w_e] = \frac{1}{9} \begin{bmatrix}
1 & 1 & 1 \\
1 & 1 & 1 \\
1 & 1 & 1 \\
\end{bmatrix} \]

(9)

The excitation correspond to each cell becomes:

\[ G_f(x, y) = S_f(x, y) C e_f(x, y) \omega^{-1} \]

(10)

where \( \omega \) is a scale and computed at every frame:

\[ \omega = 0.01 + \max(|C e_f| \cdot C_{w}^{-1}) \]

(11)
\[ G_f(x, y) = \begin{cases} G_f(x, y), & \text{if } G_f(x, y) \geq T_{de} \\ 0, & \text{otherwise.} \end{cases} \] (12)

Where \( T_{de} \) is the decay threshold. This grouping process can not only enhance the edges of immanent objects, but also filter out the sporadic excitation generated by background details. The membrane potential of the LGMD cell \( K_f \) is calculated:

\[ K_f = \sum_x \sum_y |\tilde{G}_f(x, y)| \] (13)

and then normalized by the equation:

\[ \kappa_f = \frac{\tanh(\sqrt{K_f - n_{cell}}C_1)}{n_{cell}C_2} \] (14)

where \( C_1 \) and \( C_2 \) are constants to shape the normalizing function, limiting the excitation \( \kappa_f \) varies within \([0, 1]\), \( n_{cell} \) represents the total number of pixels in one frame of image.

If the normalised value \( \kappa_f \) exceeds the threshold, then a spike is produced:

\[ S_f^{spike} = \begin{cases} 1, & \text{if } \kappa_f \geq T_s \\ 0, & \text{otherwise.} \end{cases} \] (15)

An impending collision is confirmed if successive spikes last consecutively no less than \( n_{sp} \) frames:

\[ C_f^{LGMD} = \begin{cases} 1, & \text{if } \sum_{f-n_{sp}}^{f} S_f^{spike} \geq n_{sp} \\ 0, & \text{otherwise.} \end{cases} \] (16)

Normally, the LGMD detector generate an “avoid” command if the spike last a few frames\( (C_f^{LGMD} = 1) \). However, it is not surprised when turning or nodding, a whole-field looming change will leads to false alarm. The feed forward inhibition\( (FFI) \) copes with such saccade-like movement by suppress the response to \( (C_f^{LGMD}) \). Given that the membrane potential of FFI cell is proportional to the summation of excitations in all cells with one frame delay:

\[ F_f = \sum_x \sum_y (|P_{f-1}(x, y)|)^{n_{cell}} \] (17)

Once \( F_f \) exceeds its threshold \( T_{FFI} \), spikes in the LGMD are inhibited immediately, the quadcopter will not respond to LGMD spikes in this case:

\[ C_f^{FFI} = \begin{cases} 1, & \text{if } F_f \geq T_{FFI} \\ 0, & \text{otherwise.} \end{cases} \] (18)

In our case, the LGMD result\( (C_f^{LGMD}) \) and FFI result\( (C_f^{FFI}) \) cooperate to decide the motion state of the quadcopter. The command generated by FFI result has higher priority so that it is able to suppress the response to LGMD in a saccadic-like situation. Motion task switch is handled by a task scheduler explained in Fig.5.

The initial values for each parameters are listed in TABLE.1.

### III. System overview

In this section, the outline of the whole system is described. To accomplish the obstacle detecting task, luminance information is collected by the camera on the sense board, and then input into the LGMD algorithm, the output is passed through a USART port into the flight control to monitor avoiding tasks.

#### A. LGMD Vision Detector

The LGMD vision detector is designed to process image information and to simulate the LGMD neural network on board. It is from the vision module of ‘Colias’, an open-hardware modular micro robot for swarm robotic applications\([16][17]\). The detector is mainly consist of a Micro-controller and a CMOS camera. The LGMD algorithm mentioned in the previous part is designed into a 32-bit MCU STM32F407, which clocked at 168 MHz to provides the necessary computational power to have a real-time image processing. It contains 192 Kbyte SRAM that provides enough spaces for image buffering and computing. Images are captured by a CMOS image sensor OV7670 module, which is capable to operating up to 30 frames per second(s) in VGA mode with output support for RGB422, RGB565 and YUV422. The viewing angle is approximately 70 degrees. As a trade-off for image quality and data consumption, we choose a resolution of 72×99 pixels at 30fps, with output format of 8-bit YUV422. The Detector also provides USART interface to transmit results between the flight control module .

#### B. Quadcopter Platform

In this paper, we use a DIY quadcopter with the skeleton size of 33cm between diagonally rotors as the testbed for the collision detector. The flight control module we used is based on a STM32F407V and provides 5 USART interface for extra peripheral. It is an open source flight control module\([http://www.anotec.com]\) which contains basic posture stabilization algorithm and communication protocol against the ground station, and could be easily modified to accommodate our tasks. A Pix4Flow optic flow module\([11]\) is introduced to generate relative position information and help stabilize the quadcopter. This module usually serve as an alternative of GPS especially in indoor situation where GPS signal is weak or constricted. The source data from the Pix4Flow module is
velocity in two axis, this velocity works as the input of a new cascaded PID loop to help nail the quadcopter. In our test, we also integrate the velocity as the approximately position information. The battery is 2200 mAh, which can endure 10-12 minutes without drop-off.

C. Ground Station and Supporting Softwares

Data of the flight control could be transmitted between the flight control module and the off board ground station(PC) through a nRF24L01 2.4GHz wireless module. In all the trials, we set the data exchange rate at 100 Hz. In addition, we used a pair of bluetooth module(HC-05) to transmit sample images during trials. One of the bluetooth is connected to the LGMD detector while another is connected to the computer.

D. Motion Control Mechanism

In this section, the logical bridge between the output of the LGMD sensor and the UAVs action is elaborated. The mechanism will include how the optic flow sensor is used to estimate the UAVs position and to feedback the control loop.

1) Stabilizing Mechanism: The quadcopter is stabilized by using the algorithm of a cascaded PID loop which is composed of the angular control loop(outer loop) and the angular velocity control loop(inner loop). Traditionally, the input of the outer loop is the data from the remote control, which represents expected angular of the quadcopter. The output of the outer loop is cascaded to the inner loop as the expected angular velocity. The structure of the PID loops is illustrated in Fig.5.

2) Hovering Methods: Generally, the basic cascaded PID control works well to keep the posture of the quadcopter but cannot nail it in the air. That’s because we cannot get the accurate velocity of the quadcopter through the accelerometer unless the accumulative error is insignificant. In our test, consider to the indoors condition, to accomplish the hovering function is necessary. Thus, an additional velocity sensor is needed to revise the accumulative error caused by the accelerometer. A Pix4Flow sensor is used in our quadcopter. This optic flow sensor supplies the optic flow velocity in two axis, and can be integrated to reflect position information of the quadcopter. We added a new PID control loop for optic flow data. As the velocity information of the quadcopter, the optic flow data is also cascaded to the angular control loop(the outer loop).

3) Task Scheduler: When flying in the arena, the flight is restricted in a 2-D plane. The quadcopter is challenged to switch its motion state in response to impending collision appropriately. The motion state is handled by a task scheduler, which switches tasks among "cruise, avoid and slowdown, depending on the decision made by the cooperation of LGMD and FFI. The quadcopter will fly in straight line if its clear on the route, and will shift to the side by an approximate distance to avoid the obstacles if the LGMD detected an potential collision. The task flow is illustrated in Fig.5.

IV. EXPERIMENTS AND RESULTS

As discussed, this bio-inspired collision detector is tested to verify its properties. 3 kinds of tests were implemented to verify the superiority of the LGMD collision detector and its compatibility with quadcopter.
Avoiding
Cruise
Slow-
down

LGMD detector.

avoid it automatically by the command generated from the
quadcopter flies automatically approaching the obstacle and
middle of the room, as the 'obstacle'. Our task is to let the
flow sensor. A box(pasted with textured paper) is set in the
put on the ground to enhance the accuracy of the optic
The arena is indoors, flex banner with special texture is
copter to challenge its performance in obstacle avoiding case.

C. Static Obstacle Avoiding Test

finally, we tested this bio-inspired method with the quad-
copter to challenge its performance in obstacle avoiding case.
The arena is indoors, flex banner with special texture is
put on the ground to enhance the accuracy of the optic
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middle of the room, as the 'obstacle'. Our task is to let the
quadcopter flies automatically approaching the obstacle and
avoid it automatically by the command generated from the
LGMD detector.

A. Fixed Detector & Moving Object Tests

We first tested the performance of the LGMD Detector
confronting factors that cause to luminance change with
the detector stationary. Both video simulation and real moving
object have served as the target and the results shows LGMD
collision detector’s superiority in differentiating complex back-
ground and approaching foreground without any pre-study of
the environment.

B. Features analysis & Parameters adjustment

Before the quadcopter is pushed to accomplish avoiding
tasks, we analyzed the features and characters of the LGMD
when the quadcopter is flying in the Arena. The detector’s
parameters are adjusted to the degree that it hardly alarms
falsely except when flying towards surrounding backgrounds.
The quadcopter is also tested to verify that it responds differ-
ently when image motion is generated by itself deviation and
by approaching object, see Fig.8

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V. CONCLUSION

In the above sections, the bio-inspired vision detector is
challenged on a quadcopter platform to accomplish obstacle
avoiding task. The results shows the reliability and efficiency
of this novel method. The approaching selectivity and comput-
ing efficiency are the main priority of this bio-inspired method.
The LGMD collision detector is capable to cope with coming
 collisions for a quadcopter platform, and has the potential to
 cooperate with the current exited collision avoidance solutions.

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LGMD is ignored and a slow down command is generated to reduce influences spikes cannot stay sufficient frames upon the threshold. The response of the threshold but the FFI spikes increase so quickly to hit the line that the LGMD the quadcopter, and make the quadcopter rotates, the both line exceeds their

Fig. 8. Self-rotation test. In this case, When we give an external force to continuously until the jar hit the camera at around 600(10ms).

(a) Sample images for lateral shifting

(b) Sample images for approaching object

Fig. 7. Spiking results for moving object with the detector fixed. We put a jar onto a small mobile robot (Colias) and let the robot moves laterally or towards the camera from the same start point. As the result shows, the spike value keeps a low level towards lateral shifting object, while increase quickly towards approaching object. In the approaching object test, the imminent collision is detected at around 460(10ms), and the spike value increases continuously until the jar hit the camera at around 600(10ms).

Fig. 10. Result of the obstacle avoiding test in the arena. The green line is the output of the FFI layer; The blue line is the output of the G layer (LGMD cell); The obstacle was first detected at the point marked with red star, and the quadcopter succeeded to avoid the obstacle before colliding. The excitation keeps a high level during the avoiding process, where we close the response to the repeated excitation until an avoiding process finished.

(c) Result of laterally shifting objects test.

(d) Result of approaching objects test.

(b) Spiking results in avoiding test

Fig. 9. A glimpse of the arena. Obstacle highlighted with yellow rectangle

(a) Sample frames when heading the obstacle

(a) Sample frames of the surroundings during self-rotation

(b) Spiking results caused by self-rotation

Fig. 8. Self-rotation test. In this case, When we give an external force to the quadcopter, and make the quadcopter rotates, the both line exceeds their threshold but the FFI spikes increase so quickly to hit the line that the LGMD spikes cannot stay sufficient frames upon the threshold. The response of the LGMD is ignored and a slow down command is generated to reduce influences from self-rotation.

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Fig. 11. Automatically flying trajectory during the obstacle avoidance test.

Fig. 11(a) A typical comparison of two kinds of position information result. The green line is the position information generated by integrating the speed information from the optic flow sensor (Pix4flow), the red line is the trajectory detected by the overlook camera. Both methods have inaccuracies, but the trend in both ways shows the avoidance behavior clearly. Fig. 11(b) Trajectories (detected by a Python program using template matching method) printed onto a screen shot from the overlook camera. The obstacle is highlighted with a green rectangle, the ground is decorated with a textured flex banner for better sensitivity of the Pix4flow. Several trajectories of the center point of the quadcopter were printed onto the image with different colors; the starting point is decorated with dots. The two kinds of trajectories show clearly that the quadcopter can avoid the obstacle appropriately before striking it.

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