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Towards flapping wing robot visual perception: Opportunities and challenges

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***Abstract*— The development of perception systems for bio-inspired flapping wing robots, or ornithopters, is very challenging due to their fast flying maneuvers and the high amount of vibrations and motion blur originated by the wing flapping. Visual sensors have been widely used in aerial robot perception due to their size, weight, and energy consumption capabilities. This paper analyzes the issues and challenges for vision sensors onboard ornithopter robots. Two visual sensors are evaluated: a monocular camera and an event-based camera. First, the pros and cons of integrating different sensors on flapping wing robots are studied. Second, the paper experimentally evaluates the impact of wing flapping frequency on both sensors using experiments with the ornithopter developed in the EU-funded GRIFFIN ERC project.**

***Index Terms*— Robotic perception, flapping wings, ornithopter, event-based vision, bio-inspired robots.**

Fig. 1: GRIFFIN ornithopter prototype developed by the University of Seville equipped with an onboard DAVIS 346 event camera.

I. INTRODUCTION

The future of aerial robotics point towards the design and implementation of bio-inspired aerial robots capable of retrieving the capabilities of animals and insects. The development and production of these platforms have opened a novel field of research which main goal focuses on generating the necessary hardware and software to implement the mechanics, dynamics and perception systems that enclose the design of bio-inspired aerial robots. Ornithopters are aerial platforms that generate thrust and lift by using flapping wing mechanisms (see Figure 1). These type of platforms are the main focus of attention towards a bio-inspired flying approach. Nowadays, few ornithopters have been developed; mainly for research [1] [2] and industrial applications [3] [4]. Even though these advances show promising results, there is still a huge gap to close to build a robotic platform that behaves like real birds. The main constraints are given by the lack of knowledge to describe the whole robot aerodynamics and the components to develop the actuators that satisfy the design requirements.

Robotic perception systems are fundamental to retrieve information of the robot environment to perform tasks such as robot localization, mapping, object identification, and classification. In aerial robotics, the selection of the perception sensors is mainly constrained by three tightly coupled factors; size, payload, and energy consumption. Ornithopters increase the number of constraints as the robot design imposes size and space limitations to satisfy the aerodynamic requirements for a bio-inspired flight. Besides, the dynamic behavior of flapping wing robots generates additional challenges for vision-based perception as

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the fast-flying maneuvers produce high vibrations and motion blur. Additionally, traditional vision sensors are not well suited to work under strong changes in illumination. A multi-sensor perception solution may solve these issues by integrating sensors robust to these type of perturbations such as event-based sensors. Event cameras provide advantages such as high temporal resolution, low power consumption, and high dynamic range.

The ERC GRIFFIN Project(788247) aims at the development of a unified framework for medium and large-sized flapping wing robots with manipulation capabilities. The GRIFFIN robots will include autonomous perception, reactivity, and planning. The implementation of these capabilities encloses the evaluation of possible challenges produced by the dynamics generated by the movement of the wings and tail during flight. This work aims at analyzing the issues and challenges presented for vision sensors onboard an ornithopter robot. We focus our study on vision sensors and their advantages in terms of size, height, and power consumption w.r.t. to other perception sensors such as lasers and LiDaRs for being onboard a flapping wing platform. This paper proposes the evaluation of the challenges presented on the data captured by a monocular camera and an event-based sensor onboard of an ornithopter prototype developed in the GRIFFIN project, see Figure 1. The paper first qualitatively analyzes the pros and cons of using different sensors onboard ornithopters. Second, it quantitatively evaluates the impact of wing flapping frequency on perception with a traditional frame-based camera and an event-camera.

The rest of the paper is organized as follows. Section III presents an analysis of common robotic sensing systems and their limitations for flapping wing flight. Experimental results evaluating the interaction of wing flapping with event-based vision are presented in Section IV. Section V discusses the presented results, opportunities and limitations of event-based vision for flapping wing flight. Section VI concludes the paper and highlights future research steps.

II. RELATED WORK

The first ornithopter designs can be dated back to Leonardo Da Vinci's times in the XV century [5]. The technology of that period was not enough to solve the problems of flapping wing propulsion, mainly the lack of lightweight and resistant materials, and proper power and energy sources. The Microbat [6] is one of the earliest attempts of an electrically powered ornithopter. With a very optimized structure and lightweight components, it achieves flight times of a few seconds with its own weight, showing that flapping wing propulsion is very limited in lifting loads. In order to add payload, lift and thrust should be increased. The Smartbird made by Festo [4] elegantly mimics the flight of a seagull with complex wing movements while flapping, thanks to its wings having multiple degrees of freedom. These movements help to improve both lift and thrust, at the cost of more moving parts and mechanical complexity. Flapping frequency is limited to prevent looseness or damaging multiple parts and pieces. A lightweight carbon fiber structure and a case of foam grants aerodynamic shape to wings, tail, and fuselage. Thus, the Smartbird can be lifted at low speeds. The Robird [3] is another example of a highly nature-inspired ornithopter. Special care on aesthetics is made by painting the ornithopter to mimic the appearance of a falcon. Due to its realistic look, the Robird is used as a scarecrow in airports and farms, as other birds identify the ornithopter as a predator. Fuselage and wings are 3D printed in resin, which allows crafting complex geometries such as the peak, eyeballs, feathers on the wings, and aerodynamic shapes overall. The flapping movement is synchronized with a pitching motion to increase the thrust at the cost of mechanical complexity.

The works in [7] [8] describe a number of designs for developing home-made ornithopters and highlight the main design aspects, i.e. materials, propulsion or aerodynamics. Despite the fact that their design suffers from high take-off weight, a few seconds flight was achieved and an overview of implementation constraints was provided. Other works explore the performance of smaller scale ornithopters [1] [2] [9], showing high maneuverability and hovering capacity in exchange for high energy consumption and low payload capabilities. Hence, existing ornithopter designs show high variability in size, shape, flight time and

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payload capacity.

However, the development of perception systems for ornithopter robots is still an under-researched area. A commercial mini ornithopter was equipped with a VGA lightweight in [10] to estimate the motion direction by averaging the flow across the sensor. The optical flow estimation is sensitive to the oscillations produced by the wing frequency and requires the use of either a band-stop filter or a synchronized sampling method. The work in [11] estimates the optical flow using a 1D sensor with high aspect ratio to provide altitude feedback for a flapping wing microrobot. Despite these works approaching an initial approximation to flapping wing robot perception, none of them have made a comparison of the implications of using different sensing modalities on an ornithopter robot nor have they considered the use of event cameras.

The contribution of the work presented in this paper is twofold. First, the paper presents an overview of the issues and challenges of robotic perception in ornithopter robots. Second, the interaction between wing flapping with traditional and event cameras is evaluated. This paper presents a step towards the implementation of systems that endow ornithopter robots with the necessary capabilities to perceive their surroundings.

III. ROBOTIC SENSING FOR FLAPPING WING FLIGHT

Perception systems are core to endow robots with the necessary capabilities to interact with the environment. Existing research on aerial vehicle perception has explored the use of different sensors in order to provide an accurate representation of the robot surroundings. Generally, the sensors equipped in aerial robots are carefully chosen according to the requirements of the task and the limitations of the sensors. In the context of flapping wing robots, sensing elements are affected by two particular phenomena: the jerkiness of the robot motion dynamics, and the fast maneuvers performed during the flight. Although several sensing strategies for aerial robotic perception exist, the development of a reliable solution capable of dealing with these challenges is still an under-researched area.

A significant variety of sensors for aerial robots have been researched in the literature [12]. This work focuses on three of the most popular ones: frame-based cameras, light detection and ranging (LiDaR) sensors, and event-cameras. Aerial robots have been equipped with frame-based cameras to perform tasks such as autonomous navigation [13], obstacle avoidance [14], and to perform grasping and perching [15]. Traditional frame-based cameras are lightweight, small, and inexpensive. Frame-based cameras provide information regarding the visual appearance of objects such as texture and color. Moreover, stereo vision systems can be used to retrieve depth information at short distance, which is often used for object detection and localization for aerial manipulation [16]. However, frame-based cameras are sensitive to illumination changes, their latency is significantly high and suffer from motion blur. These limitations are significant when considering the implementation of visual perception systems in flapping wing robots. The motion of an ornithopter robot is very fast and prone to vibrations due to the lift and thrust generated during downward strokes. Therefore, the high vibration frequency hampers the extraction of information from frame-based cameras due to i.e. motion blur. However, the use of frame-based cameras could be adequate in cases when the ornithopter movements are not very abrupt such as, for instance, during gliding.

LiDaR sensing techniques provide accurate 2D and 3D point clouds of the robot surroundings [17] [18]. LiDaR sensors illuminate the surfaces using pulsed laser light and measure the reflected pulses to obtain a distance estimation. 2D/3D LiDaR sensors rotate the pulsed laser light in order to obtain several measures that provide a representation of the environment. A wide variety of robot localization [19] and mapping [20] techniques have relied on point cloud information obtained from LiDaRs. The use of LiDARs in ornithopter platforms is constrained by the payload limitations and the low scan rate (typically 10 Hz), which can be low for fast flying maneuvers. The advent of commercially available solid-state LiDAR sensors is promising regarding the payload limitations as their weight is significantly lighter than traditional electromechanical LiDAR solutions. However, the

TABLE I: Summary of sensor details.

Sensor	Dynamic range	Max. bandwidth	Power consumption	Weight
Velodyne VLP-16 Lite	-	5-20Hz	900 mA/9V	$\sim$ 590 g
DAVIS-346 (AVS)	56.7 dB	40 Hz	200 mA/5 V	170 g
DAVIS-346 (DVS)	120 dB	Async.	160 mA/5 V	170 g

low rate of data acquisition is still not adequate for the high-speed maneuvers and vibrations of ornithopter robots.

Event cameras are neuromorphic sensors that mimic biological retinas by capturing visual information in the form of events. An event represents a change of illumination in the scene. Differently from images provided by frame-based cameras, events are triggered asynchronously with high temporal resolution (i.e. order of μ seconds) and transmitted using the Address-Event Representation (AER). Each event is defined by a tuple $e = (t, x, y, p)$, where t is the timestamp in which the event is triggered, x and y correspond to the pixel coordinates, and p is the polarity of the event. The low latency, low power consumption and high dynamic range of event cameras motivated the use of these sensors in the robotics area. Currently, these sensors are being used to support and improve the performance of multi-sensor fusion applications such as visual odometry [21] [22], 3D reconstruction [23], and SLAM [24].

Table I summarizes the main properties of a typical 3D LIDAR (Velodyne HDL-64E), a frame-based camera (DAVIS-346 AVS) and an event camera (DAVIS-346 DVS) for their perception capabilities in an ornithopter robot. Considering the nature of an ornithopter robot's flight, event-based cameras have better properties than frame-based cameras and LiDAR sensors. Event cameras can cope with high-speed maneuvers and vibrations due to their very low latency and the absence of motion blur. Besides, the high dynamic range (140 db) of event cameras provides robustness against illumination changes, which often limit the use of frame-based cameras for outdoor applications. In spite of all these advantages, event-based vision involves a change of paradigm that requires the development of new vision algorithms since traditional computer vision algorithms are often inapplicable.

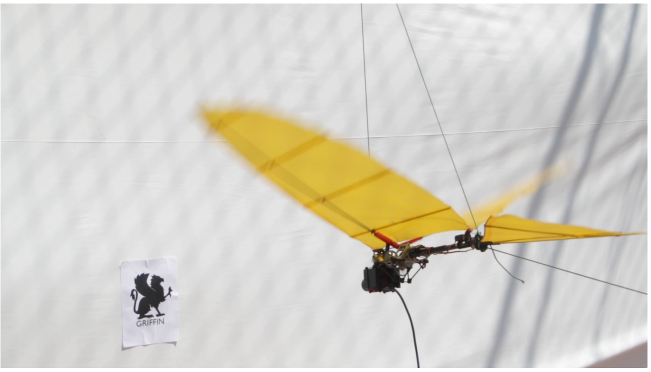

Fig. 2: The experimental set-up.

Therefore, the effect of wing flapping on an event camera needs to be analyzed to validate the opportunities and challenges arising from implementing event-based vision on an ornithopter robot. Next section describes an experiment where the performance of the DAVIS-346 (DVS) event camera onboard an ornithopter under different flapping frequencies.

IV. EXPERIMENTAL RESULTS

Although event cameras do not capture static images, the flight of an ornithopter entails the camera is constantly under motion. Therefore, a significant amount of information can be retrieved during the wing flapping. This section presents an experimental evaluation of the effect of flapping wing flight on event-camera perception. Our hypothesis is that the oscillations generated during the flapping wing flight are correlated with the number of events generated by the event camera and with the quality of the image from the monocular camera. This section is divided into two parts. First, the description of the performed experiments including the set-up and the experimental procedure is presented. The second part presents an analysis of the experimental results.

A. *Experiment set-up*

The experimental scenario was designed to retrieve the necessary information to analyze the measurements captured by the sensors onboard the ornithopter under the flapping of its wings. Figure

TABLE II: Weights chart.

	Weight (g)
Semi-wing (each)	35
Tail	45
Fuselage	245
Event camera	170

Total w/o camera	**360**
Total w/ camera	**530**

2 shows a picture taken in one of the experiments. The experiments were performed with an ad-hoc ornithopter prototype developed in the GRVC-Robotics Lab of the University of Seville. The prototype is designed to perform sustained and controlled flights, and it is intended for testing custom software and hardware during midflight.

The ornithopter has two aerodynamic surfaces, wing, and tail. During the flight, the lift is produced in both aerodynamic surfaces, most of it on the wing for efficiency, and some of it on the tail to grant stability and controllability. Thrust is produced by the wing when it flaps up and down, and it exhibits a quadratic growth with flapping frequency. Wings have one DoF, the flapping motion. Flapping is achieved with a gear crank mechanism actuated using a brushless motor and fed with a LiPo battery. The tail has two DoF (roll and pitch), and it is controlled by two servos to control the tail position during flight. The aerodynamic surfaces are made of nylon fabrics attached to a lightweight structure made of carbon fiber rods.

As shown in [25], the greater the flapping frequency, the higher the motion amplitude over the fuselage. The oscillations induced on the camera due to flapping depend on two aspects: the forces and moments (aerodynamic, inertia and weight) generated on the wings during flapping and the weight ratio between wings and fuselage. In order to minimize undesirable oscillations on the fuselage, wings should be as lightweight as possible. Table II summarizes the weight of each moving part of the ornithopter. High frequency flapping movements generate high amplitudes in the fuselage oscillations while increasing the thrust. Therefore, a compromised solution must be achieved. Figure 3 shows the flapping angles of the ornithopter to ensure proper thrust and stability during flight.

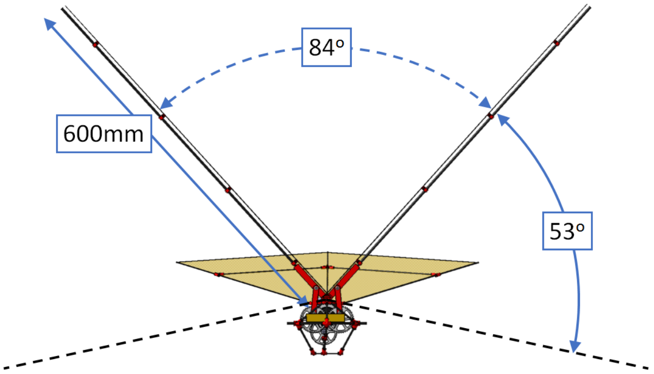

Fig. 3: Ornithopter flapping angles.

We use the DAVIS 346 sensor [26], which includes a monocular camera, an Inertial Measurement Unit (IMU) and an event camera. The sensor was mounted at the front of the ornithopter to provide frontal views while keeping the center of mass (CoM) of the robot low enough to maintain the ornithopter upwards. The camera is connected via USB to a ground station computer that records the data. The DAVIS 346 sensor points towards a fixed target in front of the robot and, thus, the image frames and the events generated around the target contour are retrieved. A correct data evaluation requires that the event camera generate events only from the target, therefore no other objects (e.g background) should move on the scene. For the experiments, we selected a white background screen with the GRIFFIN logo as the only object on the scene, see Figure 2.

Further, the size of the target on the image has to be kept as constant as possible and, as the larger the target contour is, the more events will be triggered, i.e. assuming the same sensor movement. Therefore, the camera lateral and frontal movements and the rotation around the z axes should remain as constant as possible. Based on the previous requirements, we designed an experimental set-up in which the robot hangs in the air. In the experiment, the ornithopter flaps its wings at different frequencies with constant amplitude while capturing data from the onboard sensors. The experimental set-up includes: (i) an empty frame cube structure in which the ornithopter was located to ensure safe conditions and avoid possible collisions with the ground; (ii) a static

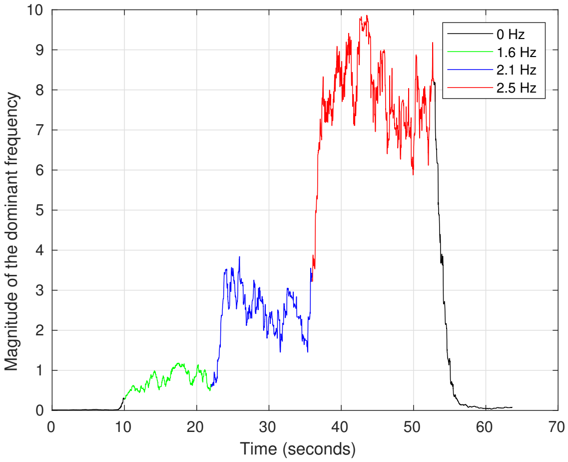

Fig. 4: Magnitude of the dominant frequency of the linear acceleration during the experiment.

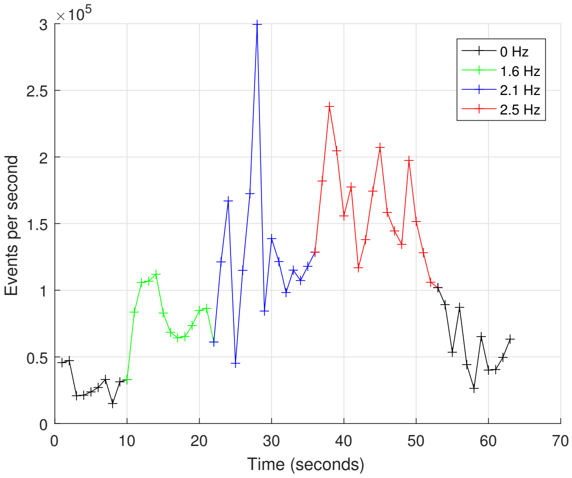

Fig. 5: Number of events per second generated during the experiment.

background screen located in front of the robot using a white fabric to cover the entire field of view of the camera and; (iii) a vertical guide rope hanged from the center of the structure to keep the robot in the air. The movement on the x and y axes was constrained by attaching two additional ropes between the main guide and the columns of the frame. In the experimental setup, the tail of the ornithopter was not actuated, and the yaw deviation was constrained by using an additional guide attached to the back of the robot. Thus, the ornithopter was kept looking at the background screen at every moment of the experiment.

B. *Multi-frequency flapping experiment*

In this section, the effect of flapping at different frequencies on the generation of events is evaluated with a set of experiments. To gather the data-sets, we continuously store all the information provided by the event camera, monocular camera, and the IMU. The experiments consist of an ornithopter flapping at three different frequencies (i.e. 1.6, 2.1 and 2.5 Hz.) while looking at a white background screen with the GRIFFIN logo attached. At the beginning of each experiment, the ornithopter was static (i.e. without flapping) and the wings were set horizontally. The flapping frequency was increased progressively until reaching 1.6 Hz and staying at that frequency during 12 seconds. Then, the flapping frequency was increased to 2.1 Hz during 14 seconds, and subsequently to 2.6 Hz during 17 seconds. During all the experiments, the tail of the ornithopter remained static.

The linear acceleration was analyzed using the data collected from the IMU. Figure 4 shows the magnitude of the absolute linear acceleration's dominant frequency overtime in one of the experiments performed. We found that the abrupt changes in this magnitude correspond to the changes of flapping frequency. Besides the IMU measurements, we are interested in the effect of flapping frequency on frame-based and event-based cameras.

Flapping frequency directly impacts on the percentage of blurred images captured by the frame-based camera and on the number of events generated by the event camera. Table III summarizes the results obtained. Flapping frequency has a deep impact on both cameras. First, the number of blurred images highly increases as the flapping frequency increases, hampering perception based on frame cameras for these type of robots. On the other hand, the number of events generated by event cameras highly increases with the flapping frequency. High event generation rate enables capturing more perceptual information at high flapping rates, entailing positive synergies for the use of event cameras in flapping wing robots. This tendency was observed in all the experiments performed.

Additionally, Figure 5 shows the number of events per second triggered during one experiment.

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TABLE III: Experimental results of flapping wing experiment at different frequencies.

Flapping frequency	**Collected images**	**Blurred images**	**Number of events**
1.6 Hz	239	15.9 %	994981
2.1 Hz	279	26.5 %	1832151
2.5 Hz	340	40.2 %	2716686

The events generated at flapping frequencies 1.6, 2.1 and 2.5 Hz are respectively represented in green, blue and red. The events retrieved when the flapping stopped –due to the residual robot motion due to inertia– are represented in black. Similarly to Figure 4, abrupt changes can be observed when the flapping frequency is changed. However, the number of events per second shows high variability, especially at high-frequency flapping. To assess this phenomenon, we used the images captured by the monocular camera and a frame-based representation of the events (see Figure 6). Events are accumulated in time windows of $25ms$ and rendered into the image by using their polarity blue (ON) and red (OFF) as reference. Figure 6b shows a frame with high levels of noise as a result of wrinkles in the background screen caused by the wind, which corresponds to a frame in the time interval between seconds 26 and 27. Although wrinkles can appear during the experiments at all flapping frequencies, the DAVIS 346 triggered a great number of events when flapping at high frequency (see Figure 6c). Moreover, we observed that a low peak at second 25 was caused by the logo being outside the field of view of the camera during a few frames. During that time range, the events were only generated by wrinkles in the background fabric and sensor noise.

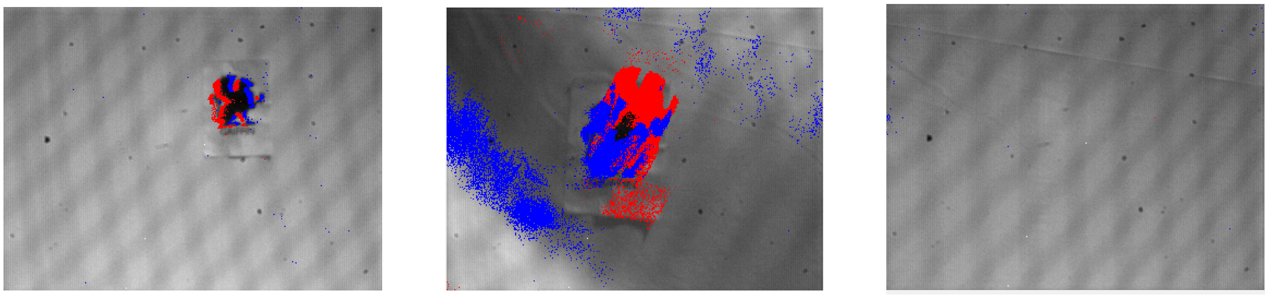
Furthermore, we computed the Pearson's correlation coefficient between the magnitude of the dominant acceleration frequency and the number of generated events (see Figures 4 and 5). The Pearson's correlation coefficient takes values within the range $[-1,1]$, where -1 is a full negative correlation, 1 is a full positive correlation, and 0 means the absence of correlation. Despite the low and high peaks on the number of events per second, a correlation coefficient of 0.7291 was obtained. Therefore, a significant positive correlation exists, which implies a linear association between both variables in the given flapping frequency range.

V. DISCUSSION

Flapping-wing aerial robot perception is a challenging problem. The flight of an ornithopter is often prone to vibrations and entails abrupt maneuvers at high speed, which limits the use of traditional sensing systems such as frame-based cameras and LiDaR sensors. These issues can be overcome through event-based vision as event cameras have very low latency and do not suffer from motion blur. However, event cameras can not capture static images and the sequential nature of Address-Event Representation data requires the development of novel vision algorithms that exploit the full potential of this sensing modality. This work presented the first approximation towards the use of event cameras onboard ornithopter robots. To the knowledge of the authors, this is the first attempt to address the perception issues during the flight of ornithopter robots and evaluate the interaction of event-based vision with ornithopter wing flapping.

The experimental results presented in this paper show a significant correlation between the magnitude of the linear acceleration and the number of events generated. This finding can be used when developing active perception systems for ornithopter robots as flapping frequency entails abrupt changes in the linear acceleration. More events involve more information that can be used to improve perception or reduce uncertainties. This is specially interesting during the take-off, landing and perching maneuvers where the flapping frequency is required to be high. Planning, control, and perception can be designed transversely to capture a greater amount of information when the ornithopter movement is not restricted and to perform accurate maneuvers when the scenario is simple or previously mapped. For instance, the robot could purposefully perform very jerky flight maneuvers for mapping a scene to obtain a great volume of information during a short period of time.

The perceptual issues arising during flapping wing flight have been analyzed in this work. Despite the fact that developing perception systems



(a) Events at low frequency

(b) Noisy peak

(c) Outside the field of view

Fig. 6: Experimental results of event camera during wing flapping.

for ornithopter robots is challenging and requires significant advances in event-based vision, this work sets the baseline for future research on event-based active perception for flapping wing robots. In a near future, developments in this area will endow ornithopter robots the necessary capabilities to perceive and interact with the environment.

VI. CONCLUSIONS AND FUTURE WORK

This paper analyses the challenges and issues existing in the development of perception systems for flapping wing robots. An evaluation of the pros and cons of the main sensors existing in the literature shows that event-cameras have the best features to address the requirements of the problem. Moreover, the interaction between wing flapping and the generation of events has been experimentally evaluated. The results show that flapping frequency, average linear acceleration, and the generation of events are correlated. These findings provide a first approximation towards ornitopther robots actively perceiving the environment in an autonomous manner. Hence, a door of opportunity to the development of active perception systems that takes advantage of the correlation between flapping wing, linear acceleration and amount of information (i.e. events) perceived in a period of time, is opened.

Our future work will focus on the implementation of active perception algorithms that allow ornithopter robots to navigate and interact with the environment. In particular, we aim at guiding and controlling the robot during the landing and perching maneuvers. In addition to active perception, we aim at investigating the combination of event cameras with other sensors. Frame-based cameras and LiDaR sensors could be used to provide episodic measurements of texture and depth that enrich the representation of the robot's surroundings.

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