Large Aperture Optoelectronic Devices to Record and Time-stamp Insects' Wingbeats

Ilyas Potamitis, Iraklis Rigakis

***Abstract*— Recording and analysis of wildlife sounds with regard to monitoring biodiversity is a developing trend in ecology. Automatic audio-based units are commonly used to record field vocalizations of birds, bats, cetaceans and amphibians. The wingbeat of insects produces audible but feeble tones. Practical automatic recording units for the wingbeat of insects are still pending. In this work we present a complete system to record the wingbeat of insects based on large aperture optical sensors that turn the light fluctuations (caused by the partial occlusion of light from the wings) into sound. Wide apertures are useful when tracking the movement of fast flying insects and the full motion of the beating wing in the case of tethered insects. The system detects a wingbeat event, auto-triggers the recording process, time-stamps the event and stores the permanent record in-situ. When the sensor is inserted in an insectary it effortlessly produces massive datasets of wingbeat recordings. We discuss implications for novel studies that are impractical to carry out manually, as they involve large numbers of insects. We also suggest potential applications such as smart insect traps that count, recognize and alert for the presence of insects of economic and public health importance.**

***Index Terms*—optoelectronic sensors, automatic recording unit, precision agriculture, electronic insect traps, wingbeat, insects**

I. Introduction

Insects affect cultivations that are vital for rural economy, local heritage and environment in both positive and negative ways: insects pollinate a large number of plant species, while certain kinds of insects are considered pests that cause major production and economic losses in agriculture [1]. On top of the hazard list, mosquitoes and biting midges can transmit serious diseases to humans and livestock. Innovative uses of sensors and networks targeting animals are starting to be translated into new ecological knowledge [2]. This work describes in detail a novel device that can be used in both applied and basic research in the context of automatic insect monitoring. In entomology one is often interested to study the flight mechanism and movement patterns of insects [3]. The proposed device can be used to derive the frequency content of wingbeats of a large number of insects on the order of hundreds to thousands. In this study we present a practical setting where the optical sensor is inserted inside insectary cages that enclose many flying adults of the targeted insect to record their wingbeats as they incidentally cross the field of view (FOV) of the sensor. We show how this setting allows to automatically record and analyze big datasets of wingbeats stemming from insects that have large economic and social importance such as fruit flies and mosquitoes. It is a daunting task to run these studies manually, based on direct observation, as insects are hard to manipulate especially on free flight and studies involving a large number of insects are not replicated through time or across sites to great extent because of the manpower requirement. In the context of our work we make a distinction between optoelectronic sensors and vision cameras as the optoelectronic sensor is always composed of a light emitter opposite to a light receiver. The beating wings of insects flying in the FOV partially intercept and modulate the flow of light. The implications of this technology are discussed in view to embedding it in insect traps to count and classify flying-in insects based on the spectrum of their wingbeat [4]. A historical retrospection of optical methods applied to measuring insect movement is presented in [5] and the references therein. Various configurations of opto-electronic systems have been developed in the past to study the movement of insects [6-9]. Prior work, reaching back 15-20 years, focused mainly on the sensor. Moreover, the sensors presented at that time were not immune to electronic and light interferences. In this work, the sensor is of high-precision, and immune to optical interferences from natural or electric light. Moreover, a complete system is described in detail where the light fluctuation in the output of the receiver is monitored by a microprocessor and the device is auto-triggered when it senses a wingbeat. Once triggered the light fluctuation is turned to an audio snippet, time-stamped and internally stored in the SD of the device as a permanent record. As in [5] this work is based on modulating-demodulating high frequency light pulses hitting the beating wings of the insect. However, in this work we introduce several novelties in the sensors' construction and offer a complete wingbeat recording system as well. In detail: a) The receiving aperture of the sensor is made large enough to accommodate the full motion of a wingbeat and to allow tracking of fast flying insects such as fruit flies that would otherwise spend little time inside the FOV while crossing the surface of a single diode. Lack of sufficient duration data is translated to poor frequency resolution for fast flying insects. We present two ways of expanding the light receiving surface: First we construct a 2D array of photodiodes

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and secondly we make use of a large aperture optical light guide. The latter one, to our point of view, opens new grounds as a deformable, slim sheet of polymer/acrylic light guides will allow tracking of flying insects inside various curved shapes of traps. b) In the new sensor, though the FOV increases by a factor 2-10 compared to a linear 1D array of diodes, a series of improvements in the circuit design result into a lower noise level than in [5]. c) In this study we send pulses at much higher rates (i.e. 455 kHz compared to the 60 kHz in [5]) allowing us to reject a wider range of light interferences.

II. Materials and Methods

In this section we describe in detail the construction of an optoelectronic sensor and the recorder that is able to record the fragile signature of a wingbeat. The sensor must be able to operate in illumination conditions ranging from darkness to bright light including in the presence of lamps commonly encountered in laboratories. In the following discussion we also include all alternative routes we tried with a view to assist the interested reader to take our implementation further.

A. Recording Devices

In this work we use infrared LEDs of the SFH4356 series at 860nm. They have a sharp raise time 12 ns. We need fast LEDs faster than e.g. TCRT5000 at 950nm with 4 μs rise and fall time [4] to respond to the frequency of 455 kHz.

Regarding the connectivity of photodiodes we have tried connecting them in row, parallel and combining both ways. In the parallel configuration (see Fig. 1 left) the change in the power of the spectrogram of the signal is smoother as the insect moves from one photodiode to the neighboring diode passing over the border and the gap that separates them. In the case of row connectivity or when combining both ways the variability in amplitude is stronger when we move a tethered wingbeating insect parallel to the diodes.

Emitting LEDs are configured as in Fig 1 (right), that is, in a combination of row and parallel connection in order to reach an equal current in all LEDs and to a smooth light distribution across the emitting light surface. Regarding photodiodes' amplifier we tried the ICs THS4281, AD8606 και OPA380. We ended up with OPA380 which is a high speed, precision transimpedance amplifier having a large bandwidth of 90 MHz and high slew rate 80V/μs and noise smaller than 10nV/√Hz. This one achieved the best results in reducing the overall noise of the system. As a single-ended input to differential output conversion circuit we used the dual rail-to-rail input and output, single-supply operational amplifier AD8606 that demonstrates low noise (8nV/√Hz) and small power consumption (1mA/channel). As an analog to digital converter we used ADS8863 that has the required analysis of 16-bit, a conversion time 930nS and a power consumption 60μW for sampling frequency 10KSPS (see Fig. 2). As a demodulator we used the lock-in amplifier AD630 functioning as a precision rectifier to extract the envelope of the high frequency content of the photodiodes' output. The envelope follows the wingbeat movement once the insect flies inside the FOV. We have also tried the lock-in amplifier ADA2200 but attained better results with AD630. As a low-pass filter applied to the output of the demodulator (see Fig. 3) we used the quad FET-input operational amplifier OPA1654 which has a very low noise (4.5nV/√Hz) and small power consumption (2mA/ channel).

The system is powered by a Li-Ion battery of 3.7V. Since the circuits need a symmetric supply of ±12V, we used the inverting DC/DC converter TPS63700 to generate a negative output voltage -12V and TPS61085 for generating +12V. The 3.3V are supplied from the LP2985-33 fixed-output, low-dropout regulator: One for powering the digital circuits and one for the analogue circuits respectively. The charging of the battery is carried out with a BQ24075 integrated Li-Ion linear charger and system power path management device. The recorded wingbeat snippets are stored locally in an SD (see Fig. 4).

In [5] we designed a rectifier using an operational amplifier while in this work we used AD630 which is designed for this purpose. The frequency of 455 kHz was chosen for two reasons: a) The LED lamps often used in internal spaces and laboratories can produce interferences reaching 60 kHz and therefore we needed to move higher in modulating frequencies, and b) The carrier frequency is far from the targeted audible bandwidth of insect's wingbeat and it was handful to use a ceramic filter at this frequency. This filter suppresses by 50 dB the signal amplitude at low frequencies prior to demodulating the high frequency signal back to the acoustic frequencies.

The greatest challenge was to improve signal to noise ratio of the output. We found that noise was due to the fact that the modulation frequency was generated by a microprocessor with not perfectly stable input since the master clock is based on a phase lock loop (PLL). We de-activated the internal PLL of the processor and used an external clock that led to a significant improvement in noise (see Fig. 5).

Regarding the light receiving configurations we have been experimenting with two types: a 2D arrangement of diodes and alternatively an optical light guide. As an optical light guide we used a common polymer sheet commonly used in edge-lit backlight units of liquid crystal displays of laptop computers (e.g. we used LTN154U2-L03). In a laptop a light source from the bottom of the layer is guided through the light-source towards the 2D surface of the screen. In our configuration we make reverse use of this functionality by directing the light stemming from the array of infrared LEDs acting as an emitter towards the 2D receiving surface. The polymer sheet guides the light at the bottom edge of the sheet. The bottom of the sheet rests on a 1D array of photodiodes and all other edges of the sheet as well its back are covered with another polymer sheet that blocks light from leaking out. The outcome of this setting is to enlarge the receiving surface of the device without increasing its cost thus avoiding to use a large number of photodiodes needed in complicated arrays. Large photodiode arrays have intrinsically large capacitance that prevents the system from achieving high frequency rates. We investigated the cause of the remaining noise: We use an array of 22 photodiodes in parallel configuration. The output of the receiver gives a signal with amplitude 1Vpp. Assuming the insect is placed in front of a diode and its wingbeat generates a light intensity change of the order of 30%, then the change in the output of the receiver will be (1V / 22) * 0.3 = 13mV. We need to amplify the output by 100 times and lead it to ADC. Amplification of the 13mV output leads to amplifying the noise from the following 21 diodes and associated circuits. In a similar device with lower number of diodes one will end up with lower noise.

Power consumption totals to 816.7mW from which 678mW are consumed on the analogue part of the device (LEDs 310 mW, demodulator 130 mW, filter 235 mW and digital potensiometer 3mW) and 138.66 mW on the digital part (MCU 18.9 mW, RTC 0.39 mW, ADC 0.33mW, diodes receiver 24.7 mW, SD 33 mW, and system clock 61.34 mW).

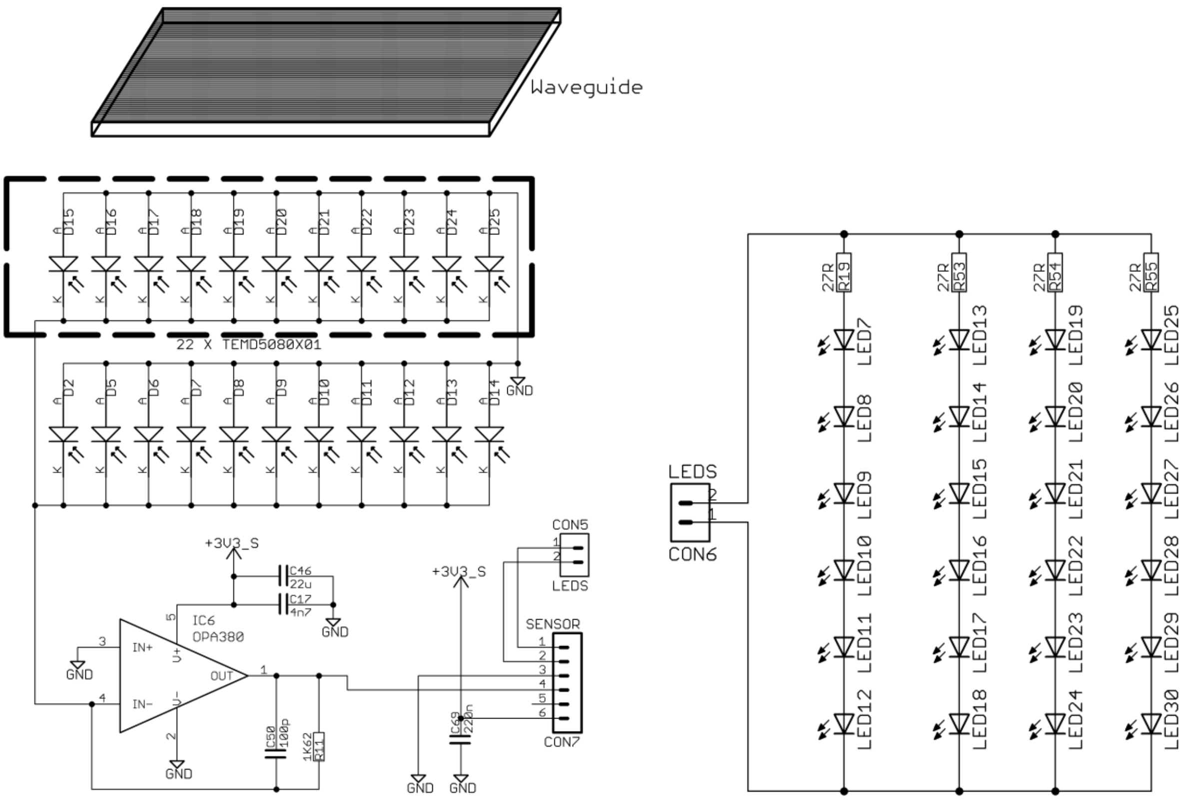

Figure 1. (Left) Optical receiver based either on a light guide or on a 2D array of diodes. (Left-top) an optical light guide attached on a 1D linear array of photodiodes. (Left-bottom) a 2D surface of photodiodes. (Right) The LED array light emitter.

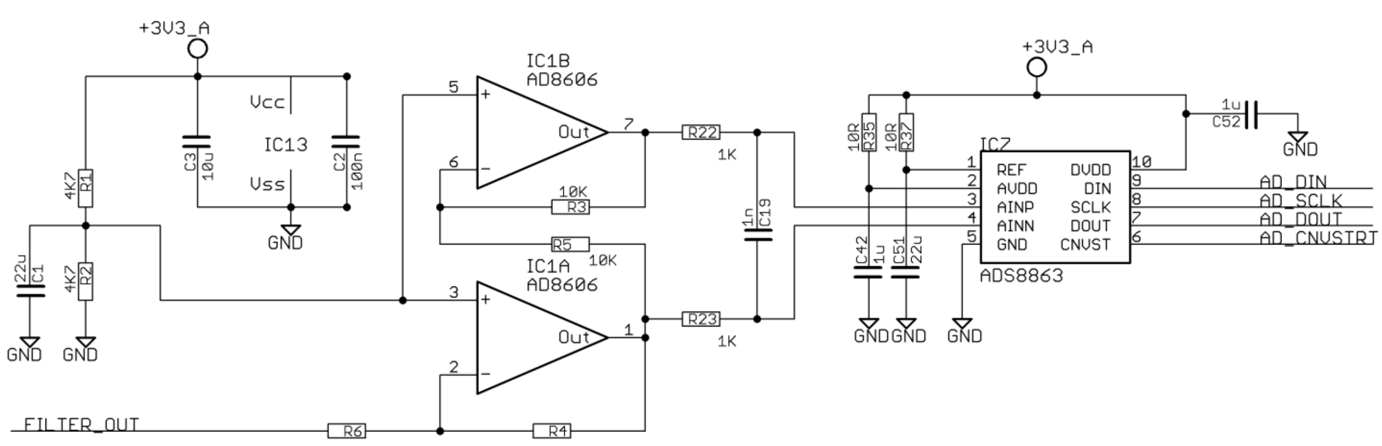

Figure 2. ADC circuit. The output of the low-pass filter is passed to the dual OPA AD8606 that converts the single output of the filter to differential in order to allow the ADC to make full use of its 16-bit accuracy.

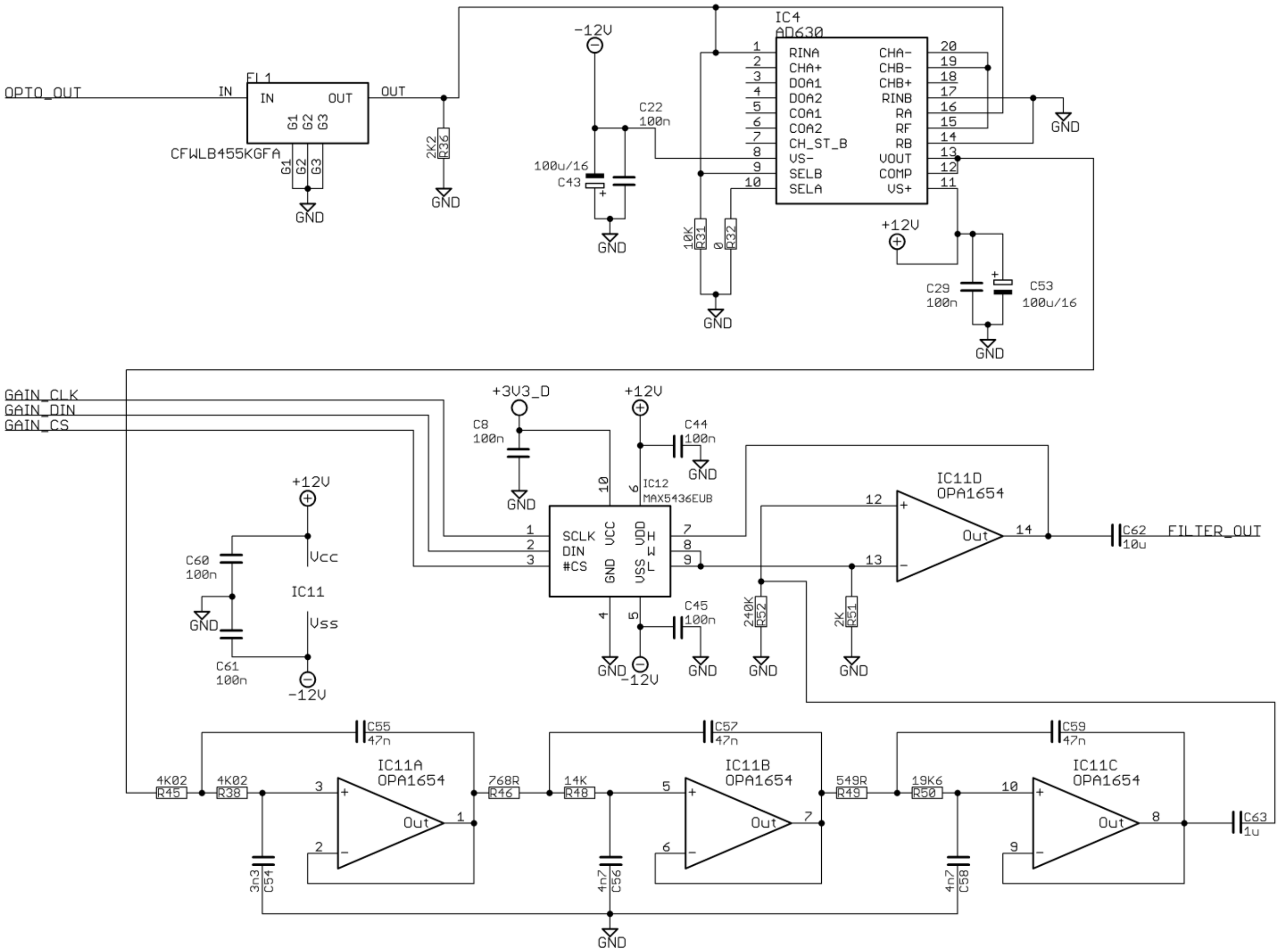

Figure 3. Demodulator Filter. The output of the diodes is passed to the AD630 demodulator through the ceramic bandpass filter FL1. The high frequency of the demodulator is filtered by the 3-stages filter IC11A, IC11B & IC11C, and is subsequently amplified by the IC11D. The amplification is controlled through the digital potentiometer IC12.

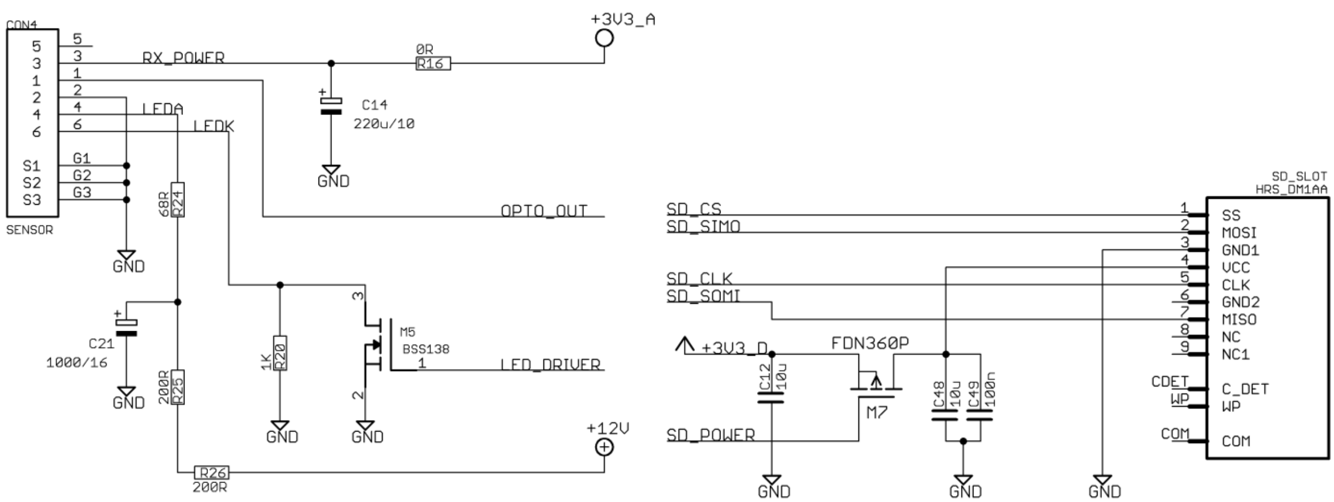

Figure 4. (Left) Sensor driver unit: CON4 connects the sensor to the recorder. It passes the output of photodiode’s amplifier, the square pulse-series of 455 kHz that drives the LEDs and the 3.3V for powering photodiode’s amplifier. (Right) SD interface. The SD_SLOT is the socket to the SD card which is connected to the microcontroller through SPI connection.

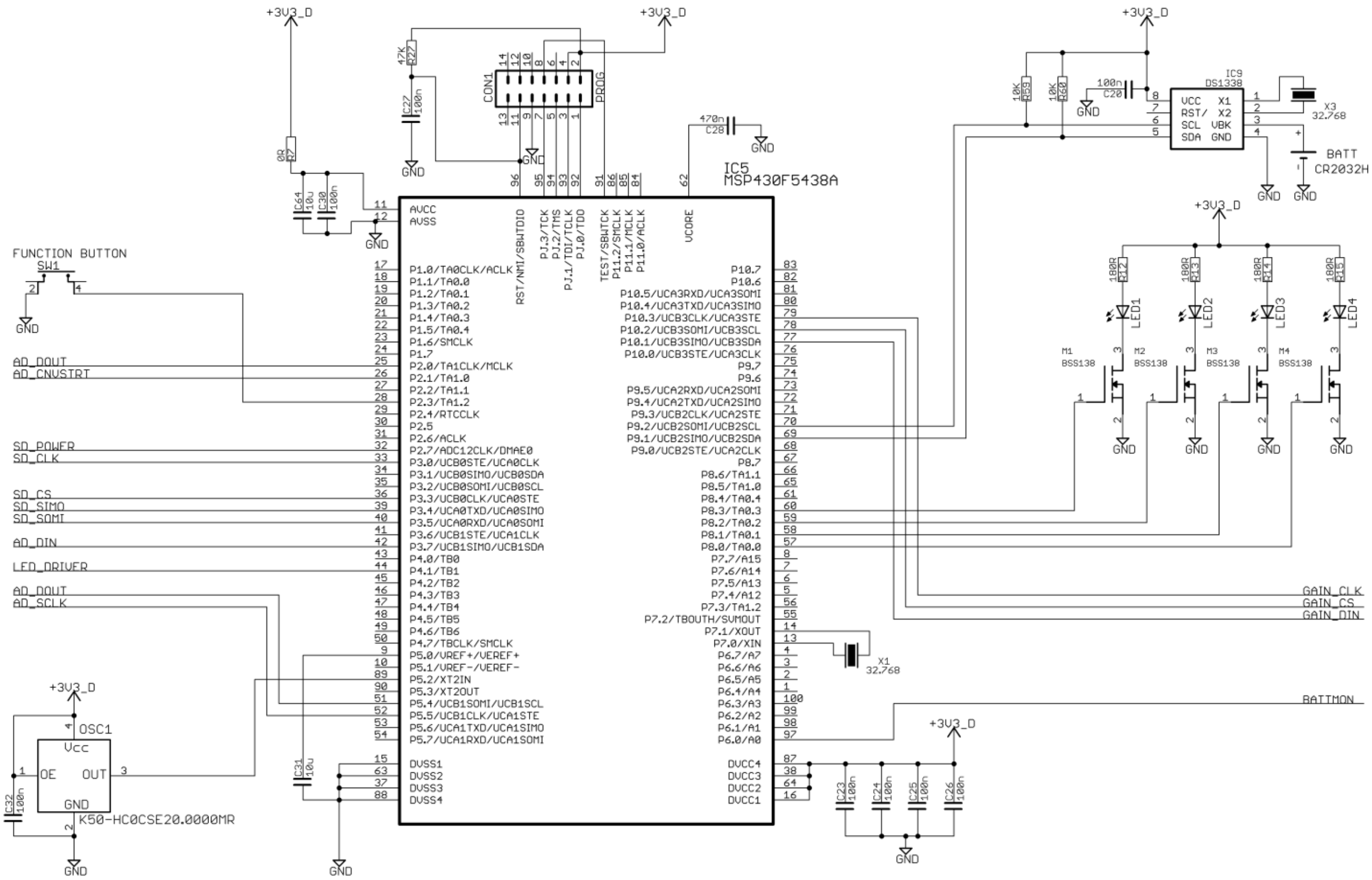

Figure 5. Microprocessor unit. The microprocessor operates at 3.3V and is synchronized by the 20MHz clock provided by the oscillator OSC1. It controls all functions of the recorder: recording to the SD card, controlling of the ADC, the analogue gain before the ADC, the real time clock IC9 that time-stamps detection events, the driving of the LEDs and the user interface through the function button and the status LEDs, named LED1 to LED4.

Optical light guide vs 2D array of diodes

A wide receiving aperture is beneficial compared to a 1D array of diodes because fast flying insects spend more time in front of the receiving surface and therefore, offer more information on the flight process (see Fig. 6 Left-Middle). The 2D has a larger FOV than the configuration presented in [4-5]. As a contrast, in [5] we cover a pyramidal volume with base 3.3mm x 50mm and length 100 mm. In the 2D case of infrared LEDs covers a volume of 70mm x 59mm x 11mm. The light guide is even larger than the 2D diodes' array and has the advantage of not having gaps in the receiving surface except the gaps of the 1D diodes array that receive light from the bottom edge of the light guide. The spectrogram of all insects we examined is slightly smoother in the case of the light guide vs the 2D array. On the other hand the larger light receiving surface makes the system more vulnerable to interferences stemming from electric light. To give an illustrative example: The 2D sensor at 15 cm from a fluorescent lamp did not trigger due to the interference while it was able to detect small object of 1 mm passing its FOV. Even though we use shading for both versions and lower frequencies are suppressed by 50 dB before demodulation the remaining interference can trigger the light guide version if it is very close to a strong electric lamp.

Triggering the recording process

The embedded microprocessor runs a constantly-looping program which processes data captured by the sensors. The board is programmed in C/C++. The line-level output from the optoelectronic sensor is copied to two circular buffers. The first buffer is used to monitor the signal's root-mean-square (RMS) using a window of 128 samples (16 ms in 8 kHz sampling rate). If the RMS of the window exceeds a pre-defined threshold, we call that an event has occurred, i.e. an insect has crossed the sensor's FOV. This triggers the recording of the signal capturing 5000 samples from the second cyclic buffer coded with 16-bit resolution, at 8 kHz sampling rate. 1000 samples are drawn before and up to the triggering point and 4000 after that point in order to ensure that the onset of a wingbeat event is not lost. Wingbeat events are short in time for fast flying insects such as flies and one cannot afford discarding any useful part of the signal such as the onset. The sampling frequency, window length and triggering threshold are pre-stored in the SD-card of the system and the settings (i.e. sampling frequency, triggering level, and record length in samples) are read once from the SD card during powering-on the device.

Figure 6. Sensors and system. (Left) The recorder. (Middle) The light-guide aperture inside a dark box providing shade and sitting on 1D array of diodes. (Right) 2D array of diodes sensor and system in their final position in an insectary cage.

Experiments

We have identified a series of use case scenarios to demonstrate the utility of the proposed system in research studies as well as its effectiveness in the context of practical applications. Regarding basic research we have chosen to carry out a series of experiments that would be very difficult and impractical to be performed manually. Hereinafter, we make use of the time-stamping possibility to derive daily flight activity of insects and the change of their wingbeat characteristics due to the change of environmental conditions. In such experiments we place a large number of insects of a single species in a cage and the recording of their wingbeat occurs the moment they pass through the rectangle of the sensors on a random basis. The size and shape of the sensor is designed is a way that is possible to pass it through the entrance of a normal insectary cage and record unattended for extended periods of time. With a view to practical application we envision that the sensors described here can be embedded in normal traps and can subsequently detect, count, recognize and eventually transmit data regarding the species captured. Depending on the targeting insect (e.g. mosquitoes) traps would include suction through a ventilator that inflicts one-directional flow of flying insects through the system. These counts are invaluable information to assess the status of an outbreak as well as to epidemic models that currently receive their input data from manual counting of dispersed traps.

A case study of very small insects

Culicoides is a genus of 1–3 mm long biting midges. Though small to the point of being invisible to the untrained eye, they are vectors of serious diseases to livestock notably of blue tongue fever. In 2006-2008 there have been huge outbreaks of bluetongue virus in Northern Europe that have caused large economic damages on cattle and sheep [10]. We attempt to study the practical limits of the device in analyzing the wing-flap of such insects with a view to develop detectors of their presence. Note that wingbeat recordings of such small insects would be problematic with microphones and the literature on these insects is scarce to non-existent as regards their wingbeat imprint (see [11] for a notable exception on midges). We have enclosed 10 *Culicoides nubeculosus* in a transparent glass jar and placed the jar in between the emitter and receiver of the optical sensor to record their wingbeat. One can see in Fig. 7 (top) that the signal-to-noise ratio is very high. Wing-flap events are resolved even for this very small insect (7-bottom) and the recordings are clearly audible. One can only admire the flying capabilities of this biological micro-vehicle literary floating on the slightest air stream while beating its wings at a rate of 330 Hz.

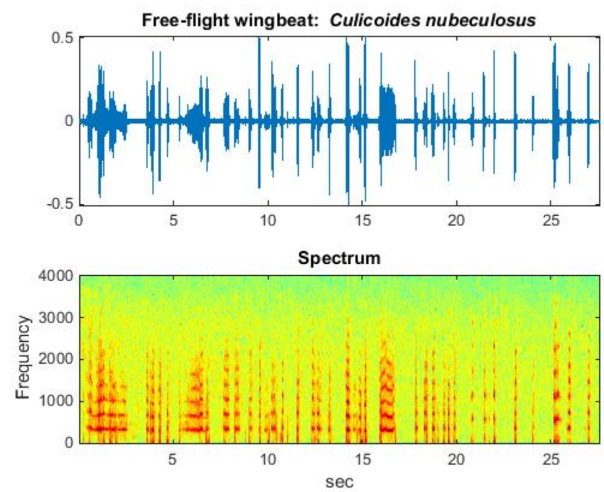

Figure 7. (Top) Ten 1-2 mm long midges (*Culicoides nubeculosus*) in flight recorded with a light-guide. (Bottom) Spectrogram of the recording. The recording is clearly audible and the frequencies resolved. Fundamental measured at 330 Hz.

Analyzing insects of economic importance

Fruit flies such as *Bactrocera oleae* (Gmelin) and *Ceratitis capitata* (Widemann), Diptera of the Tephritidae family effect a crop-loss/per year calculated in billions of dollars worldwide [12]. There is always an interest to study insects of economic importance with a view to mitigating their negative impact. In this study we enclosed in a 20x20x20 cm^3 insectary cage 220 free flying *B. oleae* adults (see Fig. 6 – right). Depending on the insect density of the cage, one can have recorded wingbeats of the order of hundreds to thousands in just few hours. *B. oleae* is ectothermic and increases its wingbeat frequency along with the rise in temperature. It is interesting to study this effect and we show that our setting is practical for carrying out such studies.

We put the cage in a control room with the temperature varying from 15-35 ^oC and we record the wingbeats of the insects. The temperature is increased 5 ^oC/day and after one hour of adapting to new temperature we record wingbeat events for the following 24 hours. Daily mortality incidents are replaced with new alive insects so that the total number remains constant through the five days experiment. Note that the sensor samples the true flight space, therefore, is proportional but not exact to the flight activity. In Fig. 8 we observe an almost linear increase in the wingbeat rate along with frequency. This increase is also confirmed in the Power Spectral Density plots vs frequency Fig. 9 where we observe a gradual shift of the fundamental frequency along with the harmonics with respect to an increase in temperature. At 15 ^oC we observed only 70 flight cases and starting from 35 ^oC and higher very high mortality rates.

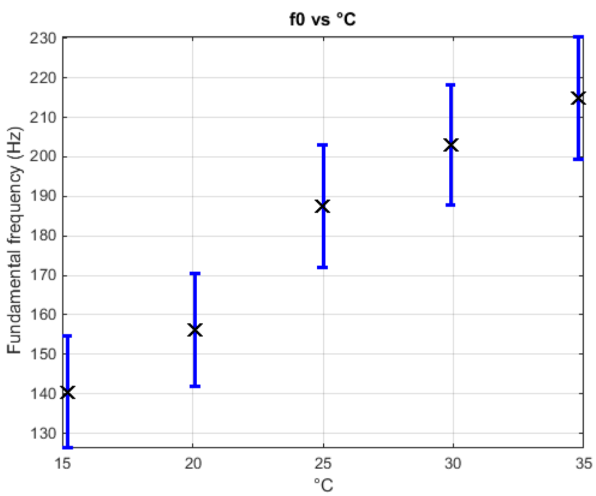

Figure 8. Mean fundamental and standard deviation vs temperature of optical wingbeat recordings of *B.oleae* in flight. The pest is ectothermic.

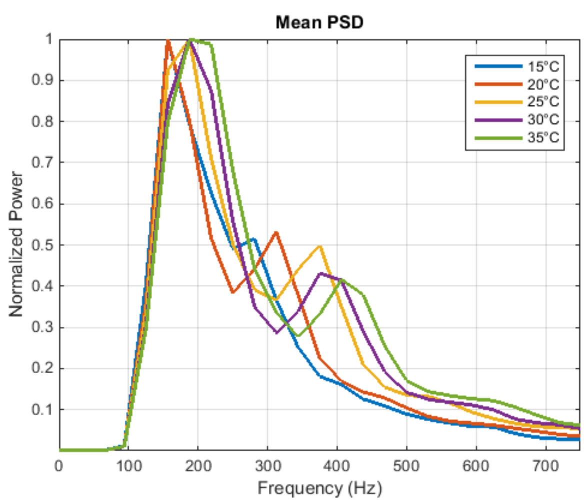

Figure 9. Mean Power spectral density (Welch) vs temperature of optical wingbeat recordings of *B.oleae* in flight. One can clearly discern the frequency shift to higher frequencies as the temperature rises in steps of 5 ^oC.

Analyzing insects of epidemiological and social importance

Aedes albopictus also known as 'Tiger mosquito' is 2 to 10 mm long. It is an aggressive and invasive type of mosquito widely spreading due to its remarkable adaptivity even in cool regions. It is a vector carrier of a series of pathogens and viruses, including West Nile virus, Yellow fever virus, Dengue fever, Chikungunya fever and a suspected competent vector of the Zika virus [13]. We inserted the sensor in an insectary containing 100 adult *Ae. albopictus*. We subsequently derived the daily flying activity pattern of the pest as depicted in Fig. 10. This information can be embedded in probabilistic detectors as an independent source of information and help classifiers discern among similar species but with differences in their activity patterns [14]. A-priori information on insect activity can also be used to plan application of insecticides as the latter ones are effective if they intercept the mosquito in flight.

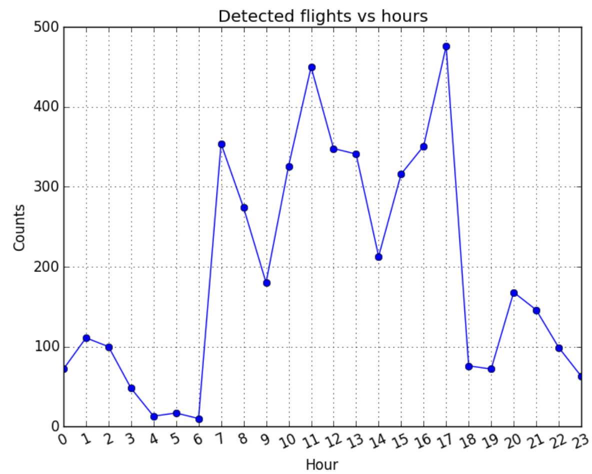

Figure 10. The system time-stamps insects crossing the sensor embedded in an insectary. Per hour flight activity in the insectary derived from about 100 insect monitored for 2 days. Cage includes both sexes, under natural lighting conditions at 24 ^oC, 66% R.H.

In Fig. 11 we analyze the spectrum of a single wingbeat to identify its wingbeat frequency at 620 Hz and clearly resolve its harmonics up to 4 kHz. Subsequently, we take 124 recordings of *Ae. Albopictus* and estimate their fundamental frequency by peak-picking the first harmonic on the spectrum. Then the spectra of the snippets are ordered from lower to higher fundamental and stacked together in Fig. 12 in order to assess visually inter-species wingbeat variability. One can see that the spectrum is quite consistent thus encouraging the automatic classification of mosquito species. Male *Ae. Albopictus* are smaller and thus they have a higher beating frequency. Frequencies below 100 Hz are due to the main body moving through the FOV of the sensor and is the part of the spectrum that is typically dropped in classification tasks. Data used in Fig. 11-12 are taken in a laboratory under the presence of light interference from two fluorescent lamps at a distance of 1.5 m from the device.

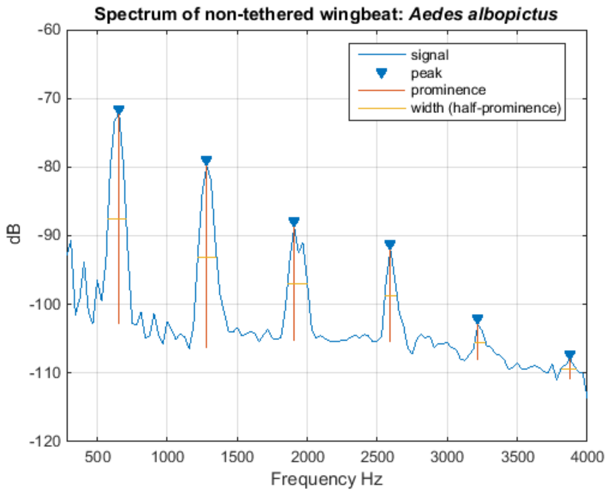

Figure 11. Spectrum of an optical recording of a single *Ae. albopictus* wingbeat in free flight.

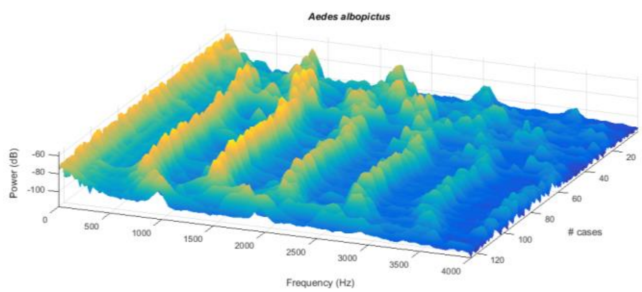

Figure 12. *Ae. albopictus*, both sexes: Spectrum of 124 flight cases stacked together and ordered based on the wingbeat frequency from lower to higher values. Optical recordings using the 2D device in the presence of strong lamps at a distance of 1.5 m. Low frequencies below 100 are due to main body movement. The first line is the fundamental frequency (500-750 Hz). The other wave patterns are the harmonics. The fundamental and the higher harmonics are clearly resolved.

Comparing 2D vs 1D photodiode arrays

In this section we compare the sensor and device reported in [5] with the one presented in this work. First, we experiment with one dimensional arrays (as the one used in [5]) and two dimensional arrays of photodiodes as receivers. We placed 1D and 2D sensors inside the same cage with approximately 100 *Culex pipiens molestus* of both sexes and we take the power spectral density (PSD) of all recordings. We observe a qualitative difference in the spectrum of the signal in favor of the 2D sensors. The 2D resolves better the higher frequencies and we also see that it effects deeper attenuation between the harmonics (see Fig. 13). The 2D array is made by two 1D arrays connected in parallel. The reception area of 1D photodiodes is smaller than 2D. 2D sensors allow for longer recordings, as the insect spends more time in the field of view and allow better tracking of the full wing movement as the effective aperture of a single diode in a 1D array is around 3.5 mm^2.

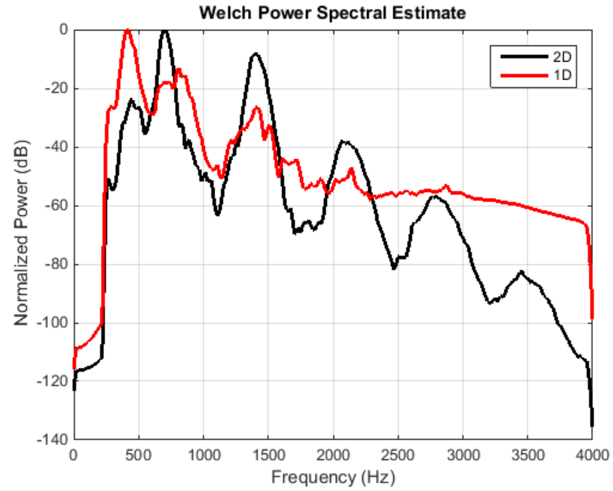

Fig. 13. Power Spectral Density of *C. pipiens molestus* wingflap as measured by a 1D and 2D photodiodes arrays inserted in the same cage simultaneously. Both sensors resolve the fundamental frequency and harmonics of the wing-flap. 2D sensors resolve better the frequency content, especially higher harmonics.

Noise measurements

In Fig. 14 we compare recordings taken with the device reported in [5] (laser version) and the one presented here. The tethered insect we experiment with is the same for both devices namely: *Musca domestica* better known as the housefly, beating its wings at around 200 Hz. In order to compare the noise level of both devices, the recording taken from each device is amplified so that the recorded wingbeat level is almost equal in both devices. The first 60 seconds are recorded with one dimensional photodiodes array and the recorder in [5]. The subsequent 60 seconds are with a 2D sensor and the device presented in this work. One can see clearly that the noise level is much lower (at -115 dB) compared to -85 dB of the device in [5].

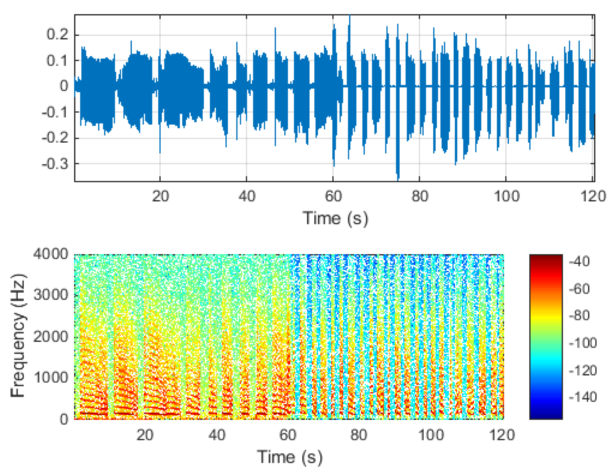

Fig. 14. *M. domestica* tethered. First 60 sec recorded with [5] and the following 60 sec with the new device. (Top) sonogram. (Bottom) Spectrogram. One can note the lower noise output of the proposed device.

B. Discussion

We have constructed a novel system that automatically detects the event of a wingbeat and triggers a recording procedure for flying insects smaller than 1.5 mm. The recording is stored locally in an SD card and in our settings is 625 ms long while the time-stamp is passed to the filename.

Since most insects beat their wings with frequencies <1 kHz and the operating frequency of photodiodes is designed to receive light pulses at 450 kHz -that is far higher than any biological organism can reach with its wings- we conclude that it can track the wingbeat of any insect starting from low frequency Lepidoptera to high frequency midges. The system is immune to physical light. This is important as we do not wish to detect something outside its FOV (e.g. from insects flying over the FOV and modulating the sun light). It is also robust against electronic interference because it modulates emitted light by sending high frequency pulses instead of continuous light, subsequently the low frequencies are suppressed and the modulated by the wingbeat signal is demodulated back in the acoustic range. Therefore, it can be operated in laboratories that use electric light in the breeding and reproduction cycle of insects as well as in the field.

III. Conclusions

We presented a complete system that can optically detect, count and timestamp objects passing its FOV. It is capable of sensing objects <1 mm and can potentially have different applications such as counting of falling beans, small objects or oscillating parts, etc. We have applied it in the context of entomology to auto-trigger and record the wingbeat of flying or tethered insects under variable illumination conditions including artificial light. We believe it fills a gap on automatic recording units dedicated to insects' wingbeat. This choice of sensors permits effortless acquisition of a large number of wingbeat recordings of insects in flight and the automatic analysis of their spectral content. The practical applications that arise in the context of entomology include optical detectors that can alert for potentially dangerous mosquito species presence in sensitive domestic environments (hospitals, elderly nurseries), traps that report counts and species composition of trapped adults and feed wirelessly these data to epidemiological models that monitor the current situation but also predict future outbreaks based on past count and species distribution.

Acknowledgments

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