BatFlash: A Head-Mounted LED for Detecting Bat Echolocation

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***Abstract*—Studies of bat echolocation and flight typically involve microphone array recordings from the ground, sometimes synchronized with video recordings. When multiple bats interact, it is often a challenge to assign a given call to the vocalizing bat. We have designed a lightweight, inexpensive device to display bat-tagged echolocation events using a head-mounted light-emitting diode (LED) that flashes when an onboard microphone detects a high-amplitude ultrasonic pulse. We describe the circuit and demonstrate its functionality in flight on the head of a big brown bat.**

***Index Terms*— head-mounted, echolocation, LED, big brown bat.**

I. Introduction

THE study of bat echolocation has largely been performed on individual bats with a focus on their sensory capabilities, while social interactions and echolocation of groups of bats in flight have been relatively unexplored. Recent work with pairs of bats has shown interesting interactions such as social hierarchy [1] as well as stealthy silent periods [2]. To study the three-dimensional (3-D) trajectories of bats, calibrated camera arrays are used to estimate the 3-D position and body orientation. Echolocation behaviors are studied using calibrated microphone arrays to estimate the head aim of the bat, along with the intensity, timing, spectral and temporal characteristics of the bat's sonar vocalizations. While the bat's position can also be extracted from the microphone data, video recording and analysis is required to track the bat at times when it is not vocalizing.

When multiple bats are studied, the microphone array analysis is significantly more complex due to the need to separate and identify the vocalizations from each bat on each microphone. Signal overlap, attenuation, and propagation delays increase the difficulty of sorting these signals with each additional bat (Fig 1). As an alternative to this hardware and software-intensive approach, we have designed an inexpensive device that is mounted on top of a bat's head that flashes a light-emitting diode (LED) when the bat generates an intense sonar vocalization. This creates a clear signal in the video recording in tandem with the microphone recordings to disambiguate which bat vocalized in each frame. This system allows for synchronized, simultaneous monitoring of the vocalizations of multiple bats using just the camera recording system.

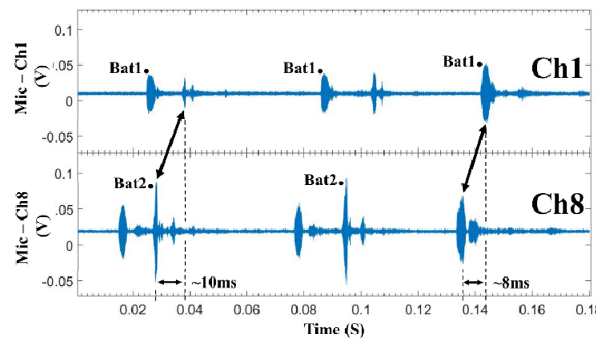

Fig 1. The challenge of separating echolocation calls. In this simultaneous audio recording (channels 1 and 8) of two bats, sound propagation, changing distances and angles create a challenging signal separation problem. Bat 2 is in flight.

In this paper we describe the circuit, discuss design considerations, show test signals, and show initial testing on a free-flying big brown bat.

II. Circuit Design and Physical Packaging

A. Circuit Design

The primary constraints in the design of the BatFlash device were weight, size, and cost. The big brown bat, our intended animal for study, weighs between 15-20 gm and has a head width of approximately 2cm. To avoid problems with the device interfering with normal flight or echolocation behavior, our target weight was approximately 2 to 3 gm (10% to 20% of the bat's weight). To fit on the head, the device must be small enough to fit between the ears on the top of the head with the microphone protruding over the snout as much as possible. To keep costs down, we used commercial off-the-shelf parts (COTS). In particular, we addressed all three constraints by minimizing the number of circuit components used.

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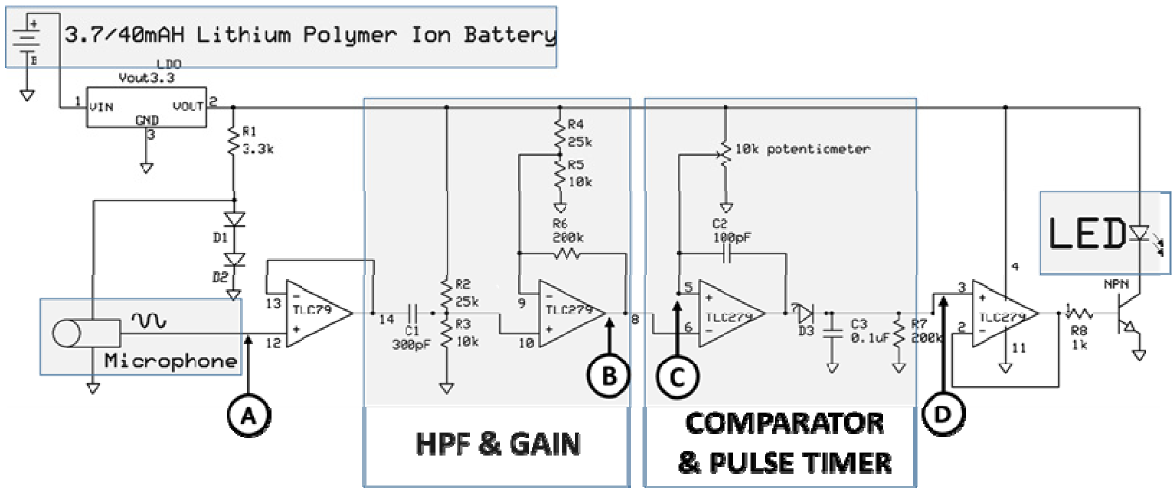

Fig 2. The BatFlash circuit schematic. A small (2.6mm dia.) Knowles microphone (signal point A) is highpass filtered and amplified (signal point B) to detect ultrasonic frequencies. When the signal exceeds a threshold (signal point C), a digital pulse (signal D) is generated that turns on the LED.

Fig 2 shows the full circuit schematic used. A lightweight 40mAh 3.7V rechargeable lithium-polymer battery (P-1S5045BC, Great Power Battery Co., Ltd. Kowloon, Hong Kong) coupled with a low-dropout 3.3V voltage regulator provides a stable power supply needed to maintain performance as the battery voltage decreases during use.

The signal chain starts with a small ultrasonic-sensitive microphone (FG-23742-D36, Knowles Electronics LLC [3]; signal point (A)) that operates on a 1.3V power supply. This voltage is created by using two silicon diodes (D1 and D2) in series from the regulated power supply. This microphone was designed for use in audio applications and has a 40 dB/decade decrease in response above 10 KHz.

After unity gain buffering (Texas Instruments TLC-279 quad op-amp), an RC highpass filter with gain (Bode plot in Fig 3) is used to attenuate the signal below about 4 KHz and counteract the falling gain of the microphone in the ultrasonic frequency range. The DC level of signal point (B) is defined by R4 and R5.

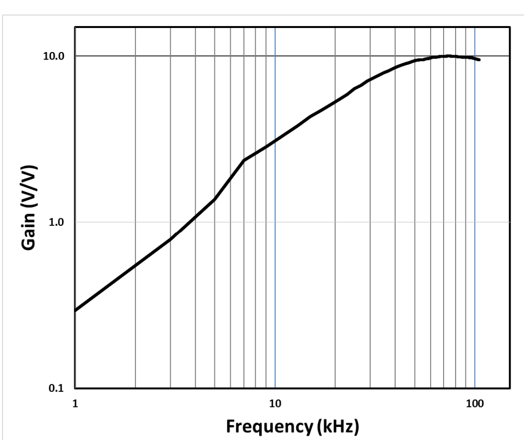

Fig 3. Highpass frequency response used to reject audio frequencies and to counteract the reduction of sensitivity in the microphone above 10 KHz. The highpass cutoff frequency was set at 75 KHz.

The filtered waveform is then compared to a threshold voltage (set by a 10K potentiometer; signal point (C)) using a comparator circuit with dynamic hysteresis (C2). This digital output signal is then passed through a diode (D3) to a capacitor (with a leak resistor, R7; signal point (D)). The capacitor extends the short pulse in time so that there is a minimum LED flash duration. This decaying pulse is then buffered and is used to drive the base of an NPN transistor. In practice, many cycles of the waveform will activate the LED, so the pulse duration will vary with the duration of the sound above threshold.

Changing the value of R7 allows the minimum on-time to be varied. In our experiments we used R7 = 200 KOhms to obtain a 20 ms minimum duration flash and R7 = 50 KOhms to obtain a 5 ms minimum flash duration.

A. Physical Packaging

Fig 4 shows the mounting hardware design for the BatFlash board and Fig 5 shows photos of the physical packaging of the board, battery, and mounting hardware. A thin printed-circuit board process (Epec [4] 0.031" FR4) was used to reduce the weight of the system.

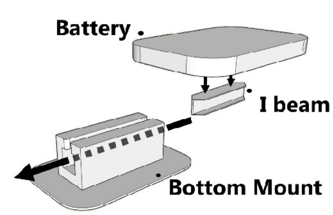

Fig 4. Mounting hardware. The bottom mount is glued to the top of the bat head between the ears.

The mounting hardware (Fig 4) comes in two pieces: the top piece is a plastic I-beam and the bottom piece is a square tube with a slot cut longitudinally along the top face from end to end. This allows the bottom portion of the I-beam to be quickly slid into the slot for a snug fit. The middle of the slot narrows slightly, to create a tight fit. The square tube is glued to a thin plastic sheet that serves as a plate for attaching the system to the bat's head. Being easily separable, the BatFlash board can be removed from the bat's head between uses, leaving just the bottom mount attached to the bat.

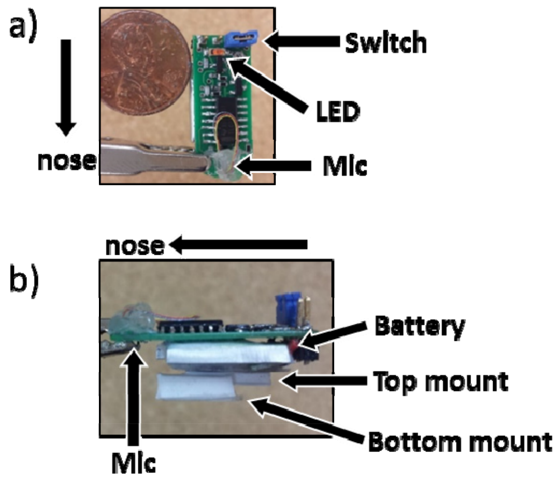

Fig 5. The BatFlash board a) Top view (shown with a U.S. penny). The microphone is located at the nose-end of the board (under a drop of hot glue) with its opening pointed through a hole in the circuit board. A high-brightness red LED is visible near the rear of the board. Also visible is a blue jumper that serves as a switch. b) Side view. The board is mounted on top of the battery and the top portion of the mount is glued to the bottom of the battery. The bottom portion of the mount is glued to the bat's head between the ears. The boards are sprayed with a thin waterproof coating.

The harmonic chirp of a big brown bat echolocation vocalization (Fig 6) has much of its energy in the first harmonic. The peak energy in this example occurs around 30 KHz. This frequency is near the middle of the filtering range where the BatFlash is most sensitive.

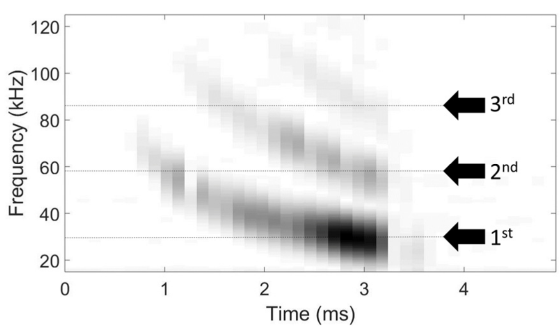

Fig 6. Spectrogram of a typical approach echolocation call from a big brown bat (Eptesicus fuscus).

Fig 7 shows the BatFlash board mounted on a big brown bat in the Moss laboratory. This board weighs 3.0 gm, right at our design specification limit.

To protect the electronics against moisture and incidental liquids, the boards are sprayed with a thin conformal plastic coating.

III. Testing

We constructed two versions of the BatFlash board and mounted them on two big brown bats. One board is configured to have a minimum flash duration of 5 ms and the other is configured to have a minimum flash duration of 20 ms. In the test trial shown in Fig 8, one bat was held in the experimenter's hand while the second bat was flying.

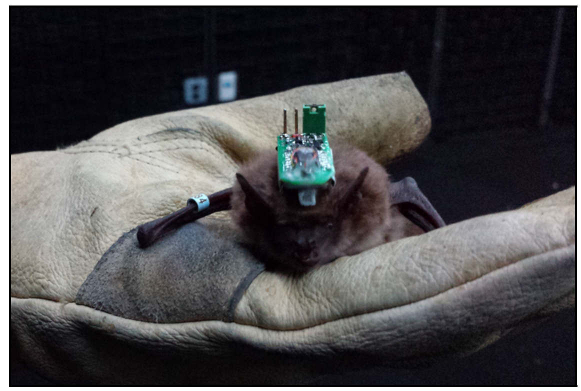

Fig 7. The BatFlash board on a big brown bat. The fur on the top of the head is depilated and the bottom mount is glued (cyanoacrylate) to the skin for secure, but temporary attachment.

Using the audio recorded from the array microphones present in the laboratory during the trial, all LED flashes were verified to correctly match bat vocalizations. Social vocalizations from the perched bat were also recorded and generated LED flashes, but were easily distinguished from echolocation vocalizations. All vocalizations from the flying bat appeared to be typical echolocation calls.

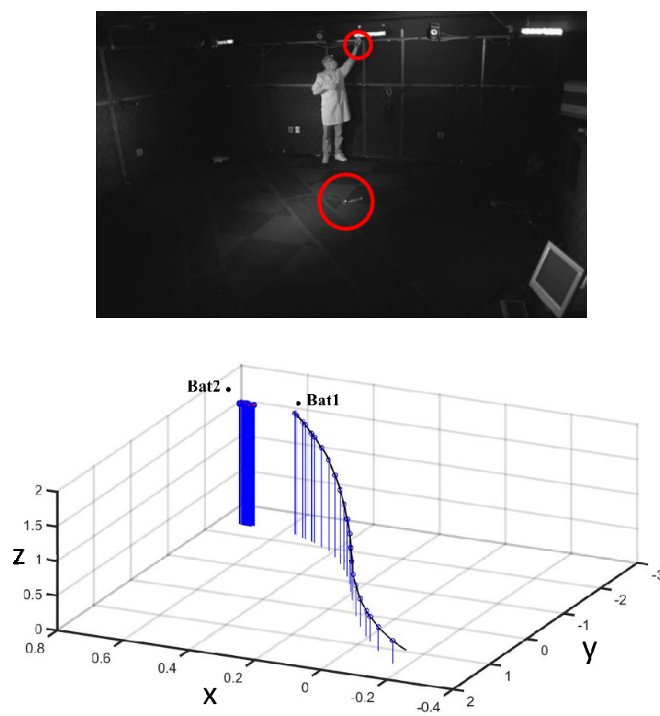

Fig 8. Top panel: video snapshot during a flight trial. Bat 2 with the 20 ms duration BatFlash board is in the experimenter's hand and Bat 1 with the 5 ms duration BatFlash board is in flight. Bottom Panel: Dots and

stems are plotted at locations where the LED flashed in the video reconstruction of the 3-D flight trajectory.

The time and location of the bat and the LED flashes were extracted from the video recordings using semi-automated software developed in the Moss laboratory and custom software developed in the Horiuchi laboratory. By identifying the approximate location of the bat head and measuring the summed pixel intensity over a fixed area, a fluctuating intensity sequence can be obtained. By normalizing and thresholding the fluctuations, LED flashes can be detected. Fig 8 (bottom panel) shows the vocalizations that occurred during the flight of Bat1. In the early portion of the flight, two echolocation calls per wingbeat are seen and verified by the video.

Fig 9 shows a close-up of a microphone recording and the normalized LED intensity sequence from two short periods of a trial in which the two bats are producing vocalizations.

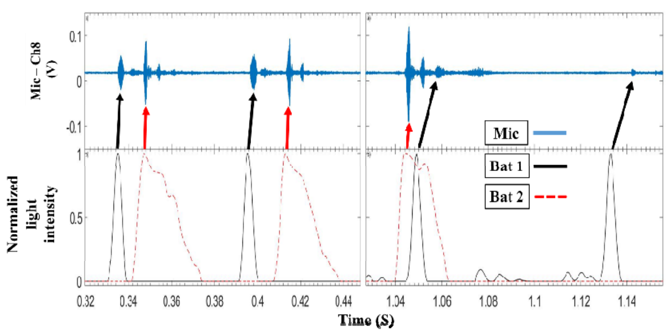

Fig 9. The normalized fluctuations in intensity from the video sequence are compared for the two BatFlash boards. The difference between the 5 ms (black trace) and 20 ms (red trace) duration flashes is evident. In the right panel, overlapping vocalizations highlight one of the strengths of this system.

One observation from Fig 9 (right panel) is that temporally overlapping vocalizations are easily resolved in the video provided that one bat's vocalization does not trigger the other bat's BatFlash unit. With a downward facing microphone close to the bat's mouth, a high triggering threshold, and a quadratically-decreasing $(1/r^2)$ signal with range, this should not be a common occurrence.

Dimensions	1cm x 2.55cm x 1.27cm
Weight	2.7 g
Power Consumption	143 mW when LED on 13 mW when LED off
Input Signal (Freq)	~ 20 to 90 KHz
LED color	Red
LED "on time"	5ms (20ms) see text
Battery	3.7V, 40 mAh LiPo
Packaging	Water-Resistant Coating

IV. Discussion

The described BatFlash circuit successfully met our basic design criteria for weight and size. While the ultimate cost per unit is difficult to estimate, the components for the prototype was approximately $50 (U.S. dollars in 2015) each.

The weight of the current prototype device, while acceptable, could be reduced further by a reduction in the use of solder and hot glue. Further reductions in the printed circuit board area could also be made with more aggressive routing and thinner lines.

One important consideration in the use of the BatFlash device is the need to extract LED flashes from the video. While our current software approach automatically placed the tracking window where the head location is expected, it was necessary for a human operator to approve or adjust the location of the tracking box in each frame. If the head were automatically identified through markers that are now commonly used for animal tracking, it would be relatively simple to automate the detection of the LED flash with high confidence.

The use of bat-mounted sensors has a long history and with significant advances in recent years on battery, computing, and sensor technologies, we anticipate many more such devices in the near future.

Acknowledgment

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