Development of a multisensor array for localizing bats in space

K. Hochradel*, T. Hohler2, A. Becher2, S. Wildermann2, A. Sutor1
1 Institute of Measurement and Sensor Technology, UMIT - Private University for Health Sciences, Medical Informatics and Technology GmbH, Hall in Tirol, Austria
2 Chair of Computer Science 12, Friedrich-Alexander-Universität Erlangen-Nürnberg, Erlangen, Germany
E-mail: klaus.hochradel@umit.at

Abstract. We present a novel multisensor array to track flight paths of bats in space. Our array is designed to be portable and, thus, field applicable. Eight microphones are employed to localize each echolocation call, whereas two cameras provide continuous information on the flight path between the calls. To reduce costs and, thus, make it available for low-budget research the array was developed from scratch including a novel acoustic signal recording and processing hardware. Our developed acoustic hardware is the first system to sample eight microphone channels synchronously at 1 MS/s/CH with 16 Bit resolution without the necessity of computers or laptops. All eight signals from the ultrasonic microphones are not only recorded but also processed in real time in the frequency as well as time domain to determine the existence of echolocation calls. Only relevant acoustic signal are recorded which enables long term deployments of the array. During the acoustic signal acquisition, the system records images of two infrared cameras at 12 Hz and, in addition, several environmental factors such as temperature, humidity and illumination. Recorded datasets can be associated with a global position and time-stamp through a GPS module and matched to the GPS coordinate system with a three-axis accelerometer. The overall system (microphones, cameras and sensors) was designed to be affordable, easy to use in the field on battery power and without the necessity of an additional laptop. Without cost optimization and only small quantity we reached a prize below 1000 EUR for a complete system.

1. Introduction

Hearing and vocalization are the groundwork of communication for animals as well as humans. Hearing is for most animals not only the basis for communication but also vital for their survival which is why some evolved a primary acoustic sense to navigate and hunt in the absence of daylight. This special group of mammals can precisely reconstruct their surroundings. Their biosonar sense is not entirely deciphered and up to date its precision and function cannot be replicated by any technology. Understanding their sensory system might improve man-made sonar systems.

Studying their sonar sense [1] demands different fields of research to work together. Neuro-, social science and engineering together will hopefully decipher this sense. Acoustic engineering allows with the help of ultrasonic microphones to investigate their echolocation calls. Multiple microphones at a priori known locations allow determining even the location of calls by means of their time differences of arrival at the microphones. These arrays of microphones are necessary to understand the sonar

* To whom any correspondence should be addressed.
systems of bats since they enable not only to study the acoustic characteristics of an echolocation call [2] but also to correlate the call characteristic with surrounding parameters [3]. So far, in bat studies microphone arrays are rarely used due to their complexity and the commercial unavailability. Thus, only researchers with access to or knowledge of engineering are able to utilize the benefit of arrays for their research. Consequently, all applied arrays are part of research projects and therewith project developments which are not commercially available. In addition to their unavailability most of the research arrays share further disadvantages, they are either only designed for laboratory measurements [4] or, in the field, an expert is needed [5–7]. This also limits the possible amount of recordings and localizations due to the effort to install and operate.

The kernel of this research is to develop a low-cost and easy to use microphone array for a variety of researches not to present yet another complex research array. To achieve this goal, we developed new hardware and software from scratch. The following article will give a brief overview of the developments starting from the novel microphones and their high performance recording and processing platform. Only having information on the location where each echolocation call was emitted might not be sufficient enough for selected researches [8]. To overcome this limitation we equipped our microphone array with two infrared sensitive cameras which enable visual localization. This offers a whole new set of research possibilities. We can for example study social behavior in the roost where we look (visual) who is talking (acoustical). Also studies on flight behavior can be widened as we can in post processing visually determine the distance to obstacles or structures.

2. Setup

We present in the following a multisensor array consisting of eight ultrasonic microphones and two near infrared sensitive cameras. To achieve a portable and modular system we designed a cross with the microphones protruding out of the cross-plane and the two cameras installed on the same level as the cross (see figure 1). This way it is possible to disassemble the array into a small size package of 500 x 200 x 200 mm (length, width, height). The microphones are designed with respect to minimizing echoes which is also why they protrude out of the cross-plane. All parts are manufactured with precise fitting to reduce possible errors during assembly and to receive reproducibility in the accuracy of the microphone positions.

2.1. Microphones

Microphones currently used for bioacoustic ultrasonic applications are in many cases the Knowles FG type capsules. Larger microphones based on EMFi [8] or electrostatic foils [9] are due to their poor directivity not applicable. The Knowles FG microphones are robust and with a high ultrasonic sensitivity. Nevertheless, they are relatively expensive [10] and their assembly is complicated. Their commercially available housings are large which has negative effects on the signal quality caused by echoes and reflections. To overcome these negative effects and to reduce costs we designed novel ultrasonic microphones based on the silicone microphone SPU0410 introduced by Knowles in 2014. Our microphones feature a minor echoic footprint due to their small diameter of 8 mm. This small housing not only provides space for the MEMS microphone capsule but also includes the amplifier. To ease the use of the microphones with other hardware we equipped the microphone with a standard 3.5
mm audio jack which makes this sensor also compatible with the audio input of standard sound cards on PCs and Laptops.

2.2. Acoustic Signal Processing Hardware

Digitizing the analogue microphone signals produces the majority of costs for microphone arrays. Currently used by researchers are for example multichannel USGs by Avisoft Bioacoustics [10] or general purpose data acquisition (DAQ) cards such as the NI-6356 by National Instruments. DAQ cards have the advantage of lower cost (4000 EUR) but require large amount of programming and electronic knowledge. Specialized multichannel USGs are built for recording echolocation calls of bats and thus easy to use. But they feature high cost of up to 20000 EUR which restricts their usage to projects of larger volume. Additionally, commercial available platforms only cover the recording hardware which leaves the mechanical setup to still be designed.

We present a novel acoustic recording device for up to eight microphones which combines the ease of use advantage of USGs with very low costs of only 500 EUR. To achieve this goal, we had to choose a different approach then commercially available products. Our design criteria were

- ease of use
- usage without laptop
- automatic recording of echolocation calls
- up to date access with any mobile devices
- configurable parameters
- battery powered
- synchronized sampling of eight microphones at 1 MS/s per channel at 16 Bit.

Figure 2: Task splitting on the Zynq 7000 All Programmable SoC

High speed synchronous recordings at 8 x 1 MS/s and 16 Bit without laptop, but still being configurable and deployable in the field demand for new approaches in hardware as well as software development. To achieve the necessary bandwidth and the synchronicity an FPGA (field programmable Gate Array) is the best practice. Disadvantages of FPGAs are their limitations in reconfiguration and their ease of use in the field. The Zynq®-7000 All Programmable SoCs combine Programmable Logic (PL) with a dual-core ARM® Cortex™-A9 MPCore Processing System (PS), fast DDR3 Memory and high-end interfaces like Gigabit Ethernet. Herewith, it was possible to split task between PL and PS. Time-critical and realtime applications are implemented directly on hardware whereas the PS executes all non time-critical and dynamic tasks (see figure 2). The final component of
the acoustic recording setup is ADC board which incorporates eight preamplifiers, eight ADCs of the type AD7980 by Analog Devices and the power supply for the eight microphones.

2.3. Stereo Infrared Cameras
To visually detect and locate bats in the manner of low costs a new approach is introduced based on the highly promoted and supported single board computer (SBC) Raspberry Pi. Adding a infrared sensitive camera, sensors and battery power supply to the offered interfaces transforms the SBC to a measurement unit for the field. The camera board is based on 5MP 1/4" CMOS sensor OmniVision OV5647 and offers to mount cs bayonet lenses. The manual zoom lens T3Z2910CS-IR completed our low-cost infrared camera module for night recordings.

3. Results
Figure 3 illustrates the localization results for one measurement of the visual-acoustical checkerboard pattern with the acoustic position of the 10 speakers ♦ and the corresponding visual position ◆ of the speakers within the pattern. Due to various dependencies, the two independent localization methods lead to slightly differing results. Accuracy of speed of sound, estimation of time differences, mechanically errors in the geometry are all reasons for the discrepancies.

Figure 3. Visual ◆ and acoustical ♦ located checkerboard pattern of all 10 ultrasonic speakers

To quantify the localization errors, we performed several measurements in increasing distances. Figure 4 shows the absolute error over multiple measurements for each distance. As illustrated, the accuracy within the xy-plane seems to be independent of the distance. On the contrary, the error in the z-coordinate is increasing with the distance. We achieved within a room of 6 x 6 m a localization accuracy of ±5 cm in the xy-plane and ±12 cm (75 percentile) in the z-coordinate.

Figure 4. Absolute localization error over all speakers along the z-axis for multiple measurements in various distances; left: 2D-error in the xy-plane with a maximum of 5mm and variation constant over distance; right: error in z-direction with its maximum at 6 m distance and strong dependency of the error on the distance
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