Non-Invasive Low Power ECG for Heart Beat Detection of Bats

Niklas Duda #, Alexander Barthule #, Simon Ripperger *,
Frieder Mayer *, Robert Weigel # and Alexander Koelpin +

#Institute for Electronics Engineering, Friedrich-Alexander-University Erlangen-Nuremberg, Germany
*Museum fuer Naturkunde - Leibniz Institute for Evolution and Biodiversity Science, Germany
+Chair for Electronics and Sensor Systems, Brandenburg University of Technology, Germany
E-Mail: niklas.duda@fau.de

***Abstract*— In this paper a small size low power electrocardiogram (ECG) system which is optimized for the heart rate detection of bats is proposed. Due to the smaller size and different physical properties of animals like bats the system has to fulfill different requirements than standard human ECGs. The usecase of animal monitoring also requires an ultra-low power approach to enable long battery runtime. The described system has been evaluated with measurements on bats and compared to a commercially available ECG integrated circuit (IC). Apart from the ECG circuit itself the electrodes and the electrode position as well as the used algorithms are evaluated.**

I. Introduction

Traditional wildlife telemetry puts its focus on tracking the movement of animals. Recent advances in biologging technology enable the documentation of complementary data on physiological parameters of the tracked individuals on the move. Such rich datasets allow researchers to study the physiological responses of free-ranging animals to changing environmental or behavioral contexts [1]. For large animals there are automated solutions available since there no strict space or energy constraints apply. For small and especially airborne animals it becomes critical to keep the system as small and light as possible to not affect the animals normal behavior [2]. At the same time a long runtime of the system is required to be able to gather information over a informative time frame. Thus other than a focus on size and weight an ultra-low power consumption is necessary.

A key vital parameter is the heart rate because it allows detecting changes in physiological state and estimating metabolic costs of different behaviors, especially when combined with already existing tracking platforms.

In this paper an approach for an ultra-low power and low space electrocardiogram (ECG) system for bats is proposed and evaluated, which shall be applied to study the so far poorly understood energetic strategies of these animals. Current systems require researchers to be close to the investigated animal to receive the heart beat information as analog signals which contain the ECG curve modulated as audio signal and can only track a small number of animals at the same time [3]. The proposed system allows future integration of ECG measurements in wireless sensor tags like for example the sensor tags developed in the BATS project [4] and thus combining location tracking with physiological parameters. Contrary to existing methods this ECG system does not require any implants and thus greatly reduced the impact and stress of the investigated individual. Also the non-invasive approach greatly simplifies the usage of the system in the field.

II. ECG Design

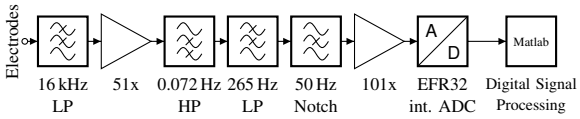

Fig. 1: ECG Signal chain

Other than in medically used ECGs for humans this design can be simplified by omitting parts like overvoltage protection against defibrillation or a galvanic isolation. In exchange here a focus on ultra-low power and low size/weight is crucial for the later application. An overview of the signal processing chain is shown in Fig. 1. In the following the single parts will be described in detail.

A. Electrodes

Gold plated copper plates in the size of 1 cm x 1 cm have been used as electrodes. The results are similar to common Ag/AgCl electrodes used in medical ECGs for humans. Thus, because of simpler handling and lower cost the gold plated copper electrodes are preferred. As electrolyte the gel Tensive from Parker Laboratories (Fairfield, NJ, USA) was used. This combines the conductive effect of standard ECG gel with an adhesive effect so that no additional measures of fixing the electrodes at the bat have to be considered. At the same time is it water soluble and thus has no long time impact on the animal since it can easily be removed after the measurements.

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This system only uses two electrodes compared to three or more in human ECG systems. One is attached below the shoulder blades, the other one at the lower back of the bat. These positions have been selected because these are areas with relatively little muscle structure but still frame the heart. At the same time these positions also don't interfere with the bats as for example electrodes attached to the wings would, that correspond to typical human ECG derivation positions. The position of the electrodes is seen in Fig. 2. Before attaching the electrodes the fur of the bat has been trimmed at the according positions for better skin contact.

Fig. 2: Electrodes attached to bat

B. Analog Frontend

The analog circuit used in this work is based on [5] and adapted to the special usecase of heart rate monitoring of bats. This includes a small size setup and ultra low power constraints.

In the electrode interface a light prefiltering is performed with a simple RC filter to suppress any radio frequency (RF) noise above the cutoff frequency of around 16 kHz. Using a LC filter would reduce the insertion loss. However, at such low frequency the inductivity would get too big to implement in the required small dimensions. While a higher resistance value would decrease the cutoff frequency and suppress more noise it also would lead to higher signal attenuation. Increasing the capacitor values for a better noise filtering is not feasible since a higher capacitance would reduce the input impedance to much [5]. Thus, the frequency of 16 kHz has been selected as for the first filter.

Afterwards, the signal gets amplified by the factor 51 and low pass/high pass filtered between 0.072 Hz and 265 Hz. This blocks any DC offset and limits the bandwidth for the following amplifier while keeping the major frequency components of the QRS complex. As operational amplifier STMicroelectronics TSU111 are used due to the small footprint of 1.2 mm x 1.3 mm and a low current consumption of 900 nA. The common mode rejection ratio (CMRR) of the chosen operational amplifier for a 50 Hz noise can be calculated with the formula derived in [5]:

$$CMRR_{eqv.}(f) = 20\log\frac{GBP_{OPA}}{f} = 20\log\frac{10\,\mathrm{kHz}}{50\,\mathrm{Hz}} = 46\,\mathrm{dB}$$

This is far lower than the recommended CMRR value for human ECG system of 100-120 dB [6]. However, because of the small body size of bats and and since bats are usually investigated in their natural environment rather than in vicinity of human infrastructure the impact of a 50 Hz powerline noise is limited which makes a low CMRR acceptable in most situations. To at least achieve a basic 50 Hz noise suppression for situations when bats are close to 50 Hz noise sources an active 50 Hz notch filter has been implemented. This way before the final amplification stage unwanted parts of the signals are removed resulting in a higher signal quality at the output. After preprocessing the signal, it is amplified by the factor 101 to use the supported voltage range of the ADC as good as possible.

C. Digitalization

To digitize the ECG signal the integrated ADC of the SoC Silabs EFR32FG is used. The sample rate is 100 kSps with a resolution of 12 Bit. While a sample rate of 500 Sps should be sufficient to comply with the Nyquist Shannon sampling theorem a higher rate was selected here during the field tests to get more flexibility for the following digital post processing and allow increasing the available resolution by oversampling. For simplicity reasons the quantized signal then is transmitted via USB to a computer for signal processing in Matlab. A further version could implement the data transfer wireless to allow an airworthy design.

D. Algorithms

To derive the heart beat frequency from the recorded ECG signal a simple threshold algorithm and a modified Pan/Tompkins algorithm have been implemented. Both allow heart beat detection and are sufficient for the desired use case of detecting the heartbeat of bats. However, both algorithms react sensitive to noise and require a plausibility check. By setting close constraints for the heart beat like maximum and minimum values and maximum change of the heart rate, faulty measurements can be detected and the error rate can be reduced. This way periods with missed peaks or falsely detected peaks which results in a sudden jump of the heart rate can be avoided. The appropriate values for this kind of plausibility checks have to be tailored to the specific species that should be investigated. In addition, it is feasible to combine the algorithms and discard values with a too high spread in the results. This way, failures of one of the algorithms can be detected and the results ignored.

The threshold based algorithm (Fig. 3) simply analyzes the amplitude of the signal and counts each value above

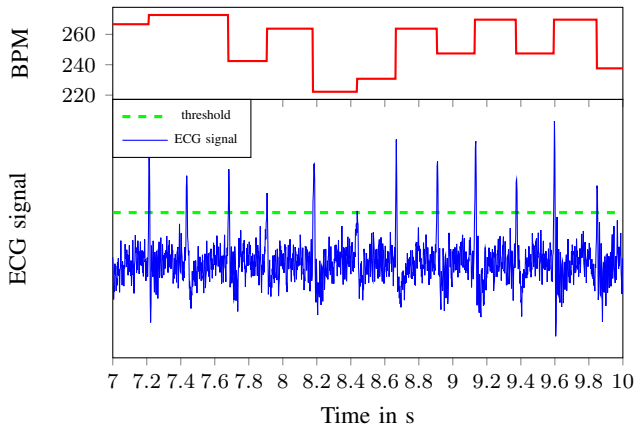


Fig. 3: Threshold analysis of bat ECG signal. The calculated pulse varies in the shown extract between 220 bpm and 270 bpm. The mean pulse value is 254 bpm with a standard deviation of $\sigma = 16.75$

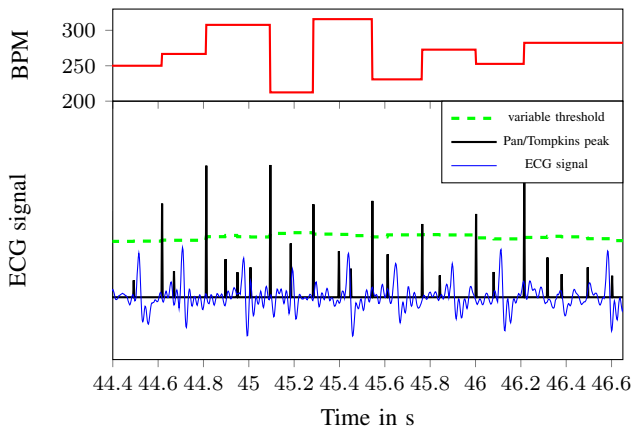
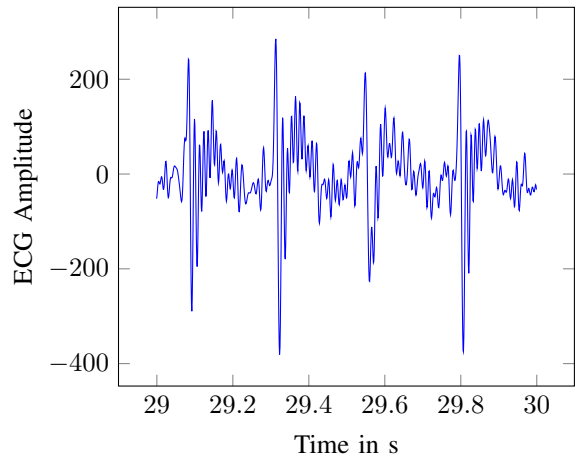
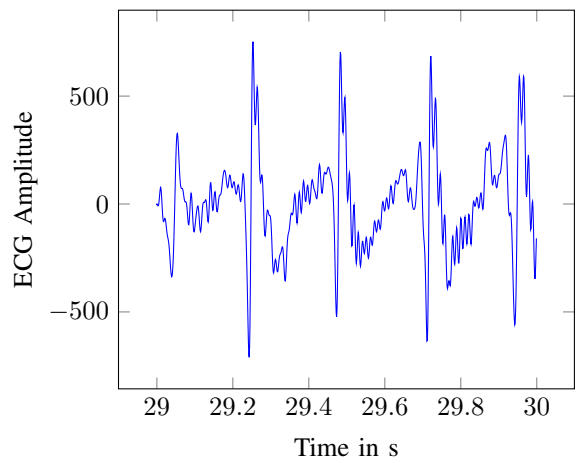


Fig. 4: Pan/Tompkins based heart rate detection. The calculated pulse varies in the shown extract between 210 bpm and 315 bpm. The mean pulse value is 270 bpm with a standard deviation of $\sigma = 30$

the threshold as QRS complex and thus as heartbeat. The Pan/Tompkins algorithm [7] (Fig. 4) works by looking for the characteristic steepness of the QRS complex. The parameters of the algorithm are adapted to the specific characteristic of a bat heartbeat. This includes a down sampling of the ADC data to 400 Sps and a filter low pass filter frequency of 45 Hz with a high pass filter frequency of 2 Hz. The moving average filter is set to a window size of 20 samples, which equals 50 ms. This is approximately the duration of one QRS complex. These parameters have been determined by optimizing the algorithm for the recorded data. Both shown windows in Fig. 3 and Fig. 4 are chosen after discarding zones with too extreme heart rates or heart rate changes.



(a) Discrete Circuit



(b) ECG IC with static reference voltage

Fig. 5: Measurement results of a Nyctalus noctula bat with gold plated copper electrodes attached to lower head and lower back

III. Field Test Results

During field tests in Berlin, Germany the proposed ECG system has been evaluated on bats. For comparison a commercial ECG integrated circuit (Analog Devices AD8232) has also been implemented. The commercial integrated solution draws a current of 148 µA while the proposed discrete circuit only draws 28 µA. This current only covers the analog ECG frontend and ignores the digitalization process since both implementations require the same digitalization and data processing. The low power consumption of the discrete solution is achieved due to using low power amplifiers as well as reducing the complexity and performance of system architecture as much as possible while still being able to record good enough data.

The results of measuring the ECG signal is seen in Fig. 5. Subfigure (a) shows the discrete ECG circuit,

subfigure (b) shows the commercial integrated ECG. All measurements have been performed on the same animal of the species Nyctalus noctula with the same electrodes at the same position to allow comparison. The ECG signals have been measured for 60 s with a 1 s frame being shown here. During the measurements a heart rate of around 250 bpm was measured which matches daytime resting heartbeat of bats [3]. This matches the observation of the bat which had a calm, torpor-like behavior during the whole measurements.

The commercial ECG IC leads to a slightly better signal compared to the discrete ECG circuit. While the signal of the discrete ECG circuit is slightly more noisy it still shows recognizable QRS complexes. Thus, both solutions are sufficient to derive a heart rate.

For that a Pan/Tompkins like algorithm or a simple threshold algorithm can be used. However, both algorithms easily can return extreme values or extreme changes in values which have to be detected and discarded during post-processing. Especially noise from movements of the ECG electrodes has a negative effect on the algorithms and results into faulty measurements. Movement on the electrodes also lead to periods with no recognizable signal due to excessive noise and bad contact between the electrodes and skin. Also the lower amplitude of the ECG signal compared to humans is a reason for the lower heart rate assessment quality. While the algorithms are not applicable for highly precise heart rate measurement because of noise, mean values of the resulting heart rate can be used to perform a classification of the bats behavior. This is possible due to the relative high spread of the heart rate of bats between 173 to 1066 bpm across a day depending on the current activity [3].

Although both circuits lead to satisfying signal quality, the discrete circuit draws considerably less current. Since the ECG IC still requires external components the required size for both solutions can be considered similar with no strong benefit for either solution. However, since the discrete circuit is composed of multiple small components it can be arranged flexible depending on the available space in the desired application. The whole discrete ECG frontend circuit can be implemented in less than 35 mm^2 using 0201 passive components.

IV. Conclusion

Contrary to state of the art systems for bat heart rate monitoring like the SP2000 HR Sparrow Systems used in [3] the proposed system allows non-invasive ECG measurement. This results in much easier handling in the field since it doesn't require any implants in the investigated individual and thus lowers the impact on the animals. Also while the SP2000 transmits an analog long wave signal that requires a receiver constantly in range and the user to derive the heart beat from a modulated audio signal the proposed system digitizes the ECG signal which allows easier storage and transmitting of the information. This enables solutions that can automatically record and store the data locally while a receiver is not in range. The small footprint and energy consumption of the circuit allows integration in wireless mobile sensor nodes like the sensor tag used in the BATS project [4].

The lower power consumption and the possibility of a more flexible layout while maintaining a similar signal quality makes the discrete solution preferred over the integrated one. The digitalization of the data transmission as well as the support of non-invasive measurements makes the proposed system preferred over previous ECG system with similar use cases.

Acknowledgment

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