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Development of a batteryless VHF-Beacon and tracker for mammals

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Abstract. In this paper, we present the design, set-up and testing of a fully energy-autonomous wildlife tracking collar that is supplied by thermoelectric energy harvesting from the animal's body heat. Attached to the neck of a mammal, the device determines the animal's activity, body-temperature and its own energy state. The data is then transmitted in regular short beacons which are also used for triangulation of the animal position. The characterization in laboratory and a field test show that the system design with an ultra-low power switch and a low-voltage step-up-converter with over 42 % efficiency is capable to measure and transmit continuously in intervals of 25 s.

1. Introduction

Wildlife telemetry systems can help here and are one of the most common practices. A subclass of these systems uses relatively simple very-high-frequency (VHF) transmitters that are attached to the animal. A typical tracking collar (e.g. [1]) sends pulses for radio bearing and also encodes temperature or activity into the transmitted signal. Wildlife monitoring becomes more and more urgent in a human-affected world where changed environmental conditions could lead to imbalances in the population of different species [2]. To prevent harm on humans and environment, understanding and monitoring the habits and needs especially of endangered species is one of the main challenges to integrate wildlife. To fulfill this task, typically information on the position, temperature and activity of some tracked animals is required to derive i.e. the migration path or mortality. A drawback of these devices is the limited lifetime of the included batteries. A promising technique is energy harvesting (EH) to get rid of these. Tracking systems that rely fully on energy-harvesting and are carried by the animal still do not exist yet. This paper presents a fully energy-autonomous VHF tracking system that also gathers vital data from the animal carrying it. Section 2 describes the used components and optimizations that were done. In section 3, the performance of the system is determined in the laboratory and in a field test.

2. Design of the system

With the developed system the most common variables such as position, activity and temperature of the animal can be retrieved. The necessary device is directly attached to the animal as a collar. The gathered data is stored internally and sent wireless to a mobile base station as well. The position of the animal is determined via radio bearing used for triangulation. The whole system is powered by thermoelectric energy harvesting only, using the animal's body as a heat resource. The following sections describe in detail each part of the system.

2.1. Energy-harvesting

Our targeted animals are mammals that produce heat, leading to a temperature-gradient between skin and the environment. When a collar is attached to the animal, a certain heat accumulation occurs at the inner side of the collar. Out of this temperature gradient, electric energy can be gathered via a thermoelectric generator (TEG) mounted through the collar. An early prototype has been built and is described in [3], using a small TEG (TEG 083-230-07, Thermalforce) with a footprint of only 18 x 21 mm^2. A field test of this TEG on a sheep is also described in [3], where a mean temperature difference of $\Delta T_{AVG} = 1.5$ K was found. The system presented here uses a similar design, but includes all electronics and now three TEGs in one housing with outer dimensions as shown in Figure 1 and inner parts in 4. The total Seebeck coefficient of the used three TEGs, in a serial electrical connection, is $\alpha = 63\,\mathrm{mV/K}$. The total internal resistance of the three TEGs is $10.8\,\Omega$. At a realistic temperature difference of $\Delta T = 1.5$ K applied to all three TEGs, this results in an open circuit voltage of $V_{OC} = 95$ mV. Up-conversion is needed to bring the voltage to usable values. This is done with a special low-voltage step-up converter described in [4] and improved acc. to [5]. This converter is self-resonant using a transformer-based Meissner oscillator for start-up and a forward converter for higher efficiency convertion. It has, on purpose, a non-regulated output voltage that directly depends on the magnitude of the input voltage and the output loading conditions. The turns ratio of the transformer was chosen such that a usable output voltage of $V_{OUT} = 2.8$ V is reached at an applied $\Delta T = 1$ K at the TEGs at the system's maximum power point, with a supposed efficiency of the step-up of 50% with a starting point at $\Delta T = 0.6$ K.

After up-conversion, the energy is used to charge a 10 mF supercapacitor (BZ05CA103ZSB, Best Cap). A comparator turns on/off the system when reaching certain voltage levels and acts therefore as deadlock protection and power management unit. A very low-power design was chosen for this according to [6]. The voltages for turning on/off the system are set to $V_{ON} = 2.5$ V and $V_{off} = 2.2$ V.

2.2. Microcontroller and sensors

An ultra-low power microcontroller (MSP430FR5969, TI) controls the attached transmitter, two temperature sensors (LMT70A), an accelerometer (ADXL362) and can read out the voltage V_{Cap} of the supercapacitor. The temperature sensors are embedded on the hot and cold side of the TEGs, for determining ΔT. All data is internally stored in a FRAM, which has a capacity for 6400 values. This data can also later be accessed via a built-in programmer interface. Additionally, the data is sent via the wireless transmitter. The duty-cycle for measuring and sending the data is set to a fixed rate. During the inactive time t_{sleep} energy is harvested for the next run. If this time is too short, the comparator will switch off the whole circuit until enough

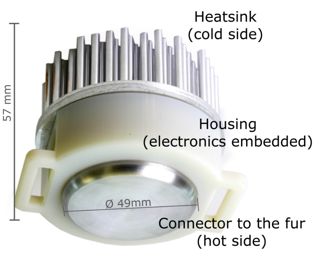

Figure 1. Left: Housing of the tracker with components and dimensions.

Figure 2. Middle: The device attached to the neck of a sheep with a collar.

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energy is gathered. The necessary sleep-time dependents on the power income P_{input}, and energy consumption for the measure task $E_{measure}$ and the wireless transmission. Equation 1 predicts the necessary sleep time based on the transmission time $t_{transmit}$, the systems supply current I_{TX} during wireless transmission and the supply current I_{sleep} during the system's power-down time, all at the supply voltage U_{DD}.

$$t_{sleep} = \frac{E_{measure} - P_{input} \cdot (t_{measure} + t_{transmit}) + I_{TX} \cdot t_{transmit} \cdot U_{DD}}{P_{input} - I_{sleep} \cdot U_{DD}} \tag{1}$$

2.3. Wireless Transmission

For maximum flexibility the encoding of the packages was completely done by the microcontroller modulating the transmitter with a simple On-off keying (OOK) scheme. For our system we have tested two Transmitters: The first one transmits at 150 Mhz and is a one-transistor, crystal-controlled RF transmitter according to [7], however modified as described in [3]. The second is a standard 433 MHz AM transmitter. One full data package consists of 8 bytes. It includes a preamble of 4 bit, a device address of 8 bit, two temperature values and the voltage (i.e. charging state) of the supercapacitor, with 12 bit each, and finally the data of a two-axis accelerometer with 8 bit each. This package is manchester-encoded and then send via OOK.

At the receiver side, a HackRF 1 with an omnidirectional antenna (SRH-789, DIAMOND) was attached to a computer. The filtering and decoding was completely done in software (GNU Radio), which has the advantage of great flexibility.

3. System evaluation

3.1. Laboratory tests

To test the efficiency of the step-up converter, its input terminal V_{in} was attached to the three TEGs, whereas the output terminal V_{OUT} was directly connected to the 10 mF supercapacitor. The supercapacitor was pre-charged to V_{off}= 2.2 V at which voltage the system would have been turned off by the comparator. A defined temperature gradient ΔT was then applied to the TEGs. The time interval for charging the supercapacitor to the system's turn-on voltage V_{on} was measured. The efficiency is determined by the mean output-power and the theoretical power of the TEGs at the given temperature for the maximum power point.

Figure 3 shows that the maximum efficiency of 42% is reached at ΔT =1.1 K with an usable output power of 44 μW. This is a quite remarkable result for such low input voltages, especially as the measurement setup does also take discrepancies like the leakage current of the supercapacitor and the changing working range within V_{on} and V_{off} into account. This performance therefore should not differ much in the field tests.

Table 1 shows the characterized current consumption of the main system. Together with the predicted input power P_{input} after the step-up converter, Equation 1 can be used to predict the necessary sleep-time for the system. To verify Equation 1, the duty-cycle of the tracker was set according to the predicted sleep-time at the applied ΔT, thus for the calculated P_{input}. As expected, the tracker was able to keep that duty cycle, and also did not gain any additional energy. Therefore Equation 1 is proven to determine the minimum duty cycle in a sufficiently correct way.

Table 1. Duration an energy consumption of the different system tasks

Task	Energy /μJ	Duration /ms	Power /μW
INIT	0.01	0.03	445
SLEEP			1.25
MEASURE	10.05	10.2	988
TX_{433MHz}	1102	128	8610
TX_{150MHz}	990	512	1935

3.2. Field tests

For a real field test, the device was attached to the neck of a sheep as shown in figure 2. This sheep was kept grazing freely during the week of the experiment in July 2017. For the test, solely the 433 MHz RF transmitter was used. The receiver station was located at a shelter for the sheep. Beside that, a mobile receiver was used for radio bearing and short-term data collection. Unfortunately, the receiver-sensitivity at the base-station was too low to receive data continuously for the whole grazing area. As the sheep preferred to come back to the shelter rarely, data aggregation was difficult. However random inspections with the mobile receiver showed that the system was working and sending data packages approximately every 25 s a package. That interval would match to a $\Delta T \sim 1.2$ K.

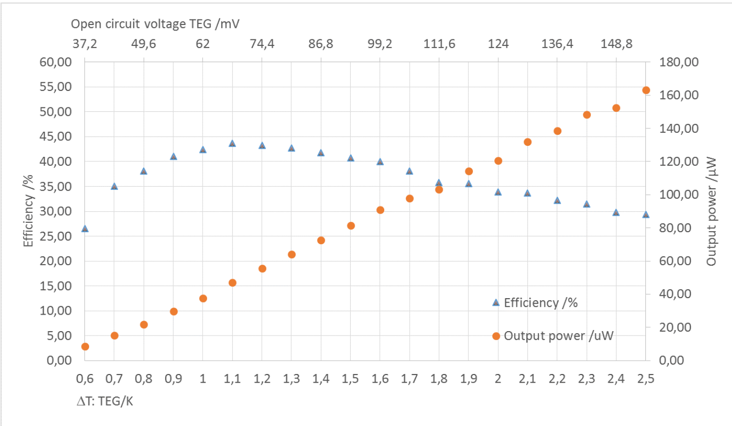

Figure 3. Output power and efficiency of the system's step-up converter as a function of the temperature difference ΔT present at the TEGs

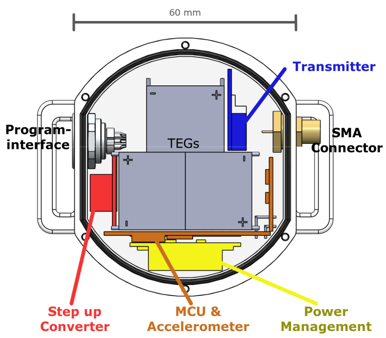

Figure 4. Top view of the tracker – around the three TEGs, the electronics are embedded into the housing

4. Summary and conclusion

We have realized a batteryless VHF tracker that can be used for radio bearing and for monitoring temperature and activity of an animal. This device solely runs on the energy gathered by thermoelectric energy harvesting from the animal's body heat. An improved and fitted design of a low-voltage step-up converter reaches an efficiency of over 42 % in the circuit with an output power around 40 μW, which is enough to supply the systems's microcontroller and all peripherals. Field tests on a freely grazing sheep show that the expected performance is fulfilled with a beacon-interval of about 25 s. To get lower intervals down to 5 s, which is a common value for battery-supplied systems, energy could be saved by sending reduced data package sizes. As the gathered data is normally not necessary in this granularity, short packages could save 90 % transmission time and energy.

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