Thermal Energy Harvesting from Wildlife

P. Woias, F. Schüle, E. Bäumke, P. Mehne, M. Kroener
Laboratory for Design of Microsystems, IMTEK, University of Freiburg,
Georges-Koehler-Allee 102, 79110 Freiburg, GERMANY
E-mail: woias@imtek.de

Abstract. In this paper we present the measurement of temperature differences between the ambient air and the body temperature of a sheep (Heidschnucke) and its applicability for thermoelectric energy harvesting from livestock, demonstrated via the test of a specially tailored TEG system in a real-life experiment. In three measurement campaigns average temperature differences were found between 2.5 K and 3.5 K. Analytical models and FEM simulations were carried out to determine the actual thermal resistance of the sheep’s fur from comparisons with the temperature measurements. With these data a thermoelectric (TEG) generator was built in a thermally optimized housing with adapted heats sink. The whole TEG system was mounted to a collar, including a data logger for recording temperature and TEG voltage. First measurements at the neck of a sheep were accomplished, with a calculated maximal average power output of 173 µW at the TEG. Taking the necessity of a low-voltage step-up converter into account, an electric output power of 54 µW is available which comes close to the power consumption of a low-power VHF tracking system.

1. Introduction
Today, wildlife monitoring is a subject of increasing interest from several reasons: Climate change as well as human intrusion into natural habitats and stopover sites takes a growing influence on migration paths, times and routines of migratory species. Some theories predict even a disappearance of animal migration [1] with drastic effects on ecology and human environment. On the other hand we see a growing intrusion of wildlife into densely populated areas, and, with that, the general necessity to combine human and wildlife environments in a suitable way (see e.g. [2]). Endangered species have to be tracked from obvious reasons. Also, livestock farming over large areas is essentially based on a wildlife-like migration, i.e. migration paths and actual positions of herds have to be monitored with a minimal amount of cost. Additional interest is on the retrieval of relevant physiological data and behaviour of livestock, as an indicator of e.g. grazing behaviour, medical condition and fertility [3,5]. This is also the scope of recent studies on an environmentally triggered behaviour of livestock, to be used as an indicator for impending natural disasters [4] or environmental catastrophes.
In all these scenarios one main challenge is to develop suitable methods and equipment for long-term observations of animals. While several more or less indirect methods (e.g. regular hunting, wildlife observation and counting) are available, position sensing with GPS transmitters - typically fitted on collars - is the most used method hereof [5]. As these systems are battery-powered today, their operational lifetime is limited and, in addition, determined by their functionality. Exhaustion of the battery requires a replacement of any collar. For that purpose the collared animal has to be found, trapped and, if required, sedated, with a considerable amount of time and cost. From ethical reasons a collar should be removed from the animal after its time of service. This can be accomplished via
automatic release buckles that leave, however, the collar in the natural environment and require a cost-intensive recovery. Other concepts try to save on battery power via a drastic reduction of all wireless communication. Instead, acquired position data are stored in the collar’s internal memory and accessed after removing the collar from the animal or after recovery from its release position.

Having all drawbacks of battery-based systems in mind, energy harvesting can be considered a reasonable alternative or addition to supply a wearable tracking system continuously with electric power. Among all conceivable concepts of energy harvesting (solar, motion, force,...) thermoelectric energy harvesting turns out to be advantageous from several reasons: (1) In almost every situation we may find small temperature differences between the body of an animal and ambient air, water, snow or ground. We have already shown in a previous study that harvesting from temperature gradients of only 1 K allows operating a wireless sensor node (WSN) with a low power RF interface [6]. (2) Mammals, frequently the target for wildlife tracking, regulate their body temperature thus providing a reliable heat source or sink (3) Motion as well as solar energy harvesting do heavily depend on animal activity and nesting behaviour which may be irregular and non-reliable for energy harvesting.

While thermoelectric energy harvesting for human applications is the focus of several publications [7,8] animal-based TEG systems are not found in literature. Therefore we have conducted a study with a small generator system to get deeper insight into these specific requirements and the potential of thermoelectric energy harvesting on smaller wildlife. To mimic the conditions of wildlife as close as possible all experiments were performed on a freely grazing sheep (“Heidschnucke”).

2. Temperature measurements:

Experimental set-up, equipment and results

In a first series of experiments the temperature difference between the animal and ambient air was determined. The corresponding measurement system uses two coin-sized temperature data loggers (DS1922L, Maxim). The data loggers were calibrated before use with a Pt 100 temperature sensor system as a reference. Two data loggers with almost identical calibration curves (deviation between 0.054 K and 0.069 K) were mounted onto both faces of a 20 mm wide nylon collar. The measurement interval and temperature resolution of both data loggers was set to 300 s and 0.0625 K, respectively. Fig. 1 shows, as a typical result, the temperatures at the inner and outer side of the collar over a period of 24 hours in May 2014, starting at midnight. In addition, temperature data of local weather observation are added to the graph. In this measurement graph the average temperature difference over the collar is 3.79 K. The slight fall of temperature during the day is reflected in the temperature data obtained from the sensor at the collar outside. In a first measurement run an average temperature difference of 2.5 +/- 0.39 K was found over a period of 14 days. As detrimental effect a certain heat feed-through from the inner side of the collar to the outer side could not be neglected. Moreover, it was observed, that the collar moved freely around the sheep’s neck, which lead to variations in temperature. Therefore a bell was added to the collar in a second and third 2-week measurement period to keep the data loggers constantly in the same orientation and in close contact to the sheep’s neck. As a result higher temperature differences of 3.53 +/- 0.33 K and 2.99 K ± 0,353 K, respectively, could be achieved in these two campaigns. The data shown in Fig. 1 are taken from the second measurement campaign with the highest gradients.
3. TEG system design and heat flux model

As a result of the temperature measurements described above a design for a TEG system was set up according to Fig. 2. This system uses a small TEG with a footprint of 18 x 21 mm² (TEG-083-230-07, Thermalforce) in a circular polymer housing, with a heat sink as TEG-air interface (ICK S R 50x20, Fischer Elektronik) on its top and an aluminium thermal connector to the fur at its bottom. One of the pins of the heat sink was replaced by an alumina can with an embedded PT 1000 temperature sensor, to measure the air temperature at the heat sink. A second PT 1000 temperature sensor was embedded in the thermal connector to measure the temperature at the fur. In general, the fur of a mammal reduces the heat flux between skin and ambient and will therefore be a problem for thermoelectric energy harvesting. For that purpose the thermal connector to the fur was designed as protruding element to flatten the fur and to increase, by that, the thermal heat flux through the TEG. TEG and temperature sensors are electrically accessed via a common waterproof connector. A miniaturized 3-channel datalogger (uLOG, SparkFun) with three micro-power instrumentation amplifiers was built into a separate housing at the collar to record all data.

In a simplified model, the electrical output power $P$ of a TEG can be described with equ. (1) to

$$P = \left( \frac{K_{TEG}}{K_{fur} + K_{TEG} + K_{HS}} \right)^2 \cdot \left[ \alpha \cdot (T_{skin} - T_{air}) \right]^2 \cdot \frac{R_L}{(R_G + R_L)^2}$$

Here, $\alpha$ denotes the TEG’s Seebeck coefficient, $R_L$ and $R_G$ the load resistance and the TEG’s internal resistance, respectively. $T_{skin}$ and $T_{air}$ are the temperatures of skin and air (see Fig. 2). $K_{fur}$, $K_{TEG}$ and $K_{HS}$ form a thermal temperature divider with the thermal resistances of the fur, the TEG and the heat sink between TEG and ambient air, respectively, as shown in Fig. 2. While reliable data are available on $K_{TEG}$ and $K_{HS}$, data for $K_{fur}$ are lacking. In general, fur shows a highly variable thermal behavior depending on several physiological and environmental influences. Realistic values for $K_{fur}$ were taken from [9,10,11] with a worst case and best case scenario (see table 1). These data show that the thermal resistance of the thermal connector (see Fig. 2) is always much smaller than $K_{fur}$ and negligible. With a temperature difference of $T_{skin} - T_{air} = 10$ K and for optimal load matching ($R_L = R_G$) equ. (1) would give an output power of 158 µW and 401 µW with an open circuit voltage of 48 mV and 76 mV, respectively.

| parameter | Value |
|-----------|-------|
| $K_{HS}$  | 5 K/W |
| $K_{TEG}$ | 20 K/W|
| $K_{fur}$ | 46 (best) and 88 (worst) K/W|
| $\alpha$  | 27 mV/K|
| $R_G$     | 3.6 Ohm|
depending on the value of $K_{\text{fur}}$. The temperature difference between the upper side of the fur, i.e. the bottom side of the TEG, and the ambient air would be 2.1 K and 3.5 K, respectively. Therefore, the measured average temperatures $T_{\text{fur}} - T_{\text{air}}$ between 2.5 K and 3.5 K are approximately matching with an assumed total temperature difference $T_{\text{skin}} - T_{\text{air}}$ of 10 K, with all uncertainties concerning $K_{\text{fur}}$ in mind.

4. TEG system test under real-life conditions, system considerations

In another measurement campaign the TEG system was mounted to a collar and applied at the animal for a real-life test. Fig. 3 shows exemplary data obtained during a 48-hour period in October 2014, starting at 9:30 A.M. The open-circuit voltage of the TEG was calculated from the acquired temperature data to eliminate the influence of electronic noise that unfortunately had been present during the measurement. Also, air temperature data from a local weather station are included in the graph. The elevation of the TEG voltage between hour 17 and 24 presumably reflects the influence of the cold night, whereas the negative voltages in hour 25 show even a reversal of the temperature gradient during the warm morning. Influence of the colder, second night is not found. Obviously the animal has taken shelter against the lower temperature.

These data have to be interpreted in a system context to evaluate the usefulness of the tested device: It has been shown in a previous publication that low output voltages of a TEG can be up-converted to higher, usable system voltages with specially tailored step-up converters [12] that run at an input voltage of 10 mV already and with a power conversion efficiency of appr. 33%. The system described in [12] exhibits a typical input resistance of 1.8 Ohm which acts as effective load resistance $R_L$ for the TEG with an internal resistance of 3.6 Ohm. Therefore according to equation (1) a no-load input voltage of appr. 30 mV is required to start step-up conversion, i.e. all voltages below 30 mV and also all negative voltages will not be valid for a realistic power calculation. With that the output voltage in Fig. 3 would, under ideally load-matched conditions, yield an average output power of 173.9 µW. With the non-ideal load matching present here and after neglecting all voltages below $+30$ mV, the useful average output power of the TEG is 164.8 µW. The step-up converter with a power conversion efficiency of approximately 33 % [12] would deliver 54 µW of average electrical power to a wireless system. In total, the available electrical energy is approximately 10.2 Ws, harvested over 48 hrs. The usefulness of this amount of energy has to be discussed with a view on potential applications: A low-power and low range VHF tracker, the smallest unit used for animal tracking, will typically send out RF bursts with a lowest repetition rate of 30 pulses per minute [13]. A realistic power figure for such a transmitter would be 10 mW over a minimal burst time of 15 ms [13]. The average power consumption of the transmitter would then be 75 µW, which is already in the range of the small TEG system tested in this study.
5. Summary and conclusion
This paper presents the results of a feasibility study of energy-autonomous wildlife tracking, as far as the authors know for the first time. A German sheep (“Heidschnucke”) has been used as a test animal due to its good availability and access, and also due to the similarity of its physiology to other, more relevant wild animals, e.g. deer. To mimic the conditions of wildlife as close as possible the sheep was kept freely grazing. In a first measurement series the temperatures at the inside and outside of the animal’s collar were recorded. Typical temperature differences of 2 to 3 K were found in three measurement campaigns, each lasting over 14 days. In a second step a small commercial TEG was used as core element for a TEG system, made of a polymer housing, a temperature connector to the animal’s fur and a heat sink as thermal interface to ambient air. Temperature sensors were integrated into the system for a determination of the TEG’s hot side and cold side temperature. With this system an electric output power of 54 µW was obtained, sufficient for a low range VHF tracking system.

On a first sight the obtained electrical power seems to be too low to justify the effort for a TEG system. However, in this study a small TEG with a footprint of only 18 x 21 mm² has been used, to comply in any case with the requirement that the mass of a tracking system should not exceed 2 to 5 % of the animal’s weight [13]. The majority of animals of interest, e.g. deer, reindeer, moose or bear, would allow for much larger devices with a much higher output power. Therefore, TEG systems come into reach that can either prolong the lifetime of a battery-operated wildlife tracker or take the role of the main power supply with a rechargeable battery for auxiliary power. In both cases the operational lifetime of the wildlife tracking system would be significantly prolonged. Also, a larger range of functionality could be conceived with, e.g., tracked animals used as mobile environmental sensors.

6. References
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