A farm animal kinetic energy harvesting device for IoT applications

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ABSTRACT

In this paper the authors present a novel application for electromagnetic kinetic energy harvesting focusing on farm animal wearables used in precision livestock farming IoT technologies. Converting the locomotion of domesticated animals, like cow steps or cow ear movement, into electrical energy with inertial kinetic energy harvesters hasn’t been fully researched thus far. The kinetic energy converted this way could potentially be used to power smart farming wearables used for location, disease or lifecycle events detection, thus eliminating the need for finite lifetime batteries. In this work, a proof-of-concept of a cow step energy harvester is presented in detail. At first a short review of the state of the art is given which formed the basis of the research, followed by locomotion logging experiments. Finite element modelling of the kinetic energy harvester is used for parameter analysis and initial design followed by laboratory testing and available power estimation. Finally, the construction of the wearable harvester is presented together with custom wearable measuring equipment. Field experiments were performed with free grazing Finncattle at a dairy farm in Tampere, Finland, which proved that a cow step based kinetic energy harvester can be used to power a Bluetooth beacon.

Keywords: electromagnetic induction, energy harvesting, kinetic energy, precision livestock farming, wearables, wireless sensor networks

1. INTRODUCTION

In the following sections, the research performed in the two-year course of the project ENTRAP\cite{1} will be disseminated focusing on the development of a proof-of-concept of a wearable electromagnetic kinetic energy harvesting (KEH) device. The acronym ENTRAP stands for ‘Energy harvesting for precision agriculture applications’ and it’s a pioneering project aimed at developing species-specific KEH devices (for cattle and goats) which will convert animal locomotion into electrical power. These KEH devices would then possibly enable precision livestock farming (PLF) technologies with autonomous power. In the current section the project motivation will be presented, accompanied with a review of state-of-the-art technology, while in the subsequent sections results emerging from cattle measurements, finite element modelling, laboratory and field tests with cattle will be presented.

1.1 Motivation – Precision livestock farming

PLF is a livestock management concept in which livestock parameters are monitored in real-time by employing IoT and wireless sensor network (WSN) technologies\cite{2}. Usually, the architecture consists of many small WSN sensor modules or nodes embedded with wireless transmitters. These nodes acquire, process and the transmit data to a dedicated gateway, server or to each other (Figure 1. a). Animal wearables are frequently employed as WSN nodes in PLF. These wearable devices are used to record numerous parameters associated with animal health, metabolism or shelter conditions in application defined intervals\cite{3} (Figure 1. b). Some of these are being marketed under brands like Digitanimal, Moomonitor+, Cattlewatch, SMARTBOW etc. Finite lifetime batteries are a preferred source of power for most PLF technologies. The implication of an increasing demand of PLF systems would be the production, and continuous replacement of hundreds of millions of batteries while battery recycling and manufacturing remains an environmental issue\cite{4}. Battery life has been increased significantly in recent times, with some brands boasting 7 years of operation (as the cSense\textsuperscript{TM} Flex Tag\cite{5}). Despite that, advanced PLF applications, like virtual fencing\cite{6}, used for animal location control (Figure 1. c), are more energy intensive and require frequent recharging.

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1.2 Kinetic energy harvesting from the animal body

Energy harvesting (EH) is the process of capturing and converting energy from the environment, like sunlight, water flow, heat or vibrations into electrical energy. This energy can be supplied to low power electronic devices like wireless sensor nodes. WSN nodes are usually low power electronic devices which require power in the range of tens of µW to 100 mW\(^7\). EH is also a prominent research field with two decades of research being performed albeit with limited industrial impact. Due to the manufacturing price being too high or limited performance, EH still hasn’t become the ubiquitous enabler of power autonomous IoT devices. Mechanical systems such as machines, vehicles and structural vibrations have been thoroughly studied as a power source in the last two decades. Tuned inertial KEH devices operate at a specific excitation frequency or in a narrow bandwidth close to it while animal locomotion occurs randomly in the range up to 10 Hz. KEH solutions which have proven to be especially suitable for these operating conditions are inertial electromagnetic (EM) devices\(^8\) with novel triboelectric generators also displaying promise\(^9\). The human body has also been studied in this regard\(^10\) while significantly less attention has been directed at non-human animals. As far as non-human animals are concerned, KEH research has been limited and considering the specific case of EM devices, research has been performed only on cattle\(^11\), fish\(^12\) and reindeer\(^13\). The simplest of inertial 1D EM harvester architectures is depicted here in Figure 2. a). A moving permanent magnet (PM) is placed inside a cylindrical tube in which it can travel axially. Inertial forces resulting from base excitation \(y(t)\) cause relative motion \(z(t)\) of the magnet travelling inside the tube. Magnetic springs made from PMs of opposing polarity are placed on both ends causing the magnetic spring force \(F_m\) to act on the moving magnet. This relative motion induces voltage in a coil placed around the tube. The adjacent equivalent circuit depicts the EM generator as an AC voltage source (the back-emf induced by the moving magnet) in series with coil resistance \(R_c\), coil inductance \(L\) and an equivalent load \(R_l\). In the project ENTRAP, we propose that the existing KEH technologies, can be implemented in PLF wearables for use on large farm animals without hindering their movement or introducing discomfort. Envisioned devices would weigh less than 0.1 kg and be small enough to be included with standard farm equipment and PLF technologies.

Figure 2. a) EM KEH device and its equivalent circuit b) measurement locations on a cow and axis arrangement, c) FFT analysis result of a single cow step time series lasting 800 ms (shown in overlapping small chart).
2. PROTOTYPE DESIGN

2.1 Cattle locomotion analysis
KEH devices are frequently designed with specific operation scenarios in mind to achieve optimal functionality and convert maximum amounts of kinetic energy into electrical energy. Animal locomotion is a specific scenario in which the events occur intermittently and randomly but with certain locomotion profiles displaying repetitive characteristics. To design a KEH device specifically for cattle, locomotion measurements were undertaken at Ahlman dairy farm (Ahlmanin koulun säätiö, Tampere, Finland) to determine specific excitation profiles, acceleration magnitudes and locomotion frequencies of freely grazing cattle. Two Finncattle cows were measured in 5 consecutive days with wireless acceleration loggers Axivity AX3 and AX6 set to 800 Hz sampling frequency and ±8 g sensitivity. These sensors were attached with rugged 3D printed casings and with a collar or leg strap to the cow’s neck, marking weight under the head and front leg, while in another set of experiments locomotion of both ears was logged as well (Figure 2. b). After obtaining locomotion profiles and estimating power spectral densities, it was visible that the least amount of power density is present on the collar while the leg locomotion proved as a strong source of excitation. This was especially visible in the vertical axis Y, coinciding with the longitudinal axis of the investigated 1D KEH architecture (Figure 2. a). Leg step time series information was analyzed with a fast Fourier transform to identify frequencies associated with cow’s stepping locomotion. Although a cow’s step can vary greatly in duration and amplitude, an average duration is 800 ms with usual characteristic frequencies occurring close to 1.3, 3.8 and 7.7 Hz (Figure 2. c). The ~8 Hz step harmonic was chosen for the design guideline as it is generally more difficult to design harvesters for low frequencies and maintain small device size.

2.2 Design and simulation tool
In the last two decades, many KEH architectures have been modelled and investigated[14]. The EM harvester has proven to be especially well suited for random meso-scale operation such as harvesting animal locomotion. Numerous EM KEH designs have been investigated due to design simplicity, device lifetime and low resonant frequencies[15]. These devices have been mostly analytically modelled as single degree of freedom spring-mass-damper systems[16] coupled with analytical solutions of magnetic fields and approximated magnetic force values. For the purpose of this work, a 2-D axisymmetric FEM simulation has been developed and tested in MATLAB. Figure 3. a) displays the meshed model geometry domains: top (green) and bottom (red) spring magnets, the moving mesh area (grey) with the moving PM indicated with a red line, two coils (black and pink) and the air domain (blue). The flux linkage of the coil and the EM force acting on the moving magnet are calculated for fixed values of the magnet position and the coil current using a series of magnetostatic solutions[17]. These precalculated solutions, coupled together with the equation of motion and electric circuit equations allow for simulation under any type of excitation profile. Specifically, a recorded cow step has been used as time stepping input to the solver which is then used to obtain magnet positions, induced voltage and power (Figure 3. b). Based on this method, a sensitivity analysis was performed over a set of parameters with looping over a range of values. It was found that the number of turns \( N \), coil dimensions \( d_c \) and load resistance \( R_l \) have optimal values (Figure 4. a). The gap between the coil and the magnet, \( t \), has a significant influence on power generation and should be minimized (Figure 3. c). Coil position relative to the magnet equilibrium also influences power generation and it was found that the middle of the coil should coincide with the magnets top/bottom surface where flux density is the strongest (Figure 2. a, \( z = 0 \)). Final dimensions of the laboratory prototype are presented in Table 1 and Figure 4. a).

![Figure 3. a) axisymmetric model mesh used in FEM simulation, b) cow step power, c) sensitivity analysis for parameter \( t \).](image-url)
2.3 Device prototype: harvester, power management and communication module

The proposed cow step KEH device was designed with Fusion360 3D modelling software (Figure 4. b) and 3D printed with the Prusa I3 MK3 3D fused deposition modelling (FDM) printers. The tube, coil formers and spring magnet attachments were printed with PLA filament while the leg strap casing was printed with a more rugged PETG filament (7 parts in total). Prototype dimensions are presented in Figure 4. a) and Table 1. To achieve desirable filament deposition orientation for minimal friction, the tube was printed in two parts, then finely ground on the inside and coated with liquid Teflon. Coil formers were slid across the tube at specific points where the magnetic flux density of the PM was strongest. The tube was then mounted on the spindle of the modified QIPANG FZ-180 coil winding machine where two 1500 turn coils were wound (connected in series). The diameter of the enamelled copper wire was 0.1 mm \( R_l = 515 \, \Omega \). PMs used for the moving magnet and the springs were the off-the-shelf N42 NdFeB magnets with dimensions shown in Table 1.

Table 1. Prototype dimensions obtained from FEM simulation and according to Figure 4. a)

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
<th>Unit</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>( h_T )</td>
<td>40</td>
<td>mm</td>
<td>Tube length</td>
</tr>
<tr>
<td>( d_{T1} )</td>
<td>22.6</td>
<td>mm</td>
<td>Tube diameter</td>
</tr>
<tr>
<td>( N )</td>
<td>3000</td>
<td>-</td>
<td>Total number of turns</td>
</tr>
<tr>
<td>( d_c )</td>
<td>10</td>
<td>mm</td>
<td>Coil height and width</td>
</tr>
<tr>
<td>( c )</td>
<td>5</td>
<td>mm</td>
<td>Coil distance equilibrium</td>
</tr>
<tr>
<td>( d )</td>
<td>0.1</td>
<td>mm</td>
<td>Coil wire diameter</td>
</tr>
<tr>
<td>( t )</td>
<td>0.8</td>
<td>mm</td>
<td>Wall thickness</td>
</tr>
<tr>
<td>( d )</td>
<td>20</td>
<td>mm</td>
<td>Distance between magnets</td>
</tr>
<tr>
<td>( h_{SM} )</td>
<td>2</td>
<td>mm</td>
<td>Spring magnet height</td>
</tr>
<tr>
<td>( d_{SM} )</td>
<td>6</td>
<td>mm</td>
<td>Spring magnet diameter</td>
</tr>
<tr>
<td>( R_l )</td>
<td>1000</td>
<td>( \Omega )</td>
<td>Load resistance</td>
</tr>
<tr>
<td>( h_{MM} )</td>
<td>10</td>
<td>mm</td>
<td>Moving magnet height</td>
</tr>
<tr>
<td>( d_{MM} )</td>
<td>20</td>
<td>mm</td>
<td>Moving magnet diameter</td>
</tr>
<tr>
<td>( m )</td>
<td>0.024</td>
<td>kg</td>
<td>Moving magnet mass</td>
</tr>
</tbody>
</table>

To rectify and condition the alternating current produced by the harvester, a suitable power management integrated circuit (PMIC) must be used. For this purpose, the SparkFun energy harvester breakout board based on the Linear Technologies LTC3588-1 IC was chosen. The chosen PMIC has an integrated full wave bridge rectifier and over voltage protection. It’s usually coupled with an output capacitor used for storing the intermittent energy harvested from different sources (vibrations or solar energy). Electronic devices used as WSN nodes are operated at specific DC voltage levels and for this purpose the output voltage of the PMIC was set to 3.3 V with a combination of solder pins on the board itself. The capacity of the output capacitor was selected based on the formula from the LTC3588 data sheet\(^{[18]}\),

\[
E = \frac{1}{2} C \left( V_{in}^2 - V_{UVLOFFALING}^2 \right),
\]

where the values \( V_{ON} = 5.05 \, V \) and \( V_{UVLOFFALING} = 3.67 \, V \) are taken from the data sheet. A maximum of 10 mW of power was assumed to be required for the duration of 1 s. Thus, with an output capacitor of \( C = 2200 \, \mu F \), an energy
output of $E = 13.24$ mJ is calculated. The nRF52840 Bluetooth USB dongle\(^{[19]}\) was chosen as the communication module which will be powered by the harvester. This module has the capability of using external power sources such as batteries or PMIC outputs and can be easily configured with the NRF Connect software via USB cable (minimum selectable wireless transmission frequency is 10 Hz).

2.4 Wearable energy harvesting data acquisition module

For the field experiments it was necessary to log the dynamics of the harvester (induced voltage levels) concurrently with the leg’s locomotion dynamics (acceleration). To achieve this, a suitable measurement and data acquisition instrument with data logging capabilities was required. As none was to be found on the market, a custom one was built based on the Adafruit Feather M0 Adalogger development board\(^{[20]}\) (Figure 5. a). This board has several analog inputs and an embedded microSD card logging shield and can be powered by a rechargeable LiPo battery (3.7 V, 550 mAh battery used in this case). For parallel acceleration measurements an Adafruit MMA8451, 3D accelerometer breakout board was selected. The Adalogger’s onboard analog-to-digital converter input is rated for a 0 - 3.3 V voltage input level which suits the accelerometer’s output but cannot acquire harvester’s signal with AC currents and voltages above 3.3 V. Thus, the harvester’s output voltage, $V_{KEH}$, had to be reduced with a voltage divider and biased with an onboard reference voltage level of 1.65 V ($V_{ref}$) (Figure 5. b). The voltage conditioning schematic was then simulated with the LTspice software and a damped sine wave input signal (Figure 5. c) and finally soldered on a prototyping board. The data acquisition algorithm was programmed with the Arduino IDE.

3. EXPERIMENTS

3.1 Laboratory experiments

Two sets of experiments were envisioned in the laboratory environment: a vibration exciter experiment and human excitation experiment. At first a vibration exciter by Bruel & Kjær was used – with a 4805 body and 4813 test head, onto which the KEH device (Figure 4. c) was mounted and pressed with two 3D printed PETG mounting plates secured by M6 threaded rods (Figure 6. a). The bottom mounting plate had also a PCB 355B02 through hole accelerometer attached with a screw and was connected to a PCB charge amplifier. National Instruments USB-6251 Multifunction I/O device was used to control inputs and outputs of the experiment via the LabVIEW SignalExpress software. Two analog input channels were used to record the harvester coil voltages and acceleration levels. An output channel was used to send SignalExpress generated sine waves to the Venable VLA1000 amplifier which was used to drive the vibration exciter (system schematic visible in Figure 6. b). To investigate the resonant behaviour of the device and changes associated with size variations of the top spring magnet, pre-programmed frequency sweep profiles with constant amplitudes were used as inputs to the exciter with test results shown in Figure 6. c). The ‘v4’ was chosen for further testing:

- ‘v1’ harvester had two spring magnets (from Table 1.) and displayed resonance around 10.5 Hz,
- ‘v2’ version had the top magnet moved 5 mm further from the moving magnet and resonance at 9 Hz,
- ‘v3’ uses a smaller top spring magnet, 1 mm diameter and 2 mm height, displaying resonance close to 7.25 Hz,
- ‘v4’ has the top magnet removed without significant influence on the resonant frequency (as in Figure 4. a).
Energy dissipation of the nRF Bluetooth dongle was measured with manual shaking experiments in the lab where the dongle was interfaced to the load output terminals of the PMIC while the harvester was connected to the input terminals. Load voltage and the PMIC’s PGOOD logic pin were monitored with a Tektronix oscilloscope together with the load current (with a Tektronix current probe). The harvester was shaken by hand and the exact number of excitations was counted until the PGOOD would reach a high logic level and discharge the energy to power the dongle. The cold start of the dongle can be identified by the sharp rise in the power curve in Figure 7. a) at 6.9 mW after which the dongle starts continually transmitting a ‘Test beacon’ signal at 10 Hz with each individual transmission consuming 49 µW. The transmission perimeter of the dongle was determined with the nRF Bluetooth LE packet sniffer during these experiments which was ~35 m around the laboratory. Vibration exciter tests were performed next with an amplitude of 2 V at a 7 Hz frequency in which the exact time required to fully charge the capacitor was measured (from a discharged state). The capacitor required 28.05 mW to reach a fully charged state during 188 s of vibration excitation. Upon reaching a PGOOD ‘high’ state the PMIC releases part of the energy stored on the capacitor to the load. The following charges require less time and energy - 13.24 mW during 40 s of excitation. In the final lab test the harvester was strapped to a student’s leg (Figure 7. b) who tried to imitate casual walking in place. Charging from a discharged state took 39 steps in average while each subsequent charge took 15 steps in average. The position of the harvester also influenced the number of steps – when placed at the back of the calf the number of steps for the second charge was 5.

3.2 Field experiments with Finncattle

Two experiments were designed and carried out again at the Ahlman dairy farm in the summer season of 2021 during daily free grazing activity. As a test subject an eastern Finncattle Pinja, three years of age, was chosen for both experiments. During the first experiment the intent was to use the custom-built logger device to record coupling of the harvester’s moving magnet to the cow’s leg locomotion. For this purpose, a tough PETG case was 3D printed to hold both the harvester and the instruments (Figure 7. c). The case was attached to the cow’s front leg by a standard pedometer leg strap as seen in Figure 8. a). The 3D printed hardware withstood harsh farm conditions and the experiment resulted with logged data with over an hour. Upon analysis of the experiment’s log, it could be seen that the motion of
the harvester’s moving magnet agrees beautifully with measured leg locomotion (Figure 8. b). Records show that a high deceleration impact occurs (in direction of gravity – visible 1 g) upon the leg’s ground impact. The harvester follows closely with a high positive and negative peak and subsequent ringdown (signalling that the moving magnet was brought into a free vibration state). Recorded data also indicated that accelerometer’s Y axis (gravity) repeatedly reached the accelerometer’s set ±6 g limits with the harvester inducing over 20 V in those cases.

Figure 8. a) KEH device mounted on Pinja’s leg, b) coupling of induced voltage to leg acceleration, c) screenshot of the NRF Bluetooth sniffer taken during experiments displaying the captured ‘Test beacon’ transmission

In the second experiment the nRF dongle was then added to the casing and interfaced to the PMIC’s output terminal. The whole wearable, together with the harvester, voltage divider and the custom-built logging device weighed ~0.2 kg in total. The Bluetooth transmissions emitted from the prototype mounted on the leg were monitored with a nRF52840 development kit transceiver. The kit was installed on a laptop and programmed as a sniffer with the Wireshark software used for capturing Bluetooth traffic. Concurrently with laptop logging, a nRF Bluetooth LE packet sniffer app was installed on two mobile phones. Several Bluetooth transmissions were logged with the Wireshark software, but it quickly proved impractical to follow the subject with a laptop. For the following three hours of the trial, we relied on the mobile phone sniffers which were used to continuously scan for Bluetooth transmissions (when movement from the cow was observed). Although this method is unreliable and inaccurate to quantify the number of transmissions it still resulted with capturing frequent transmissions labelled ‘Test beacon’ (Figure 8. c). It was noticed that a transmission would occur with every significant change in the subject’s position i.e., when at least several steps were taken. Based on the intensity of movement the transmissions would be visible by the sniffer for several seconds up to a full minute thus proving that cow step energy can be harvested with EM KEH devices. Furthermore, it should be noted that during the most energetic movements a clicking sound could be heard signalling that the moving PM was reaching the upper end stop of the device which suggests a top spring magnet should be used for damping purposes.

4. CONCLUSIONS AND OUTLOOK

In this paper the development of the EM KEH device for cattle was presented in detail. At first the locomotion logging experiments were undertaken in which characteristic frequencies were identified from several single step time series records. The 7.7 Hz frequency was identified as practical for dimensioning and building the harvester in lab with the available hardware and off-the-shelf components. An axisymmetric FEM simulation was developed to simulate the 1D EM KEH with magnetic springs. Based on the simulation results the device was dimensioned and then 3D printed, prototyped and tested in lab with a dedicated PMIC. Vibration exciter experiments showed that a 7 Hz resonant frequency was achieved without the top magnet used. In these experiments the harvester could charge the output capacitor from a discharged state during 188 s and after the energy was partially transferred to the load, each subsequent charge lasted for 40 s. Lab walking experiments were also performed where it took 15 steps in average to charge the capacitor. The KEH device was also mounted on a cow’s front leg while displaying excellent coupling with the cow’s step locomotion characteristic. Finally, a Bluetooth dongle interfaced to the harvester via a dedicated PMIC, was placed in the wearable casing as well. The dongle continuously transmitted data when the cow changed the position on the field.

In the future several new 2D and 3D EM KEH architectures and rotational generators will be investigated in a similar manner and tested on different cow body locations like the neck, bell and ears.
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