Cow locomotion energy harvester for powering IoT wearables

D. Blažević[1], S. Philipp[2], J. Ruuskanen[1], J. Dizdarević[2], P. Rasilo[1], A. Jukan[2]

[1]Unit of Electrical Engineering, Tampere University, Korkeakoulunkatu 3, Tampere, Finland

[2]Department of Electrical & Computer Engineering and Physics, Technical University of Braunschweig Hans-Sommer-Str. 66, Braunschweig, Germany

david.blazevic@tuni.fi

Abstract

This paper presents a novel idea of converting farm animal locomotion into electrical power for enabling precision livestock farming applications with autonomous power. A brief description of the problem is presented followed by a review of the state-of-the-art. Further on numerical modelling and experimental methodologies are presented which are used to analyse the proposed concept and produce a proof-of-concept. Finally a wearable prototype is built and tested in-lab and on-field with free grazing Finn cattle.

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

Introduction

In this paper, research progress and results emerging from the first two-year period of work on project ENTRAP - ‘Energy harvesting for precision agriculture applications’- will be disseminated. This is a pioneering project, aimed at developing a kinetic energy harvesting (KEH) device for converting livestock locomotion into electrical power thus enabling a wide range of precision agriculture (PA) and precision livestock farming (PLF) applications with autonomous power.

Precision livestock farming

PLF is a key staple of the PA concept and relies on extensive utilization of wireless communication and wireless sensor network (WSN) technologies (Jawad, H. M. *et al.* 2017). The usual generic WSN architecture consists of miniature battery powered nodes or motes embedded with sensing, communication and/or processing modules for edge computing (Figure 1, Left). Nodes can transmit data to the gateways which are connected to a mainframe data processing unit and/or communicate with each other. For enabling the PLF concept, the nodes are then placed on individual animals and used to record numerous animal attributes (health, metabolism etc., Neethirajan, S. 2017), as well as to monitor and control animal behavior with virtual fencing (Campbell, D. L. M. *et al.* 2017). Some of the commercially available devices are being marketed under these brands: Nofence, Digitanimal, Moomonitor+, Cattlewatch, Silent Herdsman, Afi-Act, SMARTBOW etc.

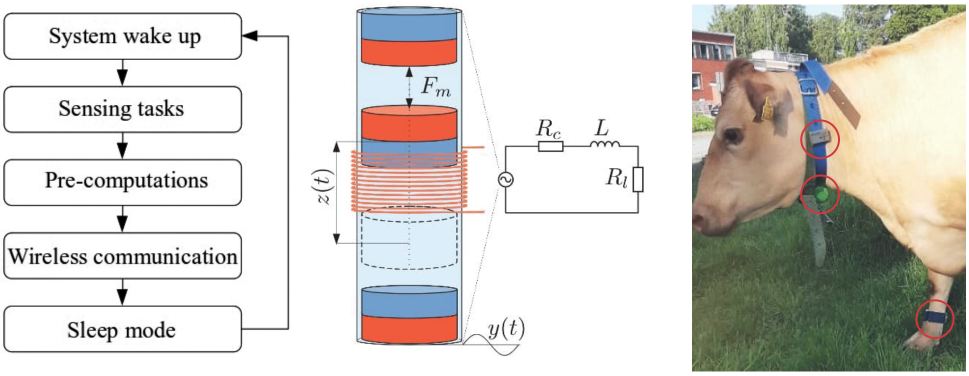


Figure 1: Left: a generic WSN cycle, Centre: a magnetic levitation electromagnetic induction energy harvester, Right: locations of instruments for locomotion logging trials

WSN: power and ecology

Most of these PLF sensors are to be driven worldwide by billions of batteries with limited lifetime, which once depleted, need to be replaced and recycled. The EU is home to more than 343 million of ungulates (E. Heidorn *et al*. 2017) and if half of these were utilized in a PLF concept requiring a finite lifetime battery - 170 million batteries would have to be produced and replaced in application defined intervals. This practice produces a hindering impact on the agricultural sustainability due to low recycling rates and high environmental burdens caused by battery production (E. Olivetti *et al*. 2011). A long-lasting alternative to finite lifetime batteries is energy harvesting. WSN nodes, depending on the application requirements, usually require power ranging from tens of µW to 100 mW in application specific intervals. An energy harvester coupled with a power management integrated circuit (PMIC) has been proven to provide as much.

Harvesting kinetic energy from the animal body

Energy harvesting is the process of converting ambient energy, like sunlight, water flow, heat or vibrations into electrical energy for powering low power. The most elegant and mature form of energy harvesting is photovoltaics, but extensive research has also been performed on thermoelectric, RF, triboelectric and kinetic energy harvesting (Shaikh, F. K. and Zeadally, S. 2016). Mechanical systems have been thoroughly studied as a power source in the last two decades, but much less attention has been directed to the energy of bio-mechanical systems such as animal bodies. Most inertial KEH devices require to be operated at a specific excitation frequency, while animal locomotion occurs stochastically in the range of 0-10 Hz so a low frequency KEH design must be considered. Based on the current state-of-the-art and recent findings, the most promising KEH solutions in this frame are inertial electromagnetic (EM) devices (Joon Kim, K. *et al*. 2010), with novel triboelectric generators also showing promise. The simplest device design to be considered is in fact the 1-D inertial EM harvester consisting of a cylindrical tube, in which a permanent magnet can travel axially, where the springs can be mechanical or magnetic (Figure 1, Centre). When excited by an outside source of vibration, the tube establishes motion marked with $y(t)$. In response to inertial forces, the central magnet then travels back and forth inside the tube with relative motion $z(t)$. The springs are defined by end stops in the shape of permanent magnets arranged so that they act with a repulsive force F_m on the moving magnet. As the magnet is traversing the tube, voltage is induced in the coil wrapped around the tube. The accompanying electric circuit shows the EM KEH as an AC generator connected in series with coil resistance R_c, coil inductance L and electric load represented by an equivalent load resistance R_l (usually a WSN sensing node and a PMIC). In this frame, the possibilities of converting human locomotion to electrical power for powering assistive wearable technologies have been thoroughly studied (Gljušćić, P. *et al.* 2019). As far as non-human animals are concerned, KEH research has been limited. The premise of project EN-TRAP is that the existing human KEH technologies can be easily transferred and used on other animals with an increase in inertial masses and device dimensions while still maintaining a small and light footprint (below 200 g).

Material and methods

This section includes a short description of animal locomotion measurements, the simulation tool developed to estimate available powers and materials and methods used for the design of the prototype and measurement devices used for field trials.

Animal locomotion measurements and analysis

To define a precise design of a KEH device best suited for a specific species of animal, field measurements were performed the details of which are presented in a separate work presented at this conference ('Kinetic energy harvesting potential of grazing livestock'). Here we offer a brief description of the methodology used at the Ahlman dairy Farm (Tampere, Finland). Locomotion of two Finncattle cows was measured in 5 consecutive trials via three Axivity wireless acceleration loggers attached to the cow's neck, marking weight and front leg strap (Figure 1, Right). The underlaying idea was to obtain locomotion profiles, analyse them and calculate Fast Fourier Transforms (FFT) to extract frequency information associated with animal movement. These frequencies would then be a starting point for designing cattle KEH devices akin to methods of eigenfrequency matching in mechanical systems. Based on the envisioned harvester concept and measurement results, the front leg strap location was chosen as suitable. This was decided due to strong accelerations of vertical leg locomotion which also coincides with the longitudinal axis of the EM KEH device. A cow's step (Figure 2, Left) can vary greatly but through all the measured steps several frequencies were identified as interesting, first the ~1 Hz walking frequency and second the interesting higher order harmonic identified in a cow step around ~8 Hz (Figure 2, Right). The latter was chosen to test the hypothesis of a frequency matched KEH device which are generally more easily designed for higher than lower resonant frequencies.

KEH device design and simulation

In the last two decades, many KEH devices have been investigated (Wei, C. and Jing, X. 2017). The EM harvester has proven to be well suited for random meso-scale operation such as harvesting animal locomotion. Numerous EM KEH designs have been investigated due to simplicity, device lifetime and low resonant frequencies (Khan, F. U. 2016).

These devices have been mostly analytically modelled as single degree of freedom spring- mass-damper systems coupled with analytical solutions of magnetic fields and experimentally obtained magnetic force values. For the purpose of this work, a 2D axisymmetric finite element model simulation has been developed and tested. The flux linkage of the coil and the electromagnetic 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. These coupled together with equations of motion and electric circuit equations allow for simulation of any type of excitation as previously reported in T. Kivimäki *et al*. 2021 where this methodology was put to test in designing a car tire EM KEH. For the purpose of this research a sensitivity analysis was performed over a set of parameters from which it was found that the number of turns N, coil dimensions d_C and load resistance R_l have optimal values. The gap between the coil and the magnet, t, also influences power generation and should be as small as possible. Final dimensions of the laboratory prototype are presented in Figure 3, Left & Table 1.

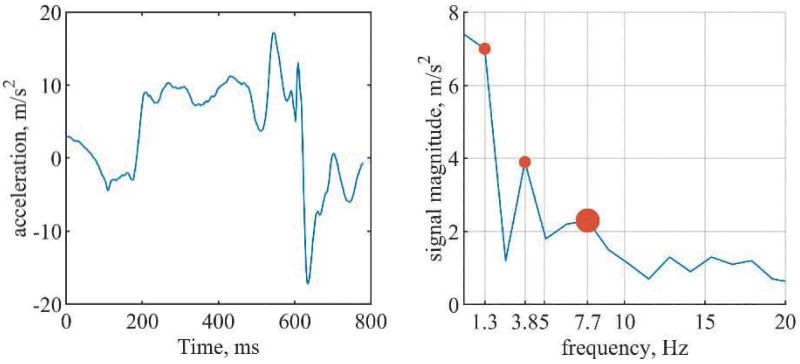


Figure 2: Left: Cow step profile, Right: Frequency information of a single cow step

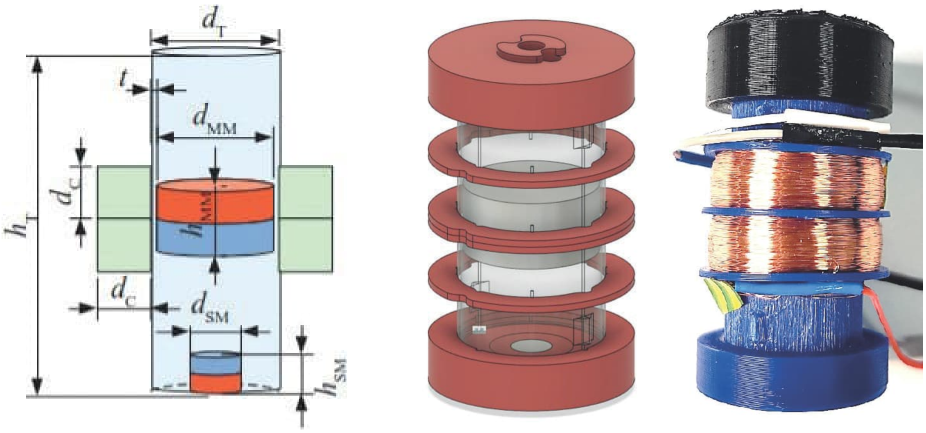


Figure 3: Left: Harvester schematic, Centre: 3D model, Right: 3D printed prototype

KEH Device prototype

The harvester structure and cow leg attachments were designed with Fusion360 3D modelling software (Figure 3, Centre). The Prusa I3 MK3 3D fused deposition modelling (FDM) printers were used in the FabLab facility of Tampere University to manufacture the parts with PLA (for the tube, coil and spring magnet attachments) and PETG filament (for the leg strap casing) totalling in 7 separate parts. The tube was printed in two separate parts for the purpose of achieving a suitable orientation of deposited print material (for lowest possible friction between the magnet and the tube) as well as the possibility of reworking the inside of the tube with fine wet sanding paper and smoothing out surface roughness resulting from the FDM process. Once assembled, the inside of the tube was also coated with Teflon spray before the magnet was inserted. Printed coil former elements were slid across the harvester tube and placed at specific points where the magnetic flux density of the PM is strongest. Two coils in series, each with 1500 turns, were wound by using a modified coil winding machine QIPANG FZ-180 using enamelled magnet copper wire with a diameter of 0.1 mm resulting with total coil resistance of 515 Ω. The magnets used were commercially available N42 grade strong NdFeB magnets with dimensions specified in Table 1.

Table 1: KEH device dimensions as seen in the left of Figure 3

Parameter	Value	Unit	Description
h_T	40	mm	Tube length
d_T	22.6	mm	Tube diameter
N	3000	–	Number of turns
d_C	10	mm	Coil height and width
c	5	mm	Coil distance equilibrium
d	0.1	mm	Coil wire diameter
t	0.8	mm	Wall thickness
d	20	mm	Distance between magnets
h_{SM}	2	mm	Spring magnet height
d_{SM}	6	mm	Spring magnet diameter
R_l	1000	Ω	Load resistance
h_{MM}	10	mm	Moving magnet height
d_{MM}	20	mm	Moving magnet diameter
m	0.024	kg	Moving magnet mass

Power management and communications module

KEH devices produce alternating currents which require rectifying and conditioning if they are to be used for powering electronic devices requiring specific DC voltage levels. For this project we selected a miniature PMIC - SparkFun Energy Harvester Breakout board based on the Linear technologies LTC3588-1 (Figure 4, Left). This PMIC rectifies AC sources with an integrated full wave bridge rectifier and has an over voltage protective shunt. It is intended to be used with an output capacitor for buffering charges from intermittent energy sources. Output voltage is selected by solder pins on the board, and for this purpose a, 3.3 V output voltage was selected. For capacitor dimensioning purposes, 10 mW of maximum required energy was assumed. Based on the formula for energy calculation available on page 13 of the datasheet (Linear Technology, 2015) and assumed capacity of the output capacitor of 2200 µF, a power of 13.24 mW was calculated. An nRF52840 Bluetooth USB dongle was chosen (Figure 4, Left) as a communication module due to in-built capability of using external power and ease of configuration via USB connection and the NRF Connect software. The beacon transmission setting was set at minimal frequency of 10 Hz.

Portable data acquisition and data logging

To determine the dynamics of the prototyped KEH device and its coupling to cattle leg locomotion, a portable and lightweight data acquisition and data logging device was required. A suitable commercial device which could simultaneously log induced voltage and acceleration is still not available, so a custom device was built. The custom device is based on the Adafruit Feather M0 Adalogger development board (Figure 4, Left), with in-built microSD card logging and battery powered operation (a 3.7 V, 550 mAh, LiPo battery was used). An additional Adafruit MMA8451, 3D accelerometer breakout board was chosen for measuring acceleration of the cow's leg. Harvester voltage output (V_{KEH}) was set to be measured with the onboard analog to digital converter (V_{ADC}) with 0 - 3.3V input levels. To achieve this, the harvester's output voltage was reduced with a voltage divider and offset into positive with onboard reference voltage set to 1.65 V (V_{ref}) (Figure 4, Centre). The system was then simulated with the LTspice software with a damped sine wave used as the input signal (Figure 4, Right).

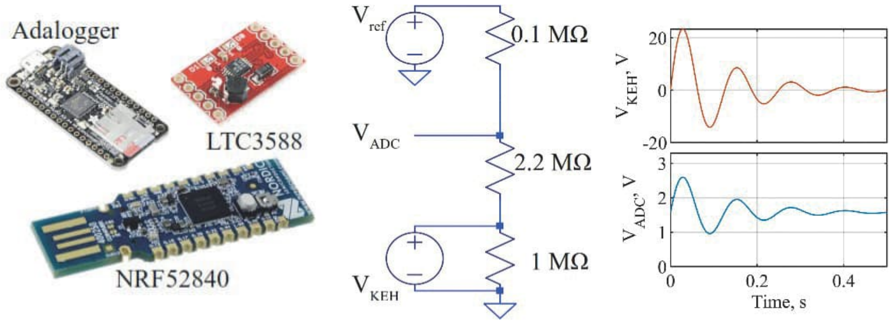


Figure 4: Left: Used components, Centre: Voltage divider, Right: LTspice simulation

Results and Discussion

Laboratory experiments: Shaker and human excitation

The shaker experiments shown in Figure 5, Left, were designed according to the schematic in Figure 5, Centre (detailed in T. Kivimäki *et al.* 2021). Frequency sweeps were performed to investigate resonant frequencies. Figure 5, Right displays the results: 'v1' harvester version has two full size spring magnets and resonance at 10.5 Hz; 'v2' has the top magnet lifted 5 mm from the moving magnet equilibrium resonating at 9 Hz; 'v3' uses a smaller top spring magnet (diameter 1 mm, height 2 mm) and resonates at 7.25 Hz while 'v4' had the top magnet removed without a further significant frequency shift. Configuration 'v4' without the top magnet was used in further tests.

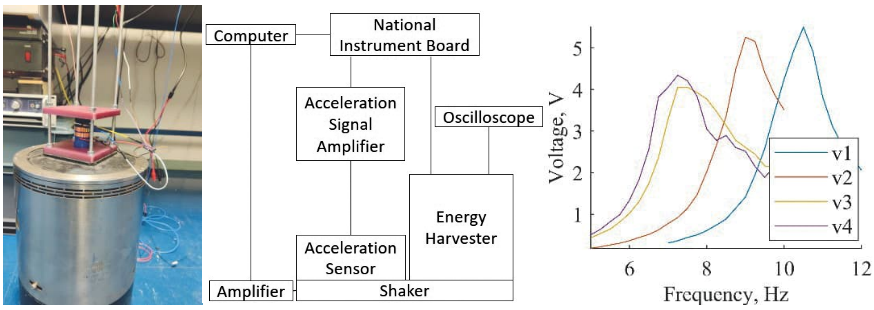


Figure 5: Left: Harvester mounted on a shaker, Centre: Experiment schematic, Right: Measurement results displaying 4 different harvester variants

The nRF dongle energy dissipation was measured with the harvester connected to the PMIC and manually shaken to charge the capacitor. The energy required for the dongle cold start-up was 6.9 mW while a single beacon transmission consumed 49 µW (Figure 6, Left). The dongle transmission distance was determined experimentally at a diameter range of ~35 m. Shaker tests were also performed at 7 Hz, 2 V sine excitation level, during which the time required to charge the capacitor was measured. In average it took 28.05 mW during 188 s to charge the capacitor from a completely discharged state. Then the PMIC releases a portion of the energy, and the next charge requires less energy – 13.24 mW during 40 s. Finally, the harvester was strapped to a student's leg for a stepping test. Here the charging from a discharged state took ~39 steps with each following charge taking ~15 steps (Figure 6, Centre).

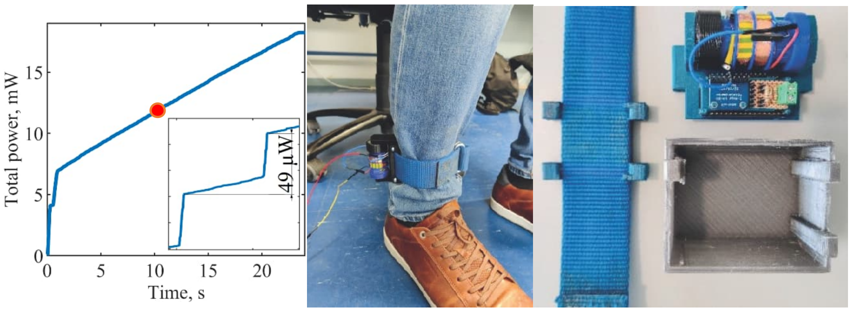
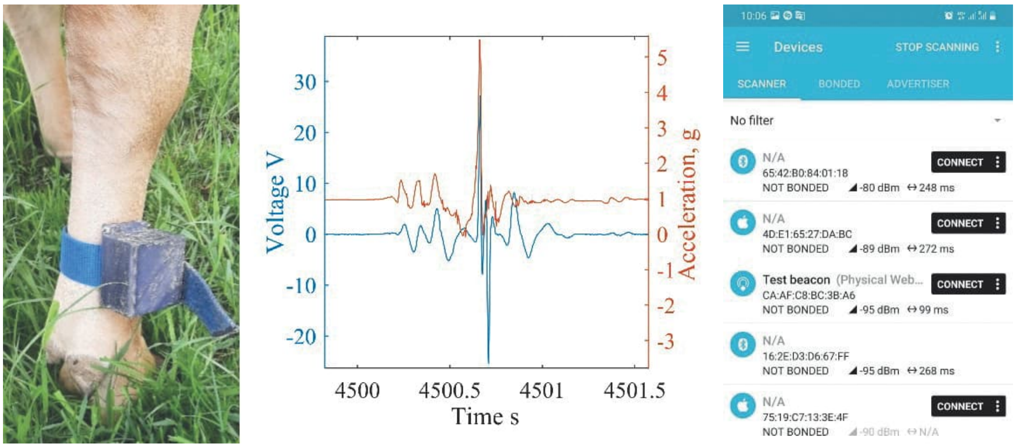


Figure 6: Left: nRF dongle power consumption, total consumption and detail of single transmission, Centre: Lab walking test, Right: Open cow leg strap assembly

Field experiments: Ahlman dairy farm (Tampere, Finland)

Two field experiments were performed at Ahlman dairy farm (Ahlmanin koulun saatio, Tampere, Finland). In the summer season the herd is allowed to freely graze in a rotational grazing scheme. A three-year-old eastern Finncattle cow Pinja was chosen as a test subject. In the first experiment the harvester was tested for leg locomotion coupling. The casing was 3D printed with PETG filament (Figure 6, Right). The whole device mounted on the front leg (Figure 7, Left), including the harvester, PMIC, logger and the rugged outer casing weighed ~0.2 kg. The subject seemed undisturbed by the wearable and moved unhindered. The device proved to withstand harsh conditions and clear collisions with farm infrastructure and the experiment resulted with 1 hour of logged data. From the analysis it was observed that the accelerometer's Z axis (gravity) often reaches its ±6g limit while in such cases the harvester induces over 20 V. Total log of the experiment displays beautiful coupling of the harvester to leg locomotion (Figure 7, Centre). Single step analysis reveals that when the cow steps on the ground, a high deceleration impact occurs. The harvester trails behind with a positive and negative peak and rings down brought into a free vibration state. A second field trial took place with the same test subject. This time the nRF dongle was used as well powered solely by the PMIC. Bluetooth traffic was monitored via laptop with Wireshark software and a nRF52840 dk transceiver. nRF Bluetooth LE packet sniffer app was also installed on two mobile phones. It proved impractical to follow the subject with a laptop and thenceforth mobile phones were used for continuous scanning of Bluetooth traffic. With this we were able to recurrently capture the 'Test beacon' signal (Figure 7, Right) which would occur when the cow would change position (5-15 steps). Based on the intensity of motion the 'Test beacon' would stay visible from 10 seconds up to a full minute.



N/A
65:42:B0:84:01:18
NOT BONDED -80 dBm ↔ 248 ms

N/A
4D:E1:65:27:DA:BC
NOT BONDED -89 dBm ↔ 272 ms

Test beacon (Physical Web...
CA:AF:C8:BC:3B:A6
NOT BONDED -95 dBm ↔ 99 ms

N/A
16:2E:D3:D6:67:FF
NOT BONDED -95 dBm ↔ 268 ms

N/A
75:19:C7:13:3E:4F
NOT BONDED -90 dBm ↔ N/A

Figure 7: Left: Trial device, Centre: Voltage (b) and leg motion (o), Right: Sniffer log

Conclusions

This paper details the development of a KEH device for converting locomotion of a cow's front leg into electrical energy for powering or recharging of IoT PLF devices. A device was built and tested in laboratory and field trials in which it was proven that it can successfully power wireless transmissions of a Bluetooth beacon and output ~13 mW of accumulated electrical power after 5-15 cow steps. The device is based on a moving magnet mechanism which comes into motion with each step taken by a cow. Animal KEH has its drawbacks - the device produces energy only during movement. This makes it suitable for free grazing scenarios where the animals change position frequently to forage. At this point the tested KEH generator can be used for recharging PLF devices and increase battery lifetimes. Some low power - low transmission frequency devices could even be made autonomous. Power generation is influenced not only by the amount and intensity of movement but also by the mounting position. In the laboratory stepping experiments, changing the position from the side to the back of the calf resulted with an increase in harvested powers. Further research is required to identify which position on the leg is the most suitable for harvesting maximum locomotion energy while still retaining comfort and wearability. Novel EM KEH architectures will be tested as well on other locations besides the cow's leg (collar, ear).

Acknowledgements

This project received funding from the European Union's Horizon 2020 research and innovation programme (Marie Skłodowska-Curie grant No 838375). The authors would like to thank the Materials science and environmental engineering group of Tampere University and Ahlmanin koulun saatio for their assistance with this work.

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