The final report of the project
ENOMA
Energy Self-Sufficient Systems
1.1.2019 – 30.10.2021

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Introduction

Energy harvesting enables the consuming device to generate the electricity it needs to operate. The source energy can be for example vibration, temperature difference, light, or RF signals. In this way devices can be powered by renewable and unpolluting energy, and also in locations, where is no electric grid available.

Content of the Project

The Aim of the Project

The research question of the project is how to get IoT devices to operate without external power source? The objective was to research and develop technologies and methods that enable devices to operate without external power source. The target can be divided to two sections: How the operating energy is produced in the vicinity of the device and How to minimize the power consumption of the device? Both of these questions must be resolved to enable the autonomous operation of the device.

Research Consortium

Research Institutions

The consortium consists of three research institutions: Tampere University (TAU), VTT Technical Research Centre of Finland (VTT), University of Oulu (UO).

Industrial Companies

The following companies participated to the project: Abloy Oy, Cargotec Finland Oy, Forciot Oy, JC Inertial Oy, Micro Analog Systems Oy, Meluta Oy, Nokian Renkaat Oyj, Radientum Oy, Reko Kumi Oy, RCP Software Oy, Teknikum Yhtiöt Oy, Wizense Oy, YL-Verkot Oy.

Modelling & Simulation

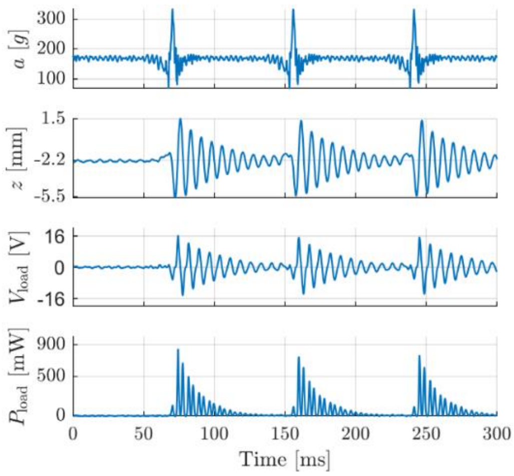
Designing an optimal device for a given application requires accurate simulation tools. For this purpose, a finite element method (FEM) based simulation tool was developed and implemented on MATLAB.

In the utilized simulation approach, we use FEM to accurately compute the electromagnetic quantities present in the system. For a given geometry, spline interpolation functions for induced voltage and magnetic force are created based on their pre-computed values at relevant magnet position and coil currents. This method makes solving the resulting time dependent problem extremely fast for a given harvester excitation.

Using the simulation tool, a harvester design can be optimized for the application of interest. An example of the obtained design parameters is shown in table below.

Parameter	Value
magnet radius	5 mm
magnet heigth	5 mm
magnet mass	3 g
magnet's remanent flux density	1.45 T
coil mass	2 x 4.5 g
turns	2 x 1000
coil heigth	4 mm
coil width	4 mm
spring constant	2.17 N/mm
optimal load resistance	310 Ω

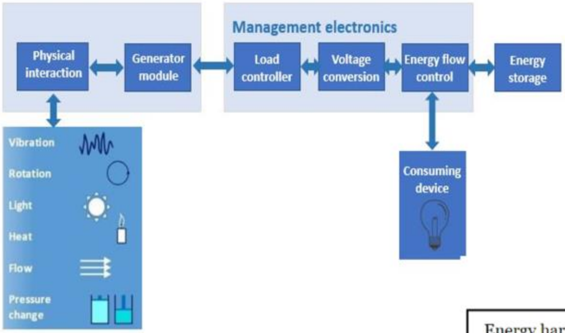
The simulation tool also models the output of the harvester, below is an estimation of the provided output voltage and power and the acceleration provided by the source energy, and the movement of the magnet of the harvester.

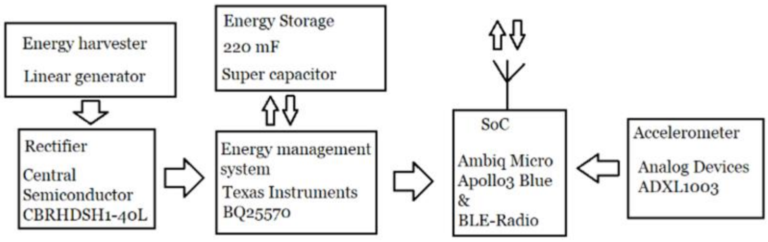


Harvester System

The general architecture of a harvesting system is presented in figure below. The power source specific microgenerator converts the source energy to electricity. The generated voltage must be converted and rectified by the energy management electronics. The charging of the energy storage is also managed by the electronics. A low-capacity energy storage is usually needed and implemented by a supercapacitor. The consuming device is electrified by the management electronics.

Below and right to the general architecture is shown how the architecture was implemented in our proto system. The components of our proto system are presented in the following sub-chapters.





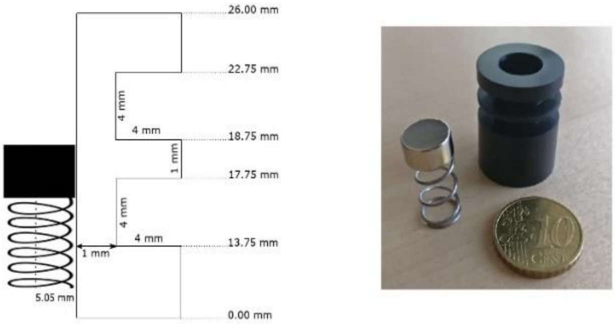
Inductive Linear Harvester

On the grounds of the results of the simulation, several prototype devices were implemented.

The housing of the harvester is implemented with a programmable turning tool with indexable insert from polyacetal bar. The housing with the springs and the magnet is shown in figure below on left (a), and on right (b) is the housing with the two coils. The coils are made of copper wire with a diameter of 0,1 mm and the number of turns is 2000 in both. The coils are winded in opposite directions.

a b

After the first prototype implemented it became aware that a harvester with smaller dimensions with the same power output would be possible to construct, if only one spring with a greater spring constant would be used. The values for the spring and the magnet were recalculated and a new housing was lathed. The housing of the second prototype has dimensions 20,10 mm x 26,00 mm, which is 7,0 mm lower than the first version. The dimensions are shown in figure below on left (a), and the housing with the magnet and the spring on right (b). The coils in single-spring version of the harvester are similar than in the double-spring version.

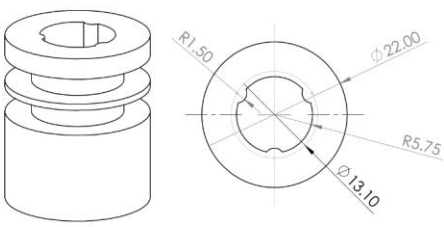


a *b*

The spring used in the single-spring design is a normal commercially available helical spring made of stainless-steel wire with a diameter of 0,81 mm. The diameter of the spring is 9,14 mm, the length of rest is 15,75 mm, and the spring constant is 2,17 N/mm.

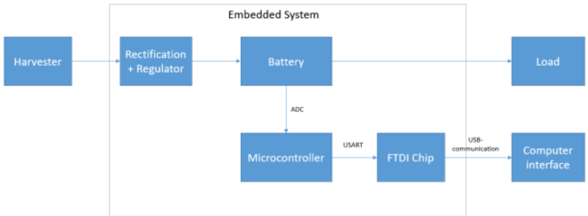
The dimensions of the disc shaped nickel-plated permanent magnet, which is also a commercial product, are 10,00 mm x 5,0 mm. The strength of the magnet is 3,3 kg.

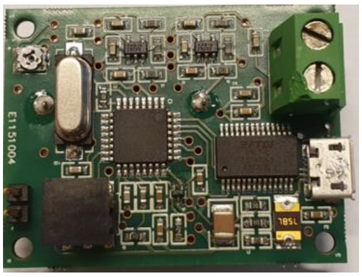
The friction between the magnet and the housing of the harvester decelerates the manoeuvring speed of the magnet and consequently the electric production of the harvester. During the construction of the third prototype, in pursuit to reduce friction between the moving magnet and the cylindrical housing of the harvester, we turned to the precision design principles and the principles of ball bearing operation. By employing three guides inside the harvester housing the magnet can be precisely aligned in space and by reducing the contact surface between the magnet and the housing, like in a ball bearing construction - the friction is minimized. The low-friction design is shown in figure below. The method of manufacture was similar to that of the previous version, likewise the dimensions, the used magnet and the spring, and the coils are identical to the preceding version.



Management Electronics

A proto version of the management electronics was designed and implemented, shown in the figure below.

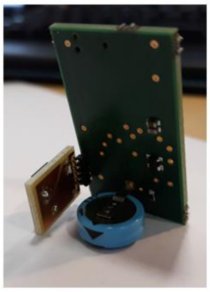




The proto also included a user interface on PC, that provided information for example about the charging current etc.

An Integrated Module Including Management Electronics, Measurement, Energy Storage and Transmitter

During the project, integrated circuits, capable to perform the power management, game commercially available. Using this kind of circuits makes it possible to implement the harvester system with less components and so in smaller scale and weight. For that reason, we substituted an integrated management circuit for the above presented management electronics.



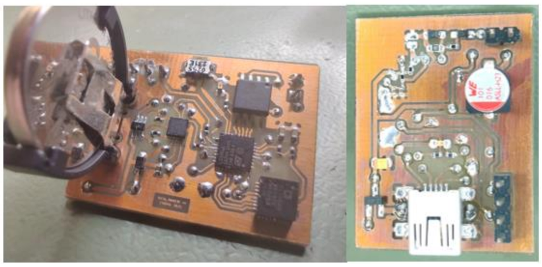
The base of the system is an Artemis module implemented with Ambiq Apollo 3 Blue Microcontroller. The microcontroller takes care of the measurements and the transmission of the measured values over BLE. The management electronics is implemented with Texas Instruments BQ25570 circuit optimized for an inductive linear harvester. The storage of the electricity is handled by a 220 mF two-layer supercapacitor. The measurements of the acceleration are performed by a single axis analogical output accelerometer ADXL1003, capable to measure acceleration up to 200 g. The dimensions of this integrated electronic packet are 20 mm x 35 mm x 15 mm.

Testing Tools

For testing purposes, different kind of tools and devices (hardware and software) were implemented, the most used are presented below.

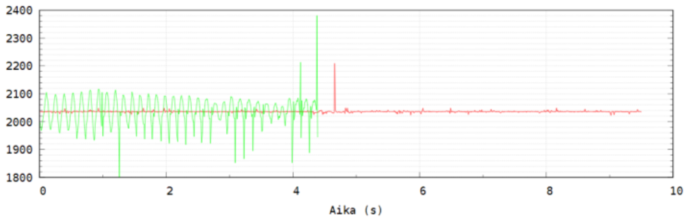
Datalogger

A datalogger was designed and implemented to measure the acceleration and the output voltage of the harvester. The logger automatically initiates the measurement when an acceleration above the threshold value affect to it. The sampling frequency can be set between 1 – 20 000 Hz. The logger has 1 Mb NVRAM memory, that is capable to store 65536 samples.



Receiver, Graphical User Interface, Android BLE Sniffer

As a receiver, an Ambiq Micro -based card was used. It was connected to a laptop running a software implemented to receive and illustrate the data. A Bluetooth Low Energy sniffer was implemented on Android platform, and it was used to check the operation of the transmitter.



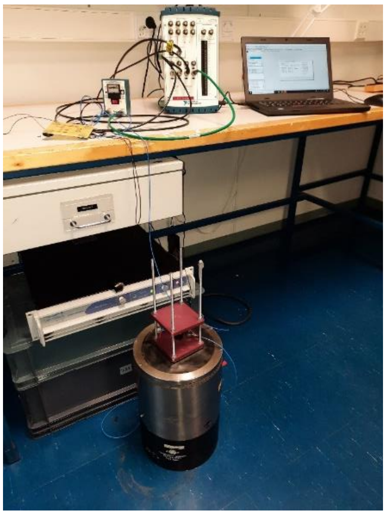
Testing

The testing of the proto system was performed in laboratory. The testing environment and results are described in the following sub-chapters.

Testing Environment

The preliminary testing of the harvester was performed by a muscle maintenance hammer. An adapter to connect the harvester to the hammer was manufactured by 3D printing. The frequency and the amplitude of the vibration provided by the hammer are adjustable. This apparatus, shown in figure below, was used to quickly and unlaboriously test the fundamental operation of the harvester.

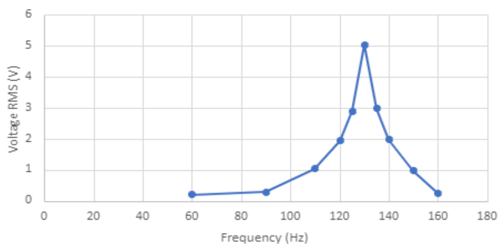
In the second phase of the testing the measurements were adjusted and performed, and the results gathered by Signal Express measurement and data-logging software running on a laptop computer. National Instruments USB6251 Data Acquisition Module was used to connect all the test and control points. The device to generate the source energy was Vibration exciter system 4805 manufactured by Brüel & Kjaer, and the control signal to the exciter was amplified by Veneable Linear Amplifier VLA 1000. The harvester was connected on the exciter between two plastic plates. The acceleration of the harvester was measured by an PCB 355B02 acceleration sensor, with a 10 mV/g sensitivity, connected next to the harvester, and PCB 480C02 Signal Conditioner was used to condition the accelerometer signal. The test configuration and devices are presented in the figure below.

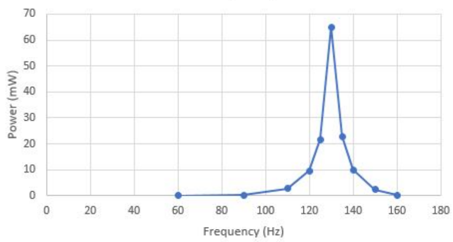


Testing Results

The tests were performed with an adjustable electrical load which was implemented with three resistors and one potentiometer and connected to the harvester, and also with the BLE transmitter as an electrical load.

The with adjustable load were performed by regulating the frequency of the vibration used as a source energy and by measuring the voltage and the current from the load powered by the harvester. The electric power rms value was calculated from the voltage and the current. A representative sample of the tests results is shown in figure below. The test results strongly indicate the characteristic of frequency dependence of inductive linear harvester. The output power has the maximum value at the resonance frequency, and the value of the output power decreases rapidly when dislocating from the resonance frequency. The resonance frequency was observed to equal 131 Hz, in the results of the simulation the value was 134 Hz. The difference between the simulated and the measured values are mainly caused by the mass of the sealing compound used to secure the springs to the magnet, which was not acknowledged in the simulation.





The tests with the real power consuming device proved that the electricity generated by the harvester is enough to power the device and to load the energy storage simultaneously. With the fully loaded energy storage, the device was capable to operate five minutes after the harvester stooped to provide energy.

Minimizing the Consumption of Electricity

The second research question of the project was “How to minimize the power consumption of the device?” In our case the device was the Bluetooth Low Energy (BLE) transmitter that was powered by the harvester. The minimizing was implemented mainly in the means of software. More precisely by shutting down the unnecessary parts of the system circuit in the set up phase, by optimizing the parameters of the BLE-profile and by changing to the deep-sleep state always when possible. Also the interval of the BLE-connection was minimized, and the latency of the peripheral was set to maximum value. The used rapid exchange of information made also possible to maximize the time peripheral can be in sleep state.

By the above-described means, the power consumption was reduced 73% compared to normal general-purpose way of BLE transmission. The power consumption of the proto device was: minimum min 3,1 µA, max 4650 µA and average 295 µA.

In addition to the software optimization, the power consumption was minimized also in electronical implementation for example in component selection and by minimizing the number of components.

The achieved results are easy to generalize to different use cases.

Publications

During the project the publications descripted in the following sub chapters were written.

Thesis

T. Salminen, Energiankulutuksen minimointi energiaomavaraisessa sulautetussa järjestelmässä, Master’s thesis, Tampere University, 2021. This thesis handles the means to reduce the power consumption in an IoT device powered by an energy harvester.

R. Laine, Bluetooth Low Energy Data Transfer in Energy Harvester System, Master’s thesis, Tampere University, 2022. The thesis researches and compares the means, tools and platforms to implement the embedded software needed in Bluetooth Low energy data transfer in a system powered by an energy harvester.

Scientific Peer-Reviewed Publications

T. Kivimäki, J. Vanhala, A. Halme, J. Ruuskanen, T. Salminen, Distributing the Generation of Electricity to Extreme Level, Proceedings of the 4th International Conference on Power and Energy Applications, 2021. This paper introduces the design, implementyation and testing of our linear inductive harvester proto system. The paper was presented in 4th International Conference on Power and Energy Applications, Busan, South Korea (on-line due to the Covid situtation), October 10th, 2021.

J. Ruuskanen, D. Blazevic, P. Rasilo, T. Tarhasaari, A. Halme, T. Kivimäki, J. Vanhala, Modelling of an Axisymmetric Linear Inductive Energy Harvester with FEM: a Spline Based Approach, IEEE Transactions on Energy Conversion, 2022. This article describes how the simulation and modelling tool, implemented on Matlab during the project, operates and can be used. The article is (will) be published in the journal IEEE Transactions on Energy Conversion.

Other

Declaration of Invention, J. Ruuskanen, Electromagnetic Induction Based Apparatus Design for Low Friction Kinetic Energy Harvesting. This invention describes a novel design for the framework of an energy harvester. The design enables a greater production of electricity by reducing the friction between the moving magnet and the framework.

Conclusions

In this project, techniques, tools, methods, and prototypes were developed by which it is possible to harvest electric energy from the source energies freely available in the environment, like for example, from mechanical vibration and movement. By energy harvesting, it is possible to get renewable and clean energy to power the electrical devices. Energy harvesting also provides several other advantages: electrical devices can be used without batteries and wires, all kinds of usability of the devices increases and also the commercial competitiveness increases.

During the project, several prototypes of inductive linear harvester were implemented. Also the management electronics and power storage were researched, implemented and tested. Furthermore, the electricity usage minimization for devices to be powered by an energy harvester, were researched and piloted. Still further, a prototype of a whole harvester platform, consisting of a energy harvester, management electronics, power supply, and an IoT device powered by the harvester were built and tested.

References

[1] T. Kivimäki, J. Vanhala, A. Halme, J. Ruuskanen, T. Salminen, Distributing the Generation of Electricity to Extreme Level, Proceedings of the 4th International Conference on Power and Energy Applications, 2021.

[2] T. Salminen, Energiankulutuksen minimointi energiaomavaraisessa sulautetussa järjestelmässä, diplomityö, Tampereen yliopisto, 2021.

[3] R. Laine, Bluetooth Low Energy Data Transfer in Energy Harvester System, Master’s thesis, Tampere University, 2022.