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ENEHRVIT

Executive summary

The flourishing of the Internet of Things (IoT) paradigm has posed impressive new challenges concerning the problem of powering small, wearable or remote electronic devices.

In this field, batteries represent the current dominant technology, but their limited power density, their short life, the difficulties and costs required for their replacement, and their significant environmental footprint call for the development of new solutions. An alternative to batteries is represented by energy harvesting, which consists of the collection of energy from the surrounding environment: such energy, which would be otherwise lost, can be successfully employed to power autonomous electronic devices.

Within this framework, the purpose of the ENEHRVIT project is twofold: on the one hand, new innovative configurations are introduced and their effectiveness is evaluated, and, on the other hand, issues concerning state-of-the-art technologies are addressed by developing new techniques to determine their impact and, hence, to outline the most efficient operations of such devices.

The final outcome is a set of software tools that can be used to test and optimize both conventional and new harvester configurations, prior to their practical implementation. An additional value is provided by the different methodologies that have been employed in the analysis, which include linear models, nonlinear dynamics techniques and stochastic analysis methods.

To draw the conclusions, not only does the value of the ENEHRVIT project lie in the developed software tools, but also in the comprehensive methodology that has been followed, which combines a deterministic and a stochastic approach, allowing to study and optimize energy harvesters under different and complementary perspectives.

Key Words

Piezoelectric harvesters, stochastic calculus, optimization, MATLAB

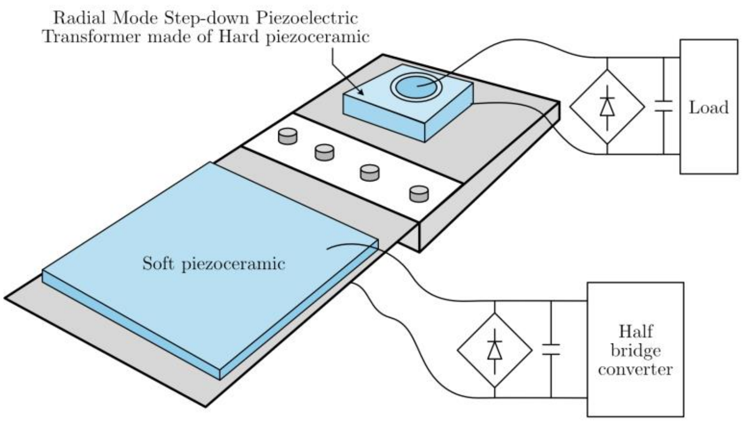
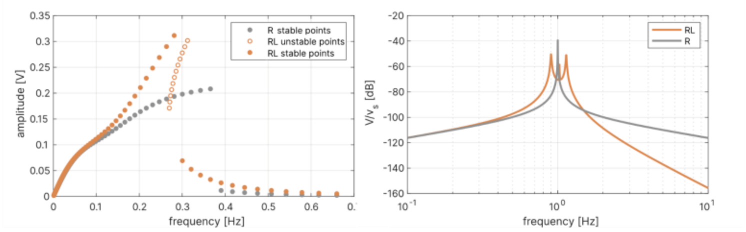


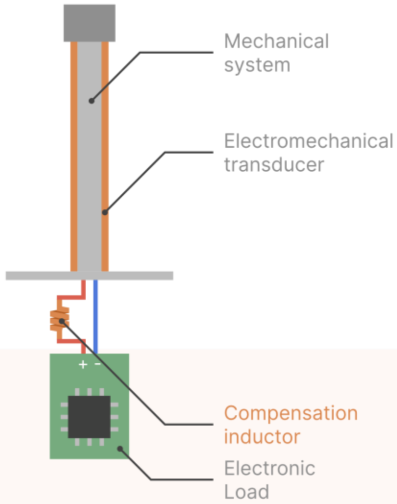
Figure 1 – An energy harvesting device based on the piezoelectric cantilever technology.

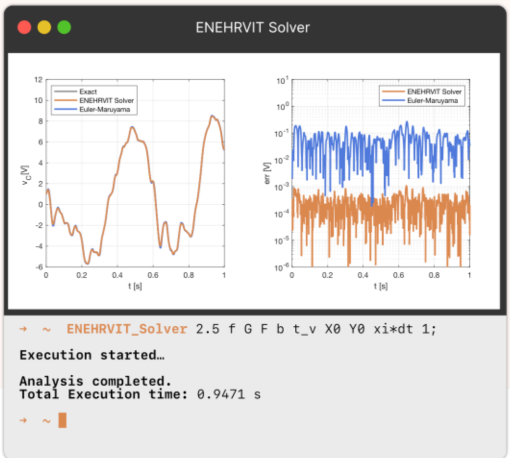
RESULTS SUMMARY

ENEHRVIT
Energy Harvesting for IoT

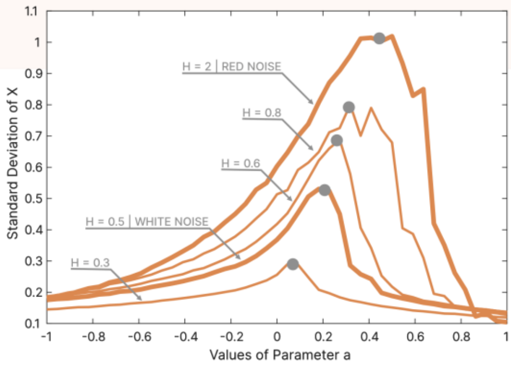
A conversion circuit configuration to improve the performance of an energy harvesting cantilever



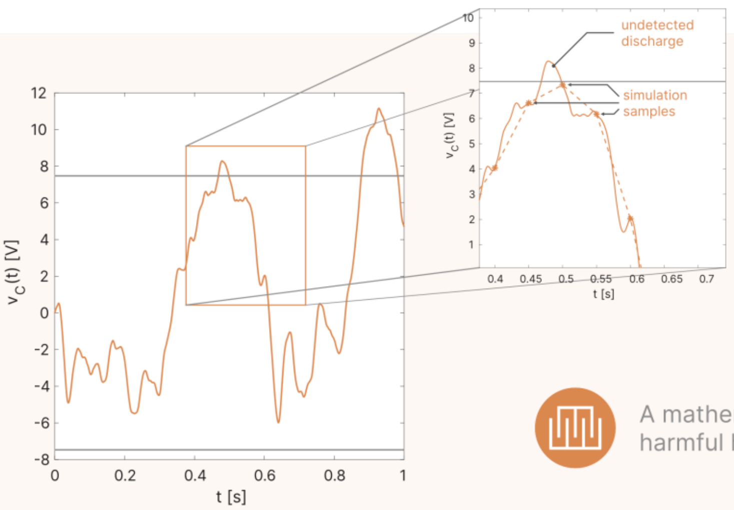


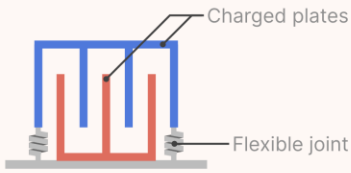


A software tool to analyze energy harvesters affected by stochastic vibrations



A mathematical method to design a bistable energy harvester with optimal parameters





A mathematical method to predict harmful hit events in electrostatic harvesters

Project description written by the Principal Academic Tutor

Real world systems are always open, because they exchange energy with the surrounding environment. Fluctuation-dissipation theorems establish that, in an open system, an energy flow must exist from macroscopic to microscopic (thermal) degrees of freedom due to dissipation. The flow in the opposite direction manifests itself as fluctuations of the macroscopic variables. In nonlinear systems fluctuations are not expected to be isotropic. As a consequence of nonlinearity, preferred directions exist along which fluctuations are amplified, while in other directions they are quenched. The result is a net, not null contribution to the expected values of macroscopic variables. The far-reaching consequence is the conceptual possibility to realize a “Maxwell demon”, capable of extracting energy from the environmental noise and convert it into usable power.

Part 1: *Modelling and analysis*. Irrespective of the working principle, most energy harvesting systems rely upon oscillators to convert random environmental energy into usable electrical power. The main model will be reviewed and analysed using state of the art methods. Different technical solutions will be compared in different scenarios (linear oscillators vs nonlinear, white noise vs coloured) using different analytical tools, i.e. time domain Monte Carlo simulations, stochastic calculus, statistical-probabilistic methods based on Fokker-Planck equation. Software tools for the simulation and analysis will be developed to test the validity of the models.

Part 2: *Development of new technical solutions*. The problem of energy extraction from noise and its conversion into electrical power will be addressed. Physical models, mathematical methods and simulation tools developed in part 1 will be used. Students will review state of the art solutions for energy conversion and for the improvement of energy, efficiency such as stochastic resonance. Students will be asked to suggest improvements and/or innovative solutions. These solutions will be implemented and tested in the software tools, and their practical feasibility will be discussed.

Part 3: *Design*. Using models and simulation tools developed in part 1, and having identified improvements or new solutions, a methodology to optimize the response of energy harvesting systems will be designed. In particular, the device parameters associated to significant physical properties (such as shape, dimensions, material, electrical properties, etc.) should be identified and properly optimized. We expect that this task will require the development of a software tool oriented to numerical optimization techniques and design.

Team description by skill

The team is very suitable to deal with any real-life challenges. In particular, all of the team members are characterized by a strong engineering background that ranges from energy and nuclear engineering to mathematical and aeronautical engineering. Each team member is therefore endowed with an extraordinary technical knowledge, concerning especially energy devices and numerical aspects of any problem. For the same reason, the team is interlaced with a natural logical and analytical reasoning.

Thanks also to previous courses, the whole team benefits from very useful soft skills such as enhanced teamwork, very good communication and well-trained problem-solving abilities. As well as this, most of them gained organization skills and a consolidated experience in managing complex projects.

Finally, the whole team is permeated by a strong sense of creativity which is exploited in order to face the different problems with an out-of-the-box thinking approach.

Goal

The main goal of the ENEHRVIT project is to evaluate the potential of novel principles for the development of innovative devices capable of harvesting energy from the environment and transforming it into electrical energy, available for powering the next generation of autonomous information and communication technology devices. However, there are also other objectives such as:

Scientific objectives: gaining better understanding on the role of different kinds of noise sources (white and coloured) in electrical and mechanical systems. The project also aims at understanding the role of nonlinearity in the dynamics of noisy systems.

Technological objectives: developing innovative solutions for powering wearable wireless device, monitoring systems, etc. Although the energy that could be extracted from noise is very limited (of the order of microwatts), it may still be relevant for low power, wireless sensors and actuators. Moreover, the development of software tools for simulation of stochastic process, noise analysis, optimization and design may raise the interest of both academia and industry.

Didactic objectives: learn and work on practical topics (energy efficiency, power saving, renewable energy), in front-end technological areas.

Understanding the problem

The development of the internet of things paradigm poses impressive new challenges, in particular concerning the problem of powering small, wearable, or remote electronic systems. Old fashioned solutions, i.e. disposable batteries, are not viable because of the limited power density, short life and practical impossibility of replacement once exhausted. An alternative solution could be the use of a system able to gather energy where and when available. Energy harvesting refers to a set of technical solutions to collect energy from the surrounding environment, so that it can be used both to supply power to systems, or to extend the battery lifetime when continuous operation without maintenance is highly desirable. Therefore, the main problem is represented by the identification and the design of a suitable technology for energy harvesting.

Furthermore, even once a suitable technology is identified, in order to opportunely study the behaviour of energy harvesting a completely new and complex mathematical framework is needed. Indeed, the surrounding environment generally provides the energy source in terms of a random input, which entails many more challenges both for simulation and application purposes, reflecting a more complex identification of the key factors needed to design the energy device.

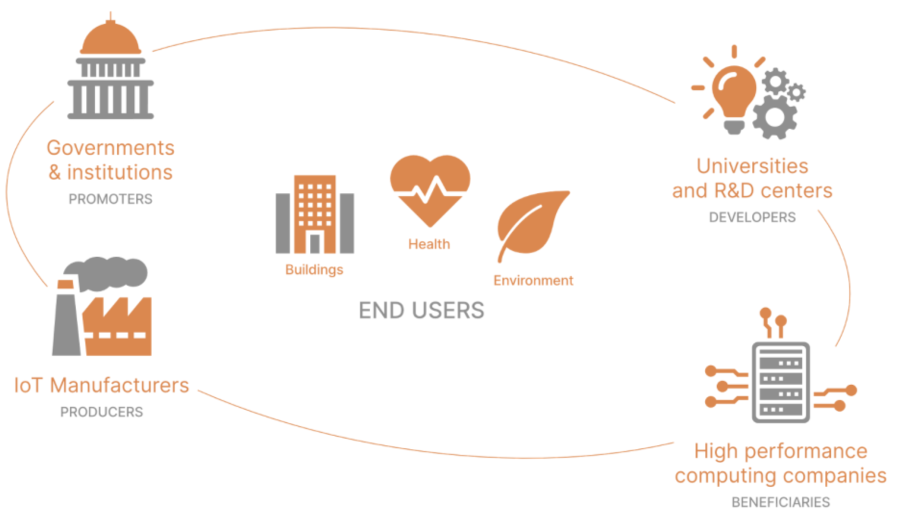


Figure 2 – Scheme of the main stakeholders in the current Energy Harvesting market.

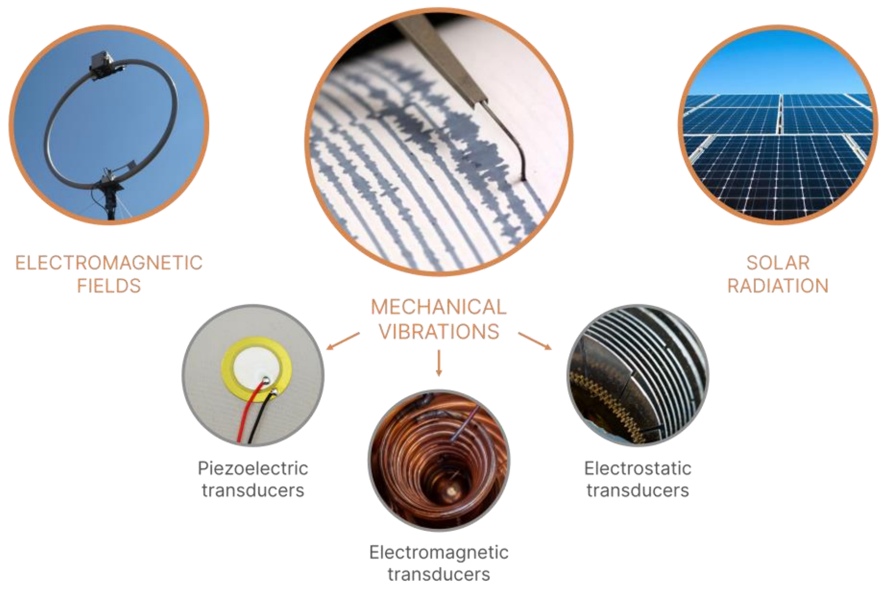


Figure 3 – Some of the main Energy Harvesting sources and main available technologies to harvest mechanical vibrations.

Exploring the opportunities

Depending on the characteristics of the source, the conversion into electricity of energy provided by the environment is possible through different physical mechanisms.

The large majority of harvesters are based on the conversion of kinetic energy. Piezoelectricity, electromagnetism and electrostatics are the three main transduction principles exploited. The vibrational kinetic energy is, basically, available everywhere and, differently from other renewables energy sources as the Sun or wind, it does not suffer large fluctuations during the day or the year.

Electromagnetic or electrostatic harvesters can generate enough energy to power the most common electronic devices, such as wearables and mobile phones. However, they are often not user-friendly being bulky and rather heavy.

Harvesters made of piezoelectric materials are the leading technology, although they can usually supply lower power levels with respect to the other devices. The astonishing versatility in terms of possible geometries and application environments is, likely, the main reason behind their success. The capability of being manufactured in a large range of configurations allows to explore a limitless variety of different technological solutions. Currently, the most widespread harvesters are cantilevers since this structure combines the simplicity of the working principle with quite high efficiencies.

Generating a solution

After properly studying the existing solutions, the piezoelectric harvester appeared as the technology with the most promising developments and performances because of their simple mechanical structure and easy miniaturization.

Because of its different nature, the energy source was analysed in two different regimes: deterministic regime and stochastic regime. In the deterministic case, the optimal harvester parameters were identified by looking at the circuit model of the system and by employing classical circuit theory techniques. Analysing both a linear and a nonlinear harvester, it was clear that the introduction of an inductor in the conversion circuit, which is usually purely resistive, allows to compensate the intrinsic capacitance of the piezoelectric material. Thanks to this adjustment, it was possible to exploit a broader operating frequency range and, hence, to ensure a higher flexibility of the device. However, in the real world, most energy sources cannot be described as a superposition of harmonics since they are affected by stochastic noise or they are stochastic processes themselves. To solve this issue, an innovative software was developed on the basis of an appropriate mathematical framework and it is believed to be the most accurate solver in scientific literature for stochastic systems affected by coloured noise, like the majority of circuits used for practical purposes. However, despite the enhanced accuracy of the simulations, due to the randomness of the energy source, there is still the threat of completely discharging the harvester, known as the *hitting problem*. Unfortunately, the performed research activity showed that the existing formulas do not work properly for coupled circuits, as the ones used to model piezoelectric harvesters. Therefore, different corrections to properly estimate the hitting time were developed and they are believed to be extremely useful for further developments. Finally, a parametric study was repeated for the stochastic regime with a major focus on the difference in efficiency between linear and nonlinear (bistable potential) models, highlighting the greater performance of the latter for Fractional Gaussian noises.

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