PhD subject description
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Fully-funded

Small-scale kinetic energy harvesting optimized by intelligent control of the electromechanical dynamics

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1 Context

1.1 Introduction to small-scale kinetic energy harvesting

The energy cost of measurement, computation and communication has been continuously decreasing in small-scale, thanks to the technological progress. It is therefore possible to make these systems autonomous by powering them using part of the energy present in their immediate surroundings, after converting it into electrical energy. In particuliar, kinetic energy harvesters (KEH) allow converting part of the mechanical energy transferred to the system {electronics to power + KEH} by its surroundings into electrical energy. The targeted consumption levels range from about a microwatt to about a milliwatt. Among possible applications, one can mention wireless sensor network nodes for structure monitoring, or implanted medical devices.

Small-scale inertial KEH are composed of a mechanical part, which is built around a mobile mass that is usually part of a mechanical resonator, of an electromechanical transducer (usually electrostatic, piezoelectric or electromagnetic), and of an electronic interface that's responsible for the electrical conditioning of the transducer.

1.2 The challenge of compatibility with low-frequency and irregular mechanical inputs

Regardless of the chosen transduction mechanism, a major problem in the design of inertial KEH is their compatibility with non-harmonic or low-frequency mechanical excitations. That is, the amounts of converted power remain low compared to the absolute limits set by the devices physics. This problem is inherent to the resonant nature of the mechanical part of most reported KEH, along with their small sizes. Furthermore, these systems exhibit nonlinear dynamics, resulting in difficult analysis and direct optimization.

Most of the past decade research efforts in the field of KEH have attempted to overcome this challenge of compatibility with low-frequency and/or irregular mechanical inputs. Research teams worldwide have notably proposed to add deliberate source of nonlinearities, either on the mechanical or on the electrical side, that can be of help in some situations. However, these nonlinearities further complicate the systematic design of KEH, constrain the analysis to very specific contexts, and are not necessarily resulting in systems that perform better than their linear counterparts [Hal13].

2 Subject of the PhD work

2.1 Principles of near-limits kinetic energy harvesting

In [HT15], another route to solving this challenge has been proposed. There, the authors design a KEH system based on the control of the system's electromechanical dynamics, computed and implemented in real-time as a function of the sensed mechanical excitation input. This control aims at actively implementing (that is, by investing some energy) a specific trajectory for the KEH's mobile mass. This trajectory depends on the mechanical input. One can show that the force implementing this control converts energy in amounts that corresponds to the physical limit, for any given mechanical excitation input, in the absence of dissipative losses. We shall call a KEH working along those principles a "near-limits KEH".

The specific optimal trajectory that is to be implemented by the control consists in toggling the mobile mass position from one geometrical extremity of the system to the opposite one, locally in time at instants that correspond to the extrema of the external mechanical input. In between two such extrema, the mass has to be kept at the system's geometrical extremities.

In addition, one can show that it might be beneficial to the overall net converted energy figure to ignore some of the input's extrema, and to not carry position toggling when those are sensed [GKB19]. This is due to the energy cost associated with each implementation of the mass toggling. Carrying this selection in a causal and optimal way in terms of total net converted energy requires to design an algorithm that takes the toggling decision. This decision has to be based on an *a priori* chosen, possibly learnt or fitted, statistical model of the inputs that the KEH is submitted to [SGK20].

2.2 Overview of the research to be carried out

In order to design near-limits KEHs that effectively approach the physical limits on energy conversion, the different components of the system have to be designed. These components are:

- the mathematical form of the control that locally implements the mass position toggling,
- the algorithm selecting the extrema of the input force at which the mass should be toggled,
- the electromechanical transducer used for energy conversion and its geometry,
- the electronics transferring the energy between the transducer and the system's energy reservoir,
- the electronics measuring the mechanical state of the system necessary to compute the control,
- the electronics computing the control at each toggling of the mass position

The difficulty in selecting and sizing these components is due to the coupling that exists between them. This coupling, in turn, comes from the constraint of minimal energy expenditure, as each of those blocks is the source of power consumption.

The objective of the PhD is to propose a systematic design flow of near-limits KEHs under specifications that are defined by each application context requirements. This design flow will be determined by an *a priori* theoretical study, validated by simulations and by experimental demonstrators of the different components whenever it applies. At the end of the PhD, it is expected that a systematic design flow is proposed for at least a subset of the constitutive blocks listed above, and that this design flow is validated by a prototype. A starting point for the design can be the architecture that has been already proposed by the research team at ESYCOM and collaborators in [KJB19]. The specific subset of the foregoing elements that the PhD candidate will study can depend on his/her thematic preferences and background.

The study is also expected to give some clear assessment of the feasibility of KEH as a mean to power autonomous devices in various applications. Hence, the PhD student will have to characterize the contexts (defined by the type of mechanical inputs and the constraints on the system) for which near-limits KEH (strongly) outperforms passive KEH designs, and conversely. This requires to build an understanding of the fundamental differences between those two classes of KEHs.

By her/his contribution, the PhD candidate will substantially contribute to solving the problem of KEH compatibility with low-frequency and/or irregular vibrations. This is a key effort in assessing the feasibility and enabling many important applications that can benefit from small-scale KEH, and in particular on-body KEH in which these types of vibration are typically present.

3 Scientific and academic setting

3.1 Kinetic energy harvesting at the ESYCOM laboratory

The recruited PhD candidate will carry out his/her research at the ESYCOM laboratory. For more than a decade, the laboratory has been a major international actor in the research on kinetic energy harvesting using both microelectromechanical (MEMS) electrostatic and triboelectric transducers. The laboratory works on all aspects of KEH, ranging from system-level modeling, to the fabrication of devices and their electrical interfaces.

The laboratory has access to a cleanroom that allows for the fabrication of MEMS devices, as well as to an electromechanical characterization lab. The experimental axis is carried at the lab by Philippe Basset (full professor at ESIEE Paris, Université Gustave Eiffel). It is complemented by a theoretical and modelling axis carried by Armine Karami (full-time permanent researcher at CNRS). The recruited PhD candidate will mainly contribute to this latter axis about theory and modelling, with some interaction with researchers from the experimental side when needed.

3.2 Other collaborations

Collaborations outside of the laboratory are to be expected with Dimitri Galayko (associate professor at Sorbonne Université) and Jérôme Juillard (full professor at CentraleSupélec), and their respective teams.

4 Sought profile for the candidate

4.1 Educational background

The ideal applicant has a degree in electrical engineering. Students with a mechanical engineering or physics background are also encouraged to apply. The applicant must have a strong appetite for the theoretical approach to engineering systems.

4.2 Scientific and technical skills

Knowledge in electronics (linear and non-linear circuits) as well as in physics (mechanics, electrostatics) is a hard requirement. The successful applicant should also have some background in control, systems theory (deterministic or probabilistic), and in statistics. Prior exposure to the analysis and control of nonlinear dynamical systems is a definite and useful plus for this research project, as well as knowledge in timeseries analysis or machine learning. Likewise, prior exposure to ultra-low power electronics for measurement or computation will be highly appreciated.

The successful applicant must also be familiar with designing, running, and interpreting results of simulations of physical systems, both deterministic and random. Hence, he/she should know at least one programming language among Python, Julia, C++ or MATLAB, as well as the associated mathematical libraries. An experience with SPICE for electronic circuit simulation is also useful to the research project. The applicant should have enough scientific computation knowledge in order to guide her/his usage of the aforementioned tools.

Some basic experience with the classical equipment of an electronics characterization lab is recommended: prototyping breadboard, oscilloscope, function generator, ...

4.3 Language

Fluency in English is a must, both spoken and written. French is a plus but is not mandatory.

5 Practical information

5.1 Starting date and duration

The PhD is expected to start on October 1st 2021 for an exact duration of three years (36 months).

5.2 Compensation

The PhD is fully funded for its whole duration, with a monthly compensation of about 1350 euro per month net salary. This salary can be increased by about 300 euros per month if the PhD candidate is additionally recruited for a teaching assistant position (64 hours per year teaching duty). Note however that the availability of teaching vacancies vary each year, and that they remain usually limited for non-French speaking PhD candidates.

5.3 Geographical location

The PhD candidate will work at the ESYCOM laboratory location, in Champs-sur-Marne, Paris metropolitan area. The center of Paris is at about 20 minutes using public transportation.

5.4 Housing

The university can help foreign PhD students to find housing at an affordable price.

6 Contact

Armine Karami
Permanent research scientist (chargé de recherche) at CNRS
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Prospective applicants are encouraged to contact Armine Karami (contact details above) for more information. Applications (at least a cover letter and a resume) have to be sent to Armine Karami.

7 Bibliography

[Hal13] E. Halvorsen. "Fundamental issues in nonlinear wideband-vibration energy harvesting". In: *Physical Review E* 87.4 (2013), p. 042129.

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[GKB19] D. Galayko, A. Karami, P. Basset, and E. Blokhina. "AI Opportunities for Increased Energy Autonomy of Low-Power IoT Devices". In: *2019 26th IEEE International Conference on Electronics, Circuits and Systems (ICECS)*. IEEE. Nov. 2019.

[KJB19] A. Karami, J. Juillard, E. Blokhina, P. Basset, and D. Galayko. *Electrostatic Near-Limits Kinetic Energy Harvesting from Arbitrary Input Vibrations*. 2019. arXiv: `2002.07086`.

[SGK20] A. Sokolov, D. Galayko, M. P. Kennedy, and E. Blokhina. "Near-Limit Kinetic Energy Harvesting From Arbitrary Acceleration Waveforms: Feasibility Study by the Example of Human Motion". In: *IEEE Access* 8 (2020), pp. 219223–219232.