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ORIGINAL PAPER

Interactive method for autonomous microsystem design

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Abstract This paper describes a multidisciplinary and interactive approach for the design of autonomous microsystems. These devices satisfy the actual requirements in terms of size, cost and autonomy. This autonomy is obtained by harvesting the energy in microsystem environment. There is no denying that microsystem design requires multidisciplinary skills and necessitates collaboration between several groups with different fields of expertise. All aspects have to be considered to get a mechanically, electronically and energetically efficient structure, consistent with the specifications and the requirements of the problem. However, few designers are competent enough in all the involved engineering fields. Thereby, we propose a multidisciplinary and interactive approach for autonomous microsystem design. This method delves into several steps. It begins by a global description and analysis of the system in its environment. This problem structuring is mainly based on the use of tools of functional analysis. Then, the autonomous microsystem is modeled, with a special care on energy harvester design. The method is applied to energy harvester design for automotive braking system instrumentation. The interactive character is present through the consideration of interactions (cognitive, physical and sensory). Finally, the multidisciplinary aspect is ensured by the collaboration and the exchanges between designers and numeric tools.

Keywords Multidisciplinary approach · Interactivity · Instrumentation · Microsystems · Energy harvesting · Piezoelectric conversion

1 Introduction

With the advance of science in electronics and the development of nomad devices, microsystems are increasingly present in a multitude of fields (automotive, aeronautics, medical, telecommunications, video games, etc.) [1,2]. By means of microsystems, manufacturing costs are reduced and miniaturisation allows increasing the integration capabilities of the system and leads to non intrusive measurement systems.

Microsystems are complex due to their heterogeneousness and there is not any adapted tool for their design. Therefore, we developed a method to overcome this problem and facilitate microsystem design. Moreover, if we want to make these devices autonomous, energy issue must be added. This constraint is required for some applications. This objective can be reached by harvesting energy from the environment. Such a solution is achievable with microsystems having very low power consumption [3].

Actually, very different fields are involved in microsystem design: electronics, mechanics, materials science, thermics, energetics, fluid dynamics, etc. The study of the global problem should require multidisciplinary skills. Nonetheless, few designers have the required knowledge in the whole fields.

Our objective is to propose a multidisciplinary and interactive method to assist microsystem designers, in a given situation. As we focus on autonomous microsystem, energy harvester design is an important part of our work. The idea is to facilitate crucial design activities and to create collaborations between designers.

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Our last works are about autonomous microsystem design. Thus, we have applied the method to energy harvester design for automotive braking system instrumentation. Before studying the energy harvesting, we need to identify the location of each microsystem.

After defining what a microsystem is, the paper is divided in two main parts. The first one exposes our multidisciplinary and interactive method for microsystem design, with a special focus on energy harvester design. It considers an application in a specific life situation. This leads to the problem structuring, essential to satisfy the need. Then, for energy harvesting design, the developed tools are presented. They are used to support the method. The second part of the paper illustrates our approach. The application considers the integration of autonomous microsystem for the instrumentation of an automotive braking system. In this example, we mainly develop the piezoelectric energy harvester design and restrict the tools to this part of the microsystem.

2 Global architecture of microsystems

A microsystem is compact, miniaturised and multifunctional. It is defined as a miniaturized intelligent system integrating sensor and/or actuator associated to their processing unit (Fig. 1). Microsystems interact with non electrical world by means of sensors and actuators. They are also able to exchange information and to communicate with the external environment or with other microsystems. They need an energy source (embedded or not) to work.

Data are collected by sensors and sent to the processing unit. They may be transmitted to a remote control station by radiofrequency, for example. The particularity of our work is to consider autonomous microsystems working with ambient energy. In this special case, the energy source is replaced by an energy harvester which is composed of:

- An energy converter to convert ambient energy into electrical energy
- An AC/DC converter if the signal has to be rectified
- A DC/DC converter to adapt the signal to a load
- An energy management unit to control and pilot the device
- An energy storage element.

In the view of the scope of microsystems, their design is dependent on the considered application. Moreover, sensors and actuators selection mobilize mechanical skills while control processing unit needs more electronic knowledge. Then, energy harvester design combines mechanical, electronic and energetic engineering fields.

To deal with the problematic of autonomy, we have to list ambient energy sources. Studies on this topic show that suitable sources for energy harvesting are radiant energy (solar, radiofrequency…), thermal energy and energy produced by mechanical vibrations or deformations [4–6].

Afterwards, the energy harvester can be evaluated, leading to the structure dimensions. To do so, several steps are required:

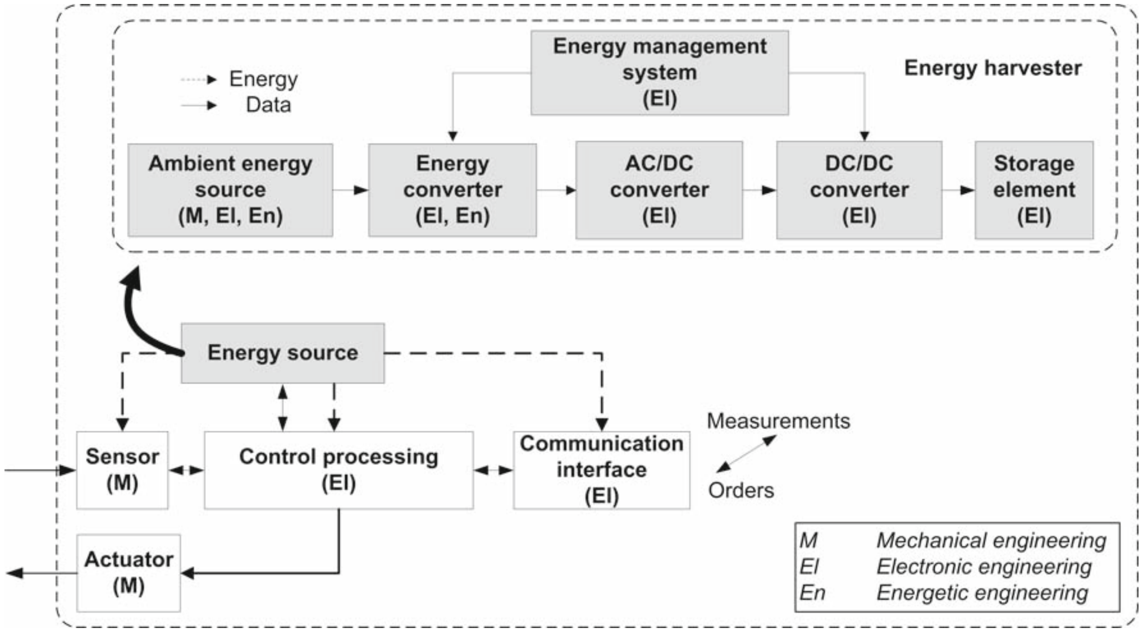


Fig. 1 Global architecture of autonomous microsystems

- Energy converter selection and modeling
- Electric converter selection and modeling
- Electric load selection to model the behaviour of the application.

From this description, microsystems clearly appear as a large scale engineering problem since it includes multiple components (electronic circuits, mechanical elements such as proof mass in sensors, etc) and multiple physics (mechanics, electronics, etc). Besides, the consideration of autonomy includes energetic engineering.

In the following sections, we describe our multidisciplinary and interactive method dedicated to the problem of autonomous microsystem. To incorporate autonomy issue, this method proposes a multidisciplinary approach for energy harvester design. The global purpose is to facilitate the design of the whole system in its environment and to develop exchanges between different engineering disciplines.

3 Problematic

Microsystems are dating back from the beginning of microelectronics. Initially, the idea was to reduce costs and to integrate sensors and circuits on the same chip. Thus, microsystem design is a recent research field. At the beginning, it was carried out by electrical engineers trained in microelectronics. They often had difficulties to understand mechanical aspects of the devices. As a result, electrically efficient microsystems are designed [7], but they may not be well designed mechanically. Later, microsystems evolved with the introduction of micromechanics. This is done concretely by the realisation of mobile parts (spring, beams, etc.) using technologies of microelectronics.

Nowadays, microsystems are present in a very large range of products to carry out specific tasks. Therefore, microsystem design has to be done, considering a particular use case, by integrating electronic and mechanical engineering. Moreover, as we include the notion of autonomy, energetic engineering has to be added. Until now, the relation between mechanical and electrical engineering is inexistent or insufficient. This leads to microsystems that don't satisfy all the requirements of the studied product.

In other words, microsystem design requires multidisciplinary skills and necessitates collaboration of several persons with distinct expertise fields. Although, each one has its own working method and its modelling languages, that are specific for each engineering field. Therefore, the aim of our work is to develop a new method to make autonomous microsystem design easier. Thus, the method takes into account the design of the energy harvester integrated in the microsystem. From this observation, we propose a multidisciplinary and interactive method to integrate all engineering fields in microsystem design with a functional approach. The concept of interactive design is described in the next section.

4 Multidisciplinary and interactive method for autonomous microsystem design

Integrated design requires multidisciplinary knowledge. Microsystems designers should have a wide range of skills and multidisciplinary knowledge in order to develop microsystems adapted to a specific field of application. In this section, we begin with a definition of interactive design. Then, we describe our Multidisciplinary and interactive method for autonomous microsystem design (MIMAMD) method.

4.1 Definition of interactivity

Interactive design is related to the notion of product which is the result of interactions between Humans with different background (cognitive interaction). A product creates relations with its user (sensorial interaction). During its lifecycle, it is placed in physical environments with Humans and material elements and modifies them through physical interactions. Thus, a product is a source of interactions.

An interaction is defined as a direct exchange of energy, material, information or sensations between the components of a system. There are three types of interactions [8]:

- physical interactions between two components of a system
- sensorial interactions between Humans and material objects
- cognitive interactions between Humans (knowledge sharing).

Interactive design considers these three types of interactions by working on the product and its environment. It takes into account interactions between humans and material objects [9,10].

Multidisciplinary and interactive microsystem design considers the microsystem in its whole environment and facilitates communication and collaboration between humans and tools. This activity requires the cooperation of several people or systems. They can be natural or artificial and adapt their behaviour to each other. Interactivity exists in all types of communication and exchange where situation management and progress are related to processes of collaboration, retroaction and cooperation between the actors.

4.2 Our multidisciplinary and interactive method for autonomous microsystem design (MIMAMD)

Our method aims at designing microsystems with a functional point of view. This is necessary to satisfy all

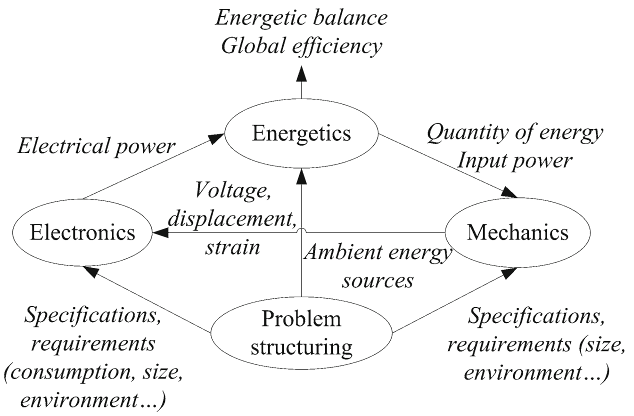


Fig. 2 Interaction between scientific fields

requirements of the application. As microsystems are used in a wide range of applications, their design begins by the definition of need and specifications to clarify the requirements.

The interactive character of the method mainly integrates mechanical, electronic and energetic engineering. Firstly, mechanical aspects are important to design a system that can be integrated in its environment and to satisfy all requirements related to the size, the weight, the strength, etc. Secondly, electronic engineering plays a part in the selection of electronic components and the satisfaction of power consumption requirements. Thirdly, as we include the autonomy feature, energetic engineering is also involved to identify the most efficient source in the considered environment. Finally, the functional approach helps selecting suitable sensors and actuators to fulfil a specific function.

Our method guides designers in the selection of components and materials. It helps then defining of the global structure. It allows retroactions, communication and collaboration between mechanical, electronic and energetic engineering fields (Fig. 2).

Subsequently, we are going to detail the method, with a presentation of the whole tools, their contribution to multidisciplinary and interactive design, their inputs and outputs and their aims.

4.3 Presentation of the whole method

Our method is based on a top-down approach [11]. It goes from a system level to a physical one, with a special care in the satisfaction of all requirements and specifications.

Multidisciplinary and interactive autonomous microsystem design breaks down into several steps (Fig. 3):

- Problem structuring
  - Product definition
  - Functional analysis
  - Physical decomposition
- Autonomous microsystem design
  - Energy harvester
  - Transducer
  - Control and processing unit
  - Communication interface.

On Fig. 3, we can see where the different engineering fields play a part.

The design of a system is highly dependant on its environment and the considered situation of life. As a consequence, a preliminary study is necessary to define the specifications of the microsystem that needs to be made. To carry out this preliminary study, we propose a method consisting in problem structuring [12]. It is based on the use of functional analysis tools [13]. This first step leads to specifications and allows identifying design variables and functional flows for

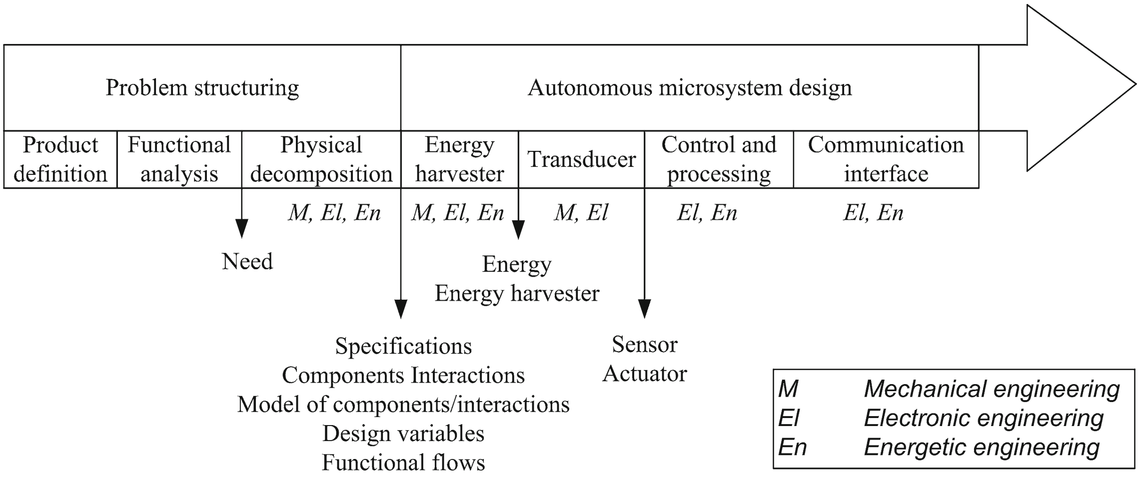


Fig. 3 Multidisciplinary and interactive method

the energy harvester of the autonomous microsystem. The second step focuses on energy harvester design and the definition of the main parts of the microsystem (sensor, actuator, data processing and control and communication interface). They are described in the following sections.

The top–down approach is obvious with this method. It ensures the generation of complex and heterogeneous systems. First, system modeling aims at describing the global behaviour of the system which is broken down into sub-systems. This global model gives functions and interactions with the external environments. Then, behaviour modeling highlights interactions between components of various domains. It contributes to a functional modeling and leads to a physical modeling, very close to the real behaviour.

4.4 Problem structuring

In this section the first part of the method is detailed (Fig. 4).

Our design approach begins by the formulation of the need [14,15]. In a specific context, this need is determined by material, technical, environmental, economical and socio-logical constraints. The context of the study must be defined accurately to identify the system and to put forwards all the requirements and the relevant data to bring the microsystem design to a successful conclusion. With the context analysis, we can see that designing a product associates different domains. The multidisciplinary aspect appears in the first step of design activity.

Once context and needs are formulated, we deal with a functional analysis of the system.

4.4.1 Functional analysis

A system evolves in an environment and its behaviour is highly dependent on its life situation. As a consequence, we have to identify life situation, external environments and functions for a given situation [16].

Life situations are phases of the product life cycle related to the different environments in which the product evolves. They can be divided into significant moments (Fig. 4). A significant moment is characterized by a single behaviour of the product, a single physical behaviour on each interface between the product and its environment and a single sensory behaviour of the product user [17,18]. External environments are connected to the system. They interact to exchange information, energy and material. It can be the user, climatic conditions, etc. For each life situation, functions are defined by showing the interactions between the product and its environment. As mentioned previously, there are physical, sensorial and cognitive interactions [19]. Moreover, these interactions can be direct or indirect. They are direct when they associate the product with one element of the environment and they are indirect when they link two elements of the environment. Interaction diagram (Fig. 4) is used to represent these interactions between the system and its environment and allows listing most of the functions.

At the end of this step, we acquire specifications of the system that are determinant for the choices of technical solutions by means of criterions. We also have physical and cognitive interactions. The description of the environment leads to the identification of all available energy sources. Moreover, as it is presented in a series of questions, this step can be handled by any designer. From this, to get further in the top-down analysis, the system has to be split into elementary blocks.

4.4.2 Physical decomposition

Physical decomposition is mainly based on Product Breakdown Structure and Functional Block Diagram [20]. These tools are used so as to be consistent with energy harvesting issue, in autonomous microsystem design. As a consequence, they put forwards design requirements for energy harvesters and other components of the microsystem.

Product Breakdown Structure (PBS) (Fig. 4) allows identifying components and interface models. To do so, the system is divided into active, passive and interaction components. Active components contribute to the realization of the action whereas passive components don't participate to it. As for interaction components, they allow the transmission of functional flows (material, energy and signal). Applying the PBS method, we obtain:

- A list of the components of the system (global architecture of the system)
- Interface constraints between blocks (constraints for microsystem design)
- Boundary conditions
- Design variables
- Models of material components.

The functional block diagram (FBD) represents the functional flows through the studied element. It describes how the functional block works and how it interacts with its environment. The chart is made of components and links, modeling surface contacts. It enables us to identify functional flows. Thereby, with functional block diagrams (Fig. 4) we highlight:

- Interactions between components and external environment (identification of the data to be measured, the type of sensor and their location)

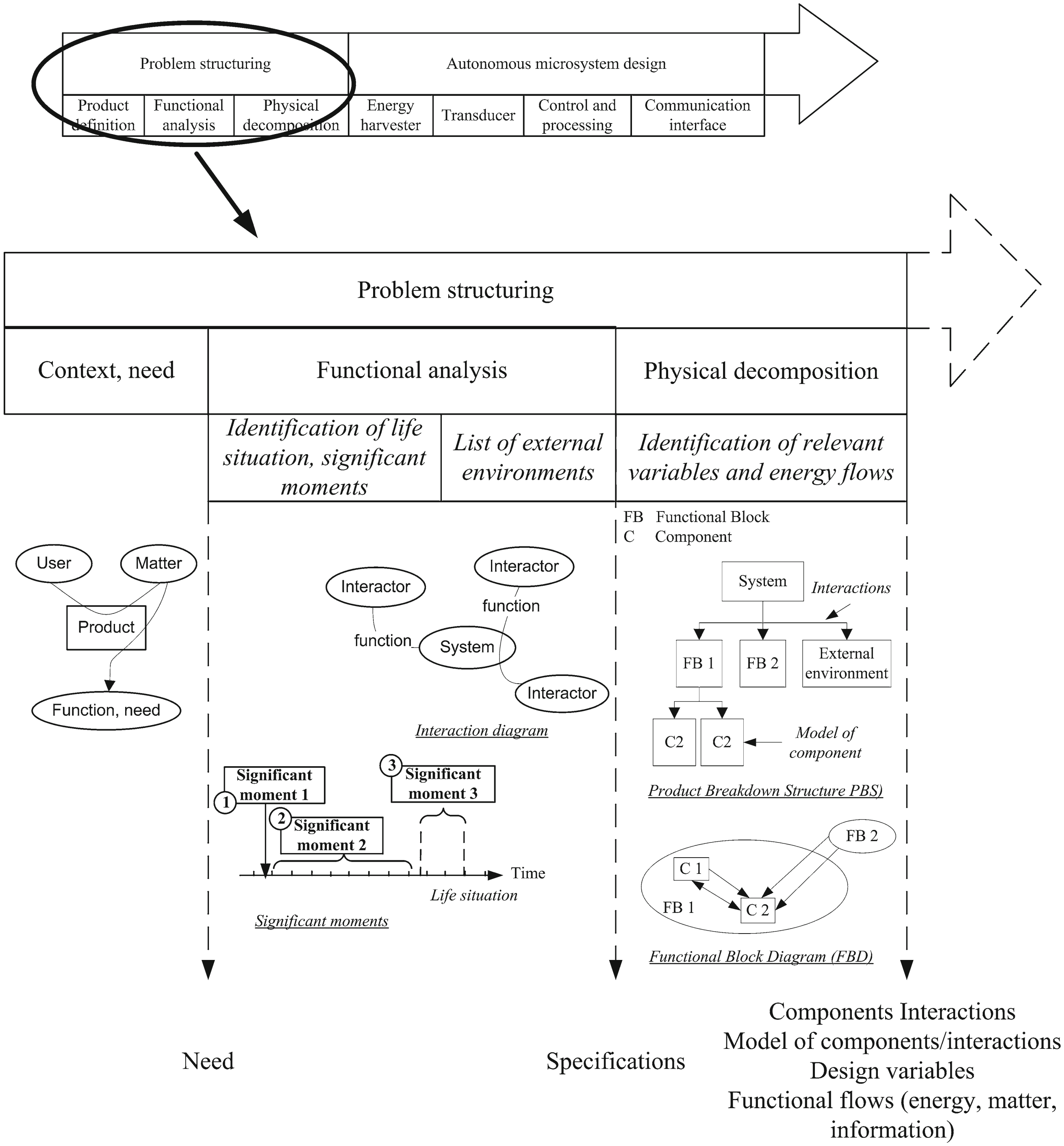


Fig. 4 Steps and tools of problem structuring

- Interactions between components
- Flow circulation (contact, energy, information or material) necessary for ambient energy source selection
- Relevant variables for the microsystem design (energy harvester, sensor, etc.)
- Models of interactions (relations between components)

All things considered, this problem structuring method is very interesting. Indeed, it provides information related to sensor types and their locations. Consequently, suitable energy source is identified and we get design constraints for our autonomous microsystem design (through functional considerations).

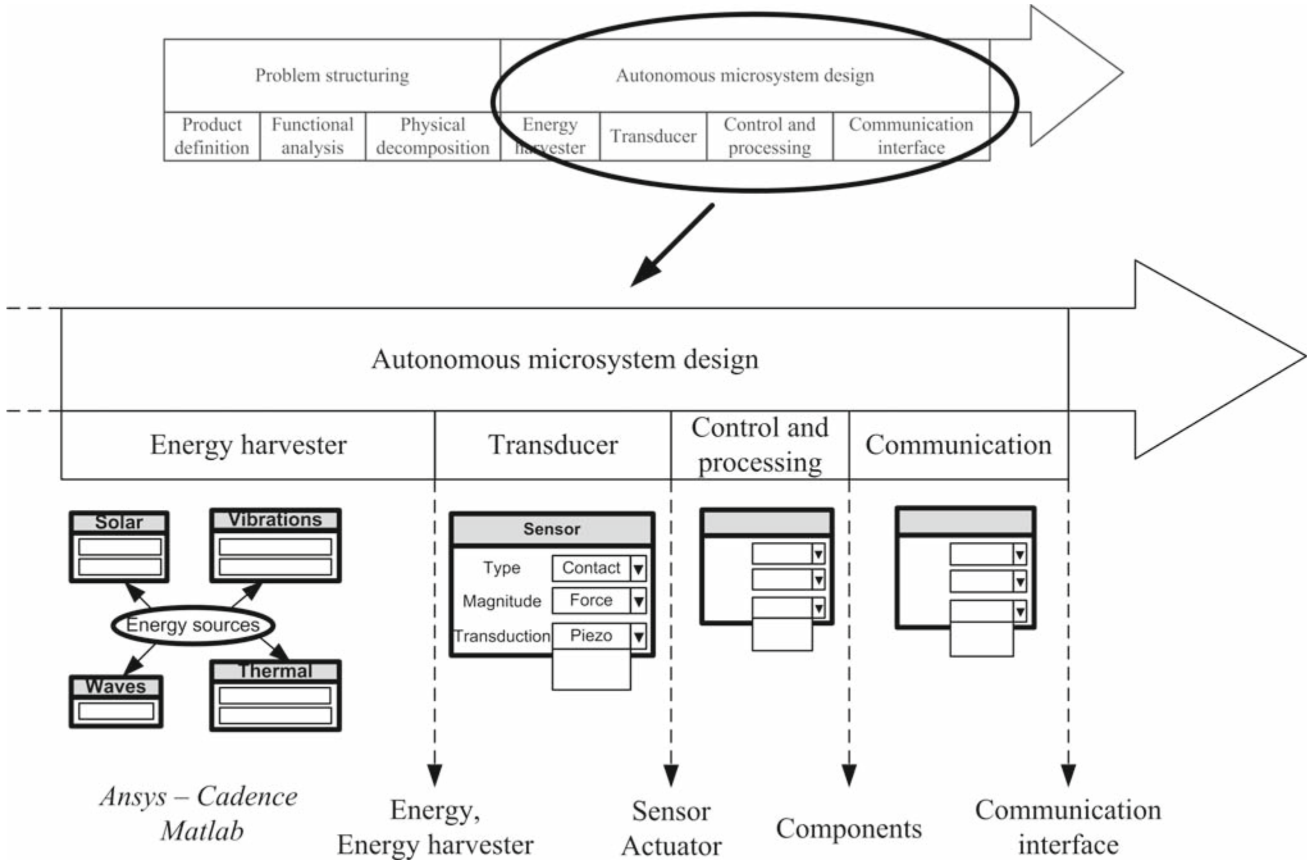


Fig. 5 Stages of autonomous microsystem design

To sum up, we have adapted PBS and FBD to go on dimensioning the autonomous microsystems. After this step of specifications, the microsystem is modelled.

4.5 Autonomous microsystem: energy harvester design

Autonomous microsystem design requires multidisciplinary knowledge and skills due to its heterogeneous composition:

- energy harvester (energetic, mechanical, electronic engineering and material science)
- sensor (mechanical and electronic engineering)
- actuator (mechanical and electronic engineering)
- data processing and control (electronic and automation engineering)
- communication interface (electronic, magnetics and optics engineering)

The multidisciplinary aspect is present through the mixed composition of microsystem and especially in energy harvester design where mechanical, electronic and energetic engineering are strongly involved (Fig. 5).

4.5.1 Energy harvester

Energy harvester is the central part of autonomous microsystem design. As it is mentioned before, it requires multidisciplinary knowledge. An energy harvester consists of an energy converter, to convert ambient energy into electric one and electronic circuits to adapt this energy to a load (Fig. 6).

As described in Fig. 6, before working on energy harvester strictly speaking, an energetic balance must be carried out to select the energy source and thus, choose the technology of energy converter. This choice is made easier by means of databases with a classification of energy harvester concept for each energy source. Afterwards, the energy converter is modelled with specific software.

By the way, most software programs are dedicated to one scientific or technical domain and require specific skills to be used correctly. However, someone who wants to design energy harvester only deals with the aspect related to its own knowledge. As a result, electronically efficient energy harvesters are developed by electronic designers but they may loose in performances because mechanical aspects are not properly considered. Reciprocally, if the energy harvester is

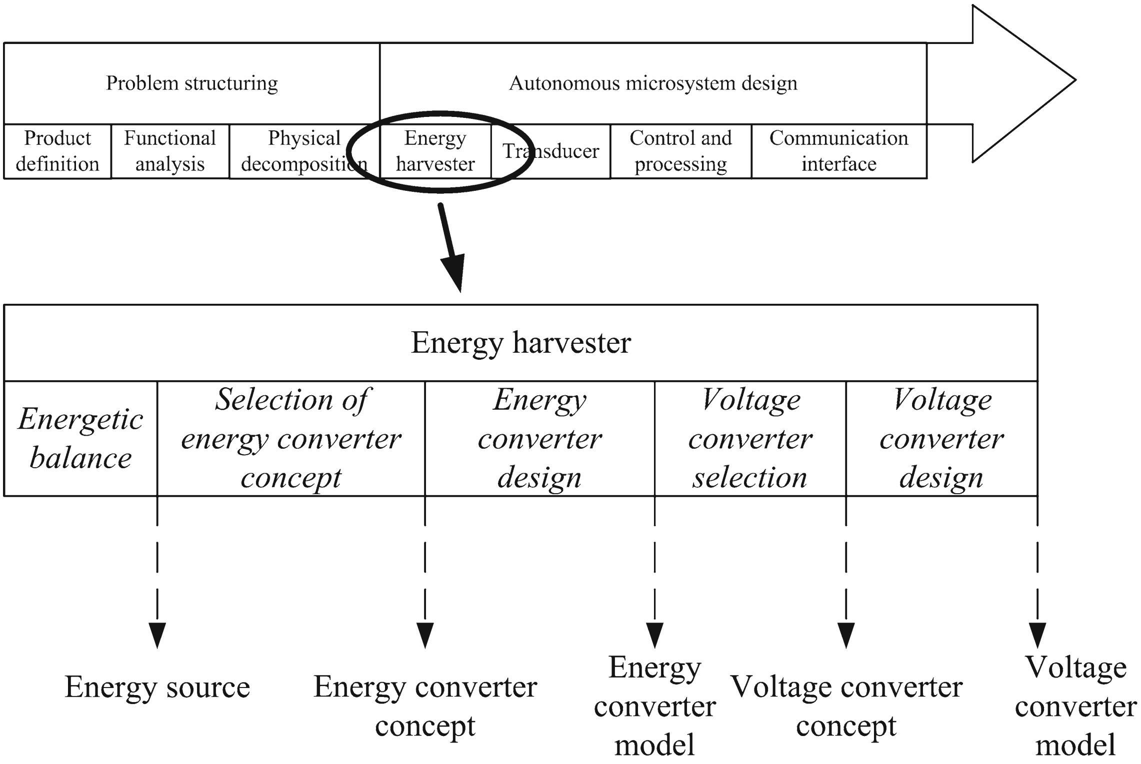


Fig. 6 Method to lead to energy harvester design

designed by considering only mechanical aspects, the structure may not harvest enough energy for a microsystem power supply.

Thus, we are working on tools that simplify the choice and the design by creating collaboration and interdependence between fields. These tools aim at overtaking the differences related to the various engineering fields and facilitate the extraction of parameters at the physical level.

We chose Ansys software for mechanical simulations, Matlab for the interface and system-level simulations and Cadence for electronic simulation and global system design. All these software programs are widely used in industrial and research fields. Our objective is to manage interdisciplinarity between the three tools in order to facilitate autonomous microsystem design. Concretely, inputs and outputs of each kind of software come from another type of software. Each one modifies and adapts its behaviour to achieve a common objective.

4.5.2 Multidisciplinary approach for energy harvester design

Matlab is used as an interface to manage input parameters and extracted data from Ansys and Cadence. It is also used to exchange data between both software programs via script files (Fig. 7). It plays a role of a gateway between the specific software programs.

Matlab software is easy to use and can either be handled through the graphical interface or directly with command lines. In addition, it is adapted to heterogeneous system simulation and integrates libraries with a large number of models. Moreover, we are able to link our work to others, like energetic modeling and the simulation of a sensor node (ESTIA Recherche) [29,30]. Lastly, Matlab is a gateway to other languages applied for mixed system modeling like System C.

Specifications and requirements, identified in the phase of problem structuring, are inputs for Matlab. These inputs are the usable energy source at a given location and the geometric constraints. From them, we deduce the energy converter type and then consistent materials as well as an evaluation of allowable dimensions. With these data, the energy converter concept can be selected and designed, by consulting databases.

Ansys is used to simulate the energy converter. It provides models matching electrical and mechanical parameters (expression of voltage versus stress). Moreover, it also gives all the characteristics of the energy converter. Geometric parameters of the structure can be optimized through this program. It provides a file with the electric signal generated by the energy converter. This file is used in Matlab as an input for the voltage converter. This component is selected by using a library of voltage converter models filled in Matlab. It will enable an evaluation of the load. Therefore,

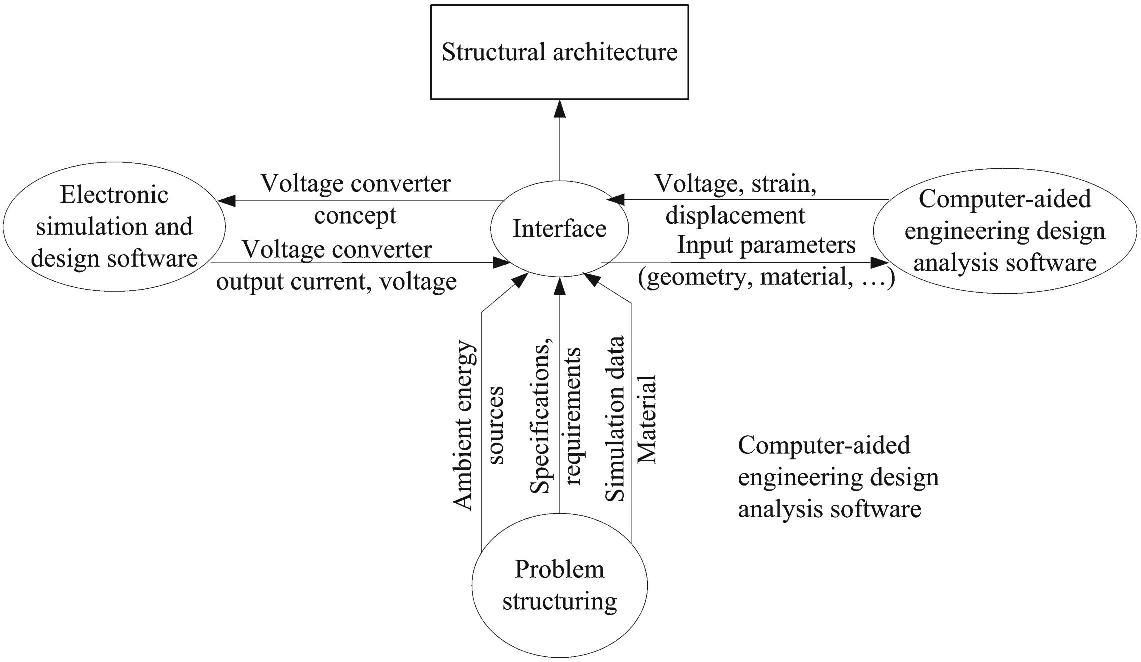


Fig. 7 Multidisciplinary approach for microsystem design

the energy converter can be modelled and simulated in Matlab. It leads to an evaluation of the electrical energy generated by the energy converter. At this stage, Cadence is used to optimise the load and model it to be as close as possible to the real one.

However, Cadence is not only a simulation tool. It is also a drawing tool used to create MEMS layout before sending it to foundry. Consequently, the whole energy harvester can be modelled with this software from all geometrical parameters optimized with Ansys.

To sum up, gateways are created between the different types of software. They ensure the multidisciplinary aspect of our approach. We have thus a global simulation integrating mechanical and electronic engineering to identify the characteristics of the energy harvester. Relations and data exchanges are automated and allow the design of efficient structures from mechanical, electronic and energetic points of view. The structural architecture of the microsystem is defined and component selection is guided by physical and technological data. The designer will be able to either choose existing components or design specific ones.

To illustrate our method, we consider autonomous microsystem design integrated in the problem of instrumentation engineering. More precisely, we deal with the instrumentation of an automotive braking system. As mechanical vibrations are present in its environment, we consider this type of energy. To simplify the example, we will only consider the energy harvesting design.

5 Energy harvester design for automotive braking system instrumentation

The application considered for our approach is about autonomous microsystem design integrated in the problem of instrumentation of an automotive braking system, with a special interest in piezoelectric energy harvesting.

The first task is the characterization of microsystems that will be designed. Then, the energy harvester is modeled. With our interactive approach, we get a structural architecture used to design the energy harvester taking into account the global system. The method is applied to identify sensor types and locations in the studied system as well as ambient energy. Next, multidisciplinary tools are used to design the energy harvester.

5.1 Problem structuring

5.1.1 Context and formulation of the need

Microsystem design is highly dependant on its environment and its life situation. As a consequence, a preliminary study is necessary to identify and locate the relevant magnitudes that have to be measured and how they need to be measured. Our method is applied to solve this problem.

Braking system is one of the main elements of active safety in a vehicle. In order to have efficient systems, automotive manufacturers made braking systems evolve. They have to assist drivers during a braking action. Now, they associate

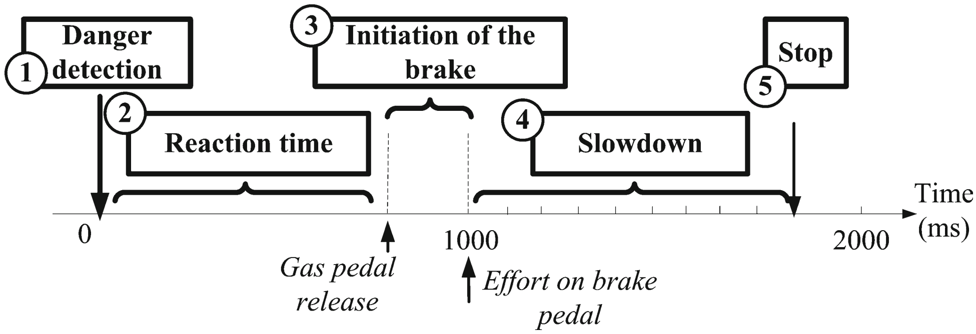


Fig. 8 Significant moments of a braking situation

mechanisms and intelligent devices to control the slowing down of a vehicle efficiently. Nonetheless, their efficiency depends on driver behaviour. Indeed, the driver commands the ignition of the system through the perception and the interpretation of one's environment.

Our objective is to instrument an automotive braking system by means of autonomous micro-sensors. Such instrumentation is chosen to satisfy automotive industry requirements in terms of cost, size, etc. Moreover, as they are tiny devices, microsystems will not modify nor deteriorate the performances of the system. This instrumentation will identify mechanical and sensory interactions in order to analyse driver behaviour in a braking action. To do so, we consider the braking system of a vehicle because it is the system allowing to slow down or to stop a vehicle in motion. We need to identify sensors that are to be used and their locations before considering energy harvesting.

5.1.2 Functional analysis

There are various life situations for a vehicle: stationary, in motion, braking, maintenance. We focus on braking situations including mere slowdowns to collision avoiding, and more precisely on panic braking situations that are characterized by a feeling of emergency. Thereby, this notion is defined.

An emergency is a situation caused by an exceptional event which could endanger physical or psychological integrity of one or several people or which causes material damages. It requires an immediate intervention, adapted and limited in the time that will make it possible to return in a normal situation.

We focus on emergency situations, where the driver wishes to stop his vehicle at the shortest distance to avoid an obstacle, or to reduce the impact speed at a maximum. In the continuation of this section, we propose an analysis of the significant moments of a braking emergency action. Such situations start with the visual detection of a mobile (pedestrian, close vehicles…) or motionless (post, parking car…) obstacle. The driver can also become aware of a state of emergency with sound cues (horns, cries…) revealing the presence of an obstacle. The detection of an emergency is thus related to the acquisition of visual and sound indices. We broke up the situation of emergency braking into 5 significant moments (Fig. 8):

- Identification of the emergency situation (1)
- Reaction time and analysis of the situation (2)
- Initiation of the brake (3)
- Braking inducing a deceleration of the vehicle (4)
- Complete stop (5).

We can note that nothing happens during reaction time, which is the longest interval. If the system could recognize the human's behaviour and anticipate future actions, it could adjust its behaviour to better suit the needs of the driver.
The main functions of a braking system are:

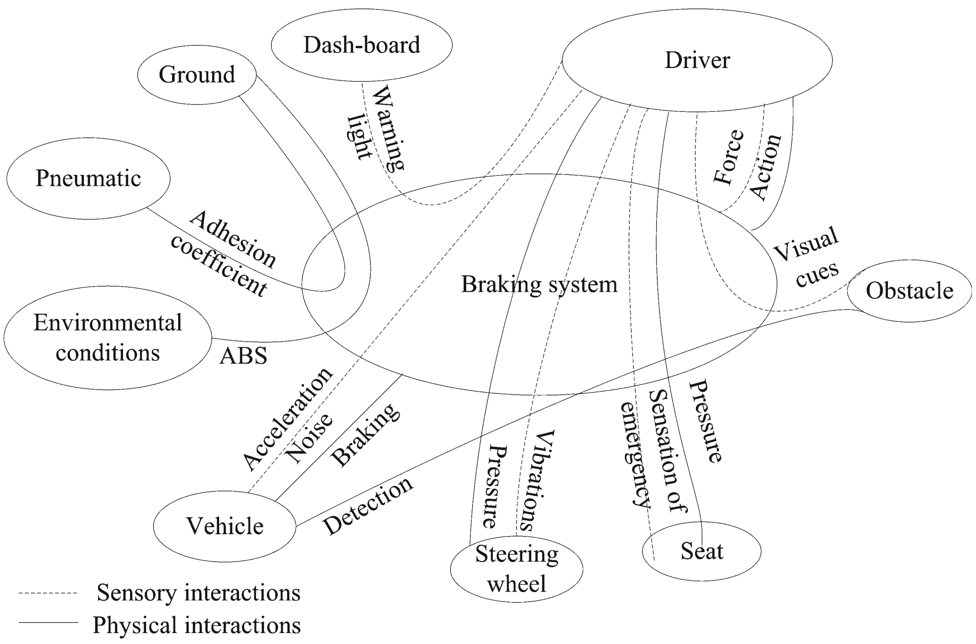
- To slow down the vehicle
- To stop the vehicle
- To guarantee the immobility of a stationary vehicle.

Figure 9 shows the relations between the system and elements of the environment identified previously. These interactions are mainly physical and sensory. The figure is deduced from the previous analysis. It represents the braking system in its whole environment. This way, we can identify the interactions. There are physical interactions between the braking pedal and the driver's foot, or between the driver and his seat, etc. This kind of interactions is mainly located on contact area of two system elements. Sensory interactions are related to perception and interpretation of the driver of an action. They are influenced by his experience. For instance, the driver can evaluate his braking action with the braking pedal force feedback and the distance evaluation.

5.1.3 Physical decomposition

With problem structuring, we identified the relevant variables for the problem considered. We also showed the energy

Fig. 9 Interaction diagram of the braking system in a braking situation



sources present in the environment of the system. Consequently, we can identify the type of sensors and their location for the instrumentation. In automotive braking systems, we know the nature of the interactions (pressure, force, displacement, speed and acceleration) and where they are produced (physical interfaces between components of the braking system, the driver and the environment: brake pedal, seat, steering wheel and wheel).

Concerning the energy issue, the main energies are mechanical ones issued from vibrations but thermal and solar energies are also usable. Mechanical energy is widely present in a car and is related to pressure, speed and deformation gradients. Thermal energy exists on the interfaces between braking elements (disc/wheel interface). Frictions created on braking devices generate heat. Finally, solar energy is present on car body.

All these data appear on the Functional Block Diagram represented on Fig. 10.

5.2 Energy converter selection and design

5.2.1 Energy converter concept

There are specific technologies of energy conversion according to the considered energy source (Fig. 11). Once the energy source is chosen (after a preliminary energetic balance), a database helps the user to select one or various adapted energy converters. For our application, we chose to harvest energy from vibrations. We listed three main technologies to convert mechanical energy into electric one.

Moreover, physical geometry is determined by considering specifications and constraints (identified during the phase of problem structuring). Then, the converter has to be modelled with mechanical and electrical parameters.

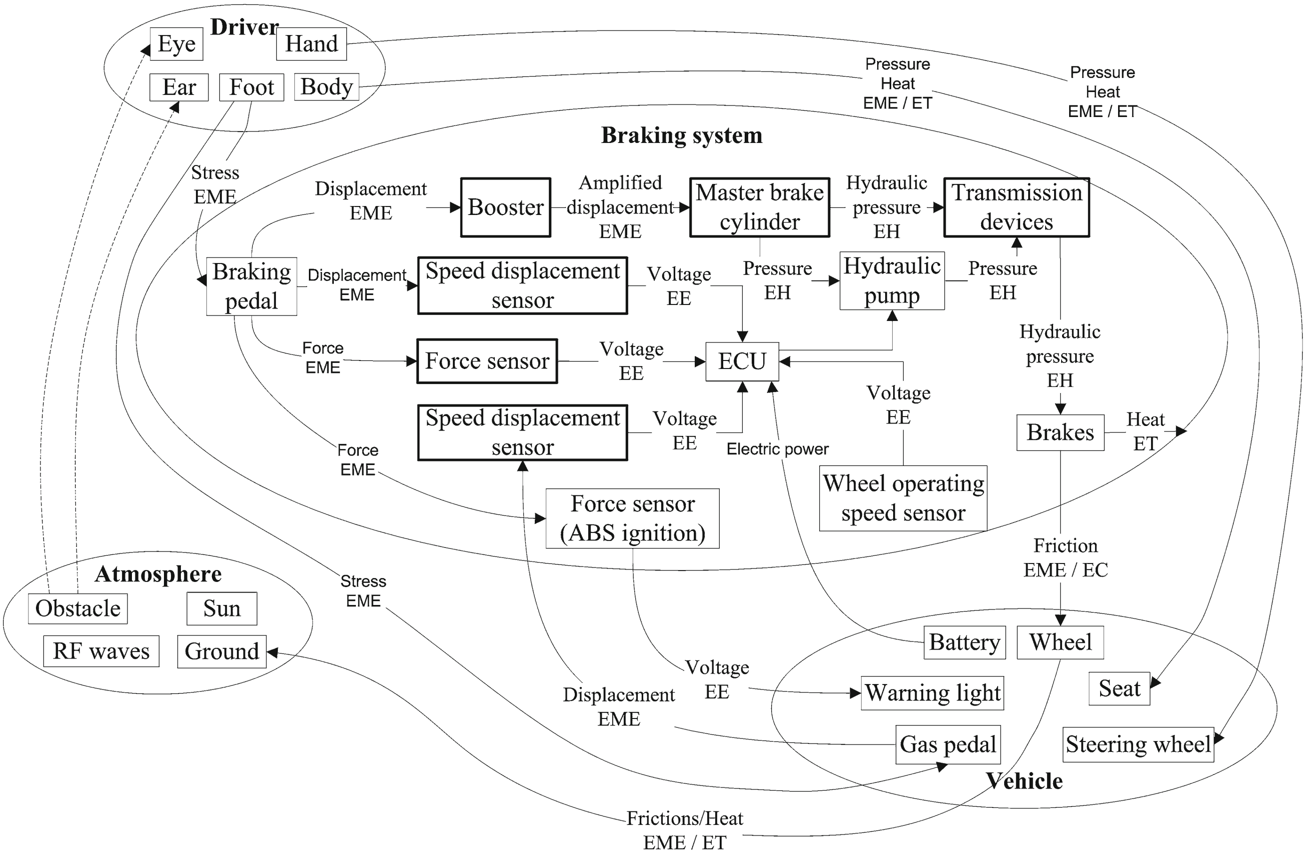
Finally, for our problem of energy harvesting, piezoelectric technology appears to be well adapted. These converters are adapted to microsystems because they are easy to integrate. This design requires knowledge on materials, mechanics and electronics and will be presented in the following section.

5.2.2 Piezoelectric material

Piezoelectric materials are used in applications where a physical connection is needed to convert mechanical energy into electrical energy. There are four systems of equations describing piezoelectric effect. They match electrical variables (electric field E in V/m and electric displacement D in C/m^2) to mechanical variables (strain ε and stress σ in N/m^2). Equation 1 represents one of these systems. Mechanical and electric magnitudes are present in this equation. It highlights the matching between electrical and mechanical engineering fields and justifies our interactive approach.

$$\begin{cases} \{\sigma\} = \left[c^{E}\right].\{\varepsilon\} - [e]^{t}.\{E\} \\ \{D\} = \left[\varepsilon_{p}^{\varepsilon}\right].\{E\} + [e].\{\varepsilon\} \end{cases} \tag{1}$$

Table 1 lists the different parameters.



Contact action	——	Energy flow	Ex		
Contactless action	------				
Material flow	M	Mechanical energy	EME	Electric power	EE
Information flow	I	Acoustical energy	EA	Magnetic energy	EMA
Contact flow	C	Thermal energy	ET	Hydraulic energy	EH
Esteem flow	E	Chimical energy	EC		

Fig. 10 Functional block diagram of the braking system in a situation of panic braking

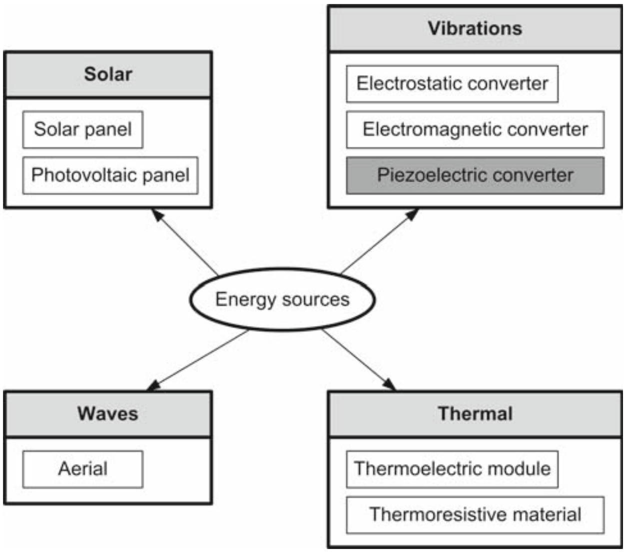


Fig. 11 Technologies of energy converters

Table 1 Piezoelectric parameters

Magnitude	Symbol	Meaning	Units	Form	Size
Electrical	$[\varepsilon_p]$	Dielectric permittivity	F/m	Matrix	3 × 3
	$\{D\}$	Electric displacement	C/m^2	Vector	3 × 1
	$\{E\}$	Electric field	N/C	Vector	3 × 1
Mechanical	$[c]$	Stiffness matrix	N/m^2	Matrix	6 × 6
	$\{\sigma\}$	Stress	N/m^2	Vector	6 × 1
	$\{\varepsilon\}$	Strain	–	Vector	6 × 1
Piezoelectric	$[e]$	Piezoelectric constant	C/m^2	Matrix	3 × 6

Piezoelectric materials are anisotropic. As a result, phenomenons depend on orientation in space and constants are written with matrix. There are many piezoelectric materials with distinct characteristics [21]. The choice must be adapted to the environment and has to satisfy the specifications of the application.

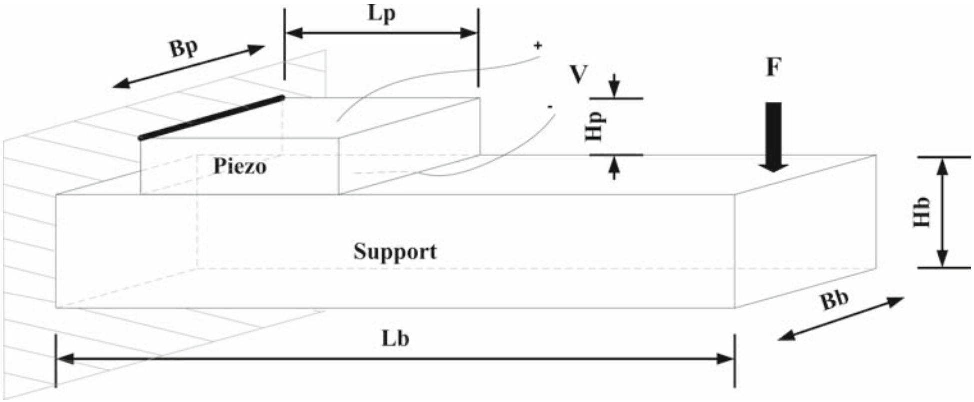


Fig. 12 Representation of a piezoelectric structure

5.2.3 *Energy converter modeling*

We select Ansys [22–25] to model the structure because it includes piezoelectric element models and is widely used in industrial and research field. Different configuration can be adopted [26]. For this example, we consider the instrumentation of the braking pedal, with a microsystem comprising a piezoelectric energy harvester. It is modelled by a cantilever structure made of a piezoelectric film deposited onto a bendable substrate (Fig. 12).

On this figure, the geometric parameters are:

Lb	support length
Hb	support height
Bb	support width
Lp	piezoelectric patch length
Hp	piezoelectric patch height
Bp	piezoelectric patch width.

They were chosen in such a way that specifications and requirements identified during the phase of problem analysis are fully satisfied.

SOLID186 and SOLID226 finite elements were selected for the elastic structure and the piezoelectric film, respectively [27]. The structure has been meshed using quadratic 20-noded-brick. It is fixed at one end and a force is applied on the other end.

Electrical aspects appear in boundary conditions. Indeed, a reference voltage point is defined to measure electric potential in the structure.

With Ansys, we get the electrical potential on each node of the structure (Table 2). This electric potential can be related to mechanical variables such as displacement and stress. For a 1 N force, the maximum voltage on piezoelectric boundaries is around 2V and corresponds to a 0.92 μm displacement (Fig. 13).

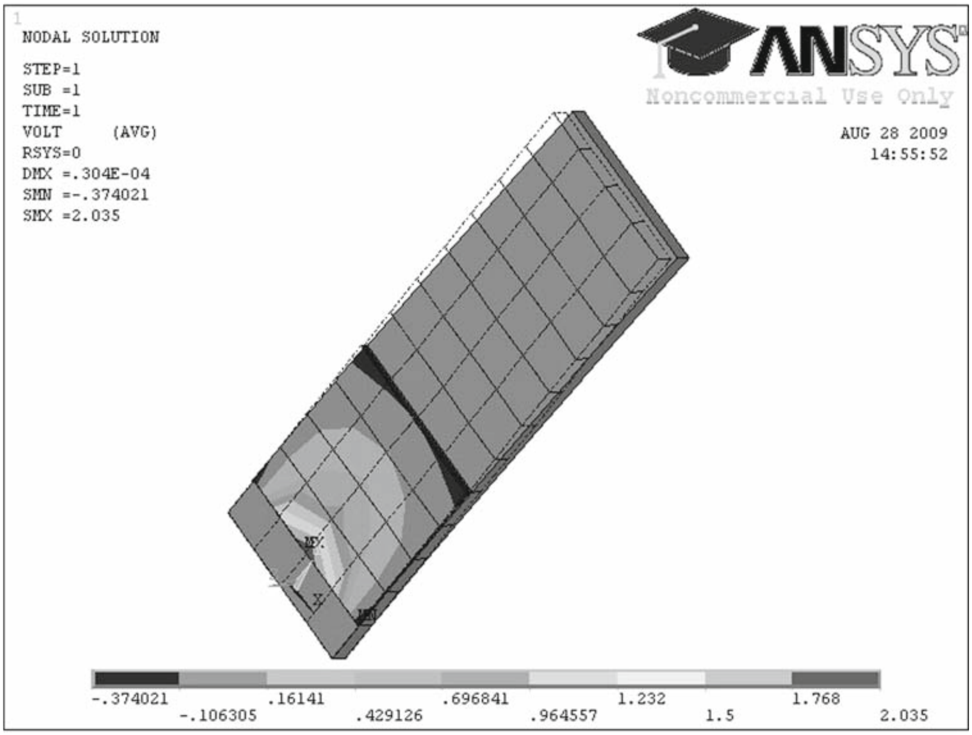
Results are used to establish electronic design parameters. Relevant data for our problematic are electric potential, stress and displacement. We can represent these variables graphically with Matlab to establish relations between them (Figs. 14, 15). Figure 14 represents the electric potential on the nodes of the bold line on Fig. 12. Figure 15 shows the displacement on the same nodes. On these graphs, we see that the maximum voltage correspond to the higher local displacement. We focus on this part of the piezoelectric layer because it corresponds to the maximal strain. This information is relevant for the electrode placement. Indeed, the generated voltage will not be the same on the whole piezoelectric element. Thus, electrodes will be placed to get the highest voltage.

Table 2 Ansys results (Nodes on bold line in Fig. 12)

Nodes	Voltage (V)	Stress (N/m^2)	Displacement (m)
446	−0.37402	95055	1.58E−07
458	0.45073		2.24E−07
459	1.3813	8.6408000E+04	2.67E−07
460	1.7833		2.85E−07
461	2.0354	8.6338000E+04	2.92E−07
462	1.7833		2.85E−07
463	1.3813	8.6408000E+04	2.67E−07
464	0.45073		2.24E−07
422	−0.37402	95055	1.58E−07

Furthermore, from a mechanical point of view, we checked the structure can withstand the maximal force that can be exerted on it with the equivalent strain.

The relation between both software programs allows improving the structure efficiency. From Ansys results, we model the energy converter at a system level with Matlab. To do so, voltage converter libraries are used. They allow us to evaluate the load corresponding to the application. This load evaluation is important because its value modifies the output signal. Matlab simulation allows us to get the curves of voltage and current that will be used as inputs for the electronic design of the voltage converter under Cadence. With this last software, the load is refined. This part is detailed in the next section.



```
NODAL SOLUTION

STEP=1
SUB =1
TIME=1
VOLT      (AVG)
RSYS=0
DMX =.304E-04
SMN =-.374021
SMX =2.035
```

Fig. 13 Electric potential produced

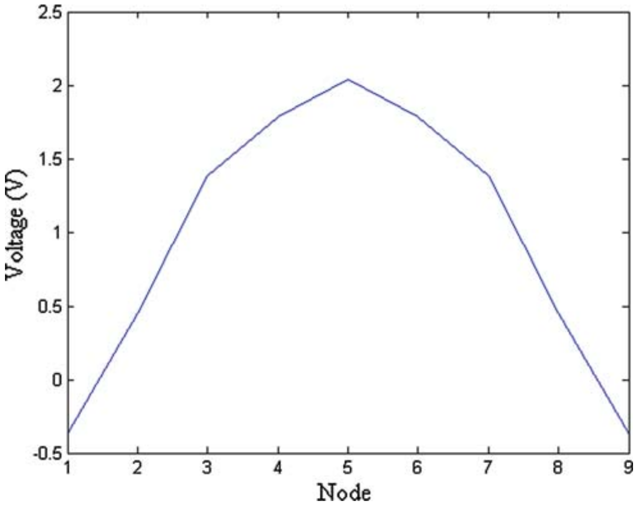


Fig. 14 Voltage on piezoelectric nodes of the bold line on Fig. 12

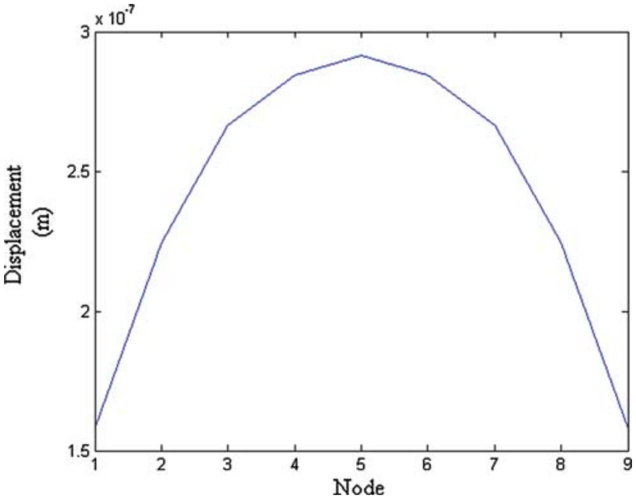


Fig. 15 Displacement on piezoelectric nodes of the bold line on Fig. 12

Today, the whole approach is hard to do because of the absence of a tool or software creating natural links between the different scientific fields. As a consequence, we propose a multidisciplinary tool where only geometric parameters and material have to be known. Other operations are automated and transparent for the user. Consequently, a designer who is not expert in one field will be able to handle with energy design.

5.3 Voltage converter

At this point, we have current and voltage output of the energy converter. This energy has to be transformed and adapted to the rest of the circuit. This is done with voltage converters.

We use specific software to simulate and design the energy harvester. In our case, this is Cadence software [28]. It is a design tool dedicated to the electronic sector. It is a world

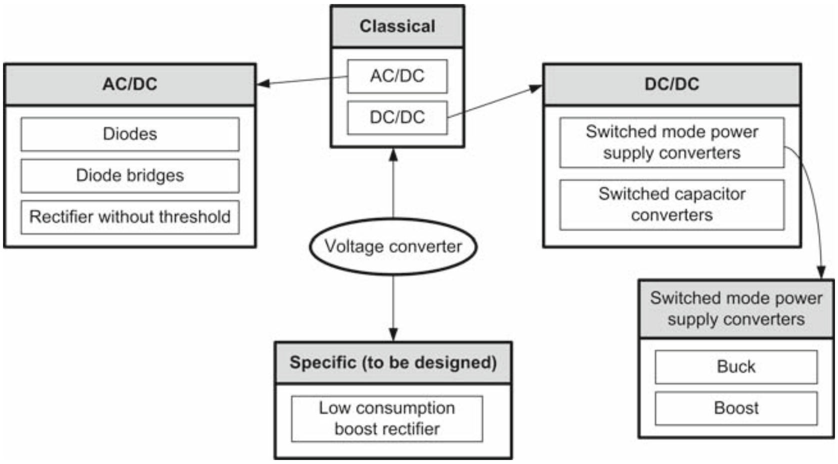


Fig. 16 Classification of voltage converters

leader of innovation in electronic design. Designers use Cadence to design and test advanced semiconductors, commercially available electronic components, telecommunication networks and computational systems. It allows system on chip design. As a consequence, we can create system with ultra low consumption. This is very important for energy harvesting problematic because most of the time, the harvested energy is low. Thus, electronic converter must work with low voltage (mV) and have a low consumption (nW).

For voltage converter selection, there are two possibilities on current and voltage range basis (Fig. 16). Existing converters can be used or a specific one has to be created (low voltage, low energy consumption, for instance).

In our application, AC/DC and DC/DC converters are needed. We created a library listing the different types of voltage converters and their associated loads. This information allows us to improve the simulation of the energy converter in Matlab, leading to more accurate inputs (voltage and current) for the electronic design.

At the end of our approach, we have a structural solution with all necessary parameters to model and design the whole energy harvester. The design is done by considering the whole system.

6 Conclusion and future works

This paper deals with a multidisciplinary and interactive approach for the design of autonomous microsystems, from a functional viewpoint. The interactive design is present through the consideration of the system in its environment and the analysis of interactions.

Moreover, this task requires multidisciplinary knowledge due to the heterogeneous composition of microsystems. Our approach is developed to make microsystem design easier by creating relations between specific software programs in mechanics and electronics. It ensures the collaboration between different engineering fields and has the advantage of being usable by a designer who is not expert in one field.

The originality of this approach lies in two points. The first one is the global method to solve a problem of microsystem design. The second one is the multidisciplinary approach adopted for microsystem design. We also presented the application of this method on energy harvesting design. Regarding this last point, we must note that the interactive approach can also be used for "classical microsystems", i.e. for microsystems fed with batteries.

For future works, we plan to go on developing tools to support our method and we also want to automate some tasks.

In this article, the multidisciplinary design is mainly detailed for the energy harvester, which is only part of the autonomous microsystem. Therefore, additional work has to be done to create tools to support the whole microsystem design, by considering the complete sensor design, for example. Besides, our interactive and multidisciplinary method could be applied for other products.

Finally, this work could be integrated with others concerning the design of ultra-low power parts for autonomous microsensors.

A global tool could be developed in order to help designers to choose the best configuration, in terms of energy sources and electronic parts, for autonomous nodes in wireless sensor networks [29,30].

Appendix

Piezoelectric material properties (PVDF)

$$s^E = \begin{pmatrix} 0.3333 & -0.0967 & -0.0967 & 0 & 0 & 0 \\ -0.00967 & 0.3333 & -0.0967 & 0 & 0 & 0 \\ -0.0967 & -0.0967 & 0.3333 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0.86 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0.86 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0.86 \end{pmatrix} \cdot 10^{-9} m^2/N$$

$$d = \begin{pmatrix} 0 & 0 & 0.23 \\ 0 & 0 & 0.23 \\ 0 & 0 & -0.33 \\ 0 & 0 & 0 \\ 0 & 0 & 0 \\ 0 & 0 & 0 \end{pmatrix} .10^{-10}$$

$$\varepsilon_p = \begin{pmatrix} 12 & 0 & 0 \\ 0 & 12 & 0 \\ 0 & 0 & 12 \end{pmatrix}$$

Silicon properties:

Young modulus $E = 160$ GPa
Poisson's ratio $\nu = 0.42$
Density $\rho = 2{,}330$ kh/m^3

References

1. Rabaey, J.M., Ammer, M.J., Da Silva, J.L., Patel, D., Roundy, S.: Picoradio supports ad hoc ultra-low power wireless networking. IEEE Comput. **33**(7), 42–48 (2000)
2. Hitachi unveils smallest RFID chip, RFID J. 14 March (2003)
3. Gilbert, J.M., Balouchi, F.: Comparison of energy harvesting systems for wireless sensor networks. Int. J. Autom. Comput. **05**(4), 334–347 (2008). doi:10.1007/s11633-008-0334-2
4. Thomas, J.P., Qidwai, M.A., Kellogg, J.C.: Energy scavenging for small-scale unmanned systems. J. Power Sour. **159**, 1494–1509 (2006)
5. Beeby, S.P., Tudor, M.J., White, N.M.: Energy harvesting vibration sources for microsystems applications. Meas. Sci. Technol. **17**, 175–195 (2006)
6. Gilbert, J.M., Balouchi, F.: Comparison of energy harvesting systems for wireless sensor networks. Int. J. Autom. Comput. **05**, 334–347 (2008)
7. Senturia, S.D.: Microsystem design (2000)
8. Fischer, X.: The interaction: a new way of designing, in research interactive design, vol. 2, pp. 1–15, Springer, ISBN-10: 2-287-48363-2, ISBN-13:978-2-287-48363-9 (2006)
9. Fischer, X.: Interactive method: a way to support decision making in design and manufacturing, in research interactive design, pp. 1–6, Springer, ISBN-10: 2-287-28772-8, ISBN-13:978-2-287-28772-5 (2005)
10. Fischer, X.: Interactive design, Mécanique et industries, Guest Editor, EDP sciences, vol. 5(2), ISSN 1296-2139 (2004)
11. Kundert, K.: A formal top-down design process for mixed-signal circuits, Adv. Analog Circuit Des. April (2000)
12. Dupé, V., Briand, R., Fischer, X.: Component Based Modeling for Structuring Measurement: Preliminary Modeling Applied to Automotive Braking Behavior. VECIMS (2009)
13. Doré, R., Pailhès, J., Fischer, X., Nadeau, J.P.: Integration of user's requirements in preliminary design: application to parabolic ski in a basic turn. Int. conf. on product lifecycle management, Lyon (2005)
14. Scaravetti, D., Nadeau, J.P., Sébastian, P.: Structuring functions and constraints formulation for enhanced embodiment design, International CIRP Design Seminar, 12–14 May, Grenoble, France (2003)
15. AFNOR.: NF X50-150/151, Value analysis, Functional analysis (1991)
16. Doré, R., Pailhès, J., Fischer, X., Nadeau, J.P.: Identification of design variables and criterion variable towards the integration of user requirement into preliminary design. Int. J. Prod. Dev. (IJPD), Inderscience Publishers **4**(5), 508–529 (2007)
17. Doré, R., Pailhès, J., Fischer, X., Nadeau, J.P.: Identification of sensory variables towards the integration of user requirements into preliminary design. Int. J. of Ind. Ergon. 37, n°1, 1–11, Elsevier, January (2007)
18. Savransky, S.D.: Engineering of Creativity, Introduction to TRIZ Methodology of Inventive Problem Solving. CRC Press, Boca Raton (2000)
19. Fischer, X.: The interaction: a new way of designing, in research interactive design, vol. 2, pp. 1–15, Springer, ISBN-10: 2-287-48363-2, ISBN-13:978-2-287-48363-9 (2006)
20. Pailhes, J., Sallaou, M., Nadeau, J.P.: Knowledge base formulation for aided design tool. In: Tichkiewitch, S., Tollenaere, M., Ray, P. (eds.) Trends and Recent Advances in Integrated Design and Manufacturing in Mechanical Engineering II, pp. 231–243. Springer (2007)
21. Zwick Rosen, C., Hiremath, B.V., Everest Newnham, R.: Piezoelectricity. Springer (1992)
22. Ansys website. http://www.ansys.com/
23. Chevallier, S.D., Ghorbel, S., Benjeddou, A.: A benchmark for free vibration and effective coupling of thick piezoelectric smart structures. Smart Mater. Struct. **17**, 964–975 (2008)
24. Benjeddou, A.: Advances in piezoelectric finite element modeling of adaptive structural elements: a survey. Comput. Struct. **76**, 347–363 (2000)
25. Kim, J., Varadan, V.V., Varadan, V.K.: Finite element modelling of structures including piezoelectric active devices. Int. J. Numer. Methods Eng. **40**, 817–832 (1997)
26. Brissaud, M.: Modelling of non-symmetric piezoelectric bimorphs. J. Micromech. Microeng. **14**, 1507–1518 (2004)
27. ANSYS 7.1 Complete User's Manual
28. Cadence website. www.cadence.com
29. Terrasson, G., Briand, R., Basrour, S., Dupé, V.: Energy Model for the Design of Ultra-Low Power Nodes for Wireless Sensor Networks. Eurosensors, Lausanne (2009)
30. Terrasson, G., Briand, R., Basrour, S.: A design technique for power constrained CMOS low-noise amplifier dedicated to wireless sensor networks. J. Of Low Power Electron. (JOLPE) August (2009)