Development of a piezoelectric energy harvesting sensor: from concept to reality

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Abstract: This study focuses on the development and integrated design over a 24-month period of a high efficiency energy-harvesting (EH) temperature sensor, based on piezoelectric materials, with applications for the sustainability of smart buildings, structures and infrastructures. The development of the device was supported by ESA (the European Space Agency) under a program for the space technology transfer, and was concluded in June 2016. The EH sensor, harvests the airflow inside Heating, Ventilation and Air Conditioning (HVAC) systems, using a piezoelectric component and an appropriate customizable aerodynamic appendix or fin that takes advantage of specific air flow effects (principally Vortex Shedding and Galloping), and is implemented for optimizing the energy consumption in buildings. The project was divided in several work-packages (some running in parallel) that cover different aspects of the device development. Some of them focus on engineering aspects (starting from the numerical modeling, prototyping, and concluding with experimental testing). Other aspects focus on the commercialization of the sensor (including the development of a business plan, the intellectual property rights, the final design and the go-to-market actions). Considering the multidisciplinary character of the project (which raises from the fact that it involves knowledge from fields such as wind engineering, electrical engineering, industrial design, entrepreneurship), this study will try to provide an insight on the complex design issues that arise when such complex, sometimes conflicting and overlapping aspects have to be managed within strict deadlines. In doing so, the most important design and development aspects (e.g. design choices, outsourcing issues, and parts optimization) will be critically reviewed.

Keywords: Building Automation, Energy Harvesting, Wireless Sensor, Project Management.

Introduction

piezoTsensor is an advanced autonomous sensor for the temperature sensing in building HVAC (Heating, Ventilation and Air Condition) systems. It consists in an Energy Harvesting (EH) device that uses a piezoelectric bender and an appropriate customizable aerodynamic appendix that takes advantage of specific air flow effects (vortex shedding and flutter) for producing energy. This kind of flow is typical in HVAC networks. The sensor is completed with a temperature probe, a wireless module and an usb dongle receiver (Fig. 1). *piezoTsensor* was developed by StroNGER srl, a consulting spin-off company that works as a link between Academic Sector and Industry in Civil and Environmental Engineering, in the field of Structural Analysis and Design.

The sensor has been thoroughly developed and the technology has been validated over a 24-month period within the ESA (European Space Agency) space technology transfer program at the Business Incubator Center (BIC) Lazio, and its harvesting potential has been demonstrated analytically, experimentally and in close to real conditions. The development included exhaustive FEM (Finite Element Method) and Multi-physics (CFD-Computational Fluid Dynamics) analyses, building different prototype configurations, extensive (over 10 sessions) wind tunnel testing at the CRIACIV wind tunnel facility in Florence, optimization of the EH circuit, and industrial design. A process to secure the IPR in the EU has begun and will be pursued further in the near future.

The activities were divided in eight tasks (work packages) developed in the 24 months as shown in Table 1. The tasks were run entirely by StroNGER partners Dr. Petrini and Dr. Gkoumas (authors of this paper), supported by Mr. Roberto Giuliani (Head of the ESA BIC Lazio) and Ms. Pasqualina Cedrone (Tutor and Business support at ESA BIC Lazio). ESA BIC Lazio assisted with consulting mostly on topics where StroNGER had little acquaintance (e.g. business idea development, go-to-market actions), through monthly meetings. StroNGER C.E.O. Dr. Crosti overview the finance for the project duration.

Considering the above, this paper aims to highlight how a simple idea became a concrete artefact.

Figure 1. Rendering of the sensor and of the dongle

Sensor development

Sensor development timeline and principal actors

Since 2010, StroNGER invested in energy harvesting research as a natural outcome of the group's expertise in structural analysis and design. StroNGER partners Dr. Gkoumas, spent research periods at the Structural Monitoring and Control (SMC) center of the Harbin Institute of Technology (2010) and the Linear and Nonlinear Dynamics and Vibrations Laboratory (LNDVL) at the University of Illinois Urbana-Champaign (2012) and had a research contract with the Sapienza University of Rome on the same topic (2012-2014). StroNGER director Dr. Petrini, who holds a PhD in fluid-structure interaction, carried out numerical simulations and obtained important preliminary results that were fundamental for the future development of *piezoTsensor*. Several research papers were presented in national and international conferences (Gkoumas 2012a, Gkoumas et al. 2012a, Gkoumas *et al.* 2012b, Petrini *et al.* 2012a, Petrini *et al.* 2012b, de Gaudenzi *et al.* 2012, Gkoumas *et al.* 2013, Ferri *et al.* 2014, Petrini *et al.* 2014), and a special session in an international conference was organized (Gkoumas 2012b).

On November 2013, StroNGER applied for a 50.000€ grant in the ESA-BIC Lazio (European Space Agency Business Incubator Center Lazio) for the space technology transfer. The proposal was successful and the project officially started on February 25 2014.

piezoTsensor development took place over a period of 24 months, from March 2014 to April 2016. StoNGER worked closely with ESA-BIC experts and renowned researchers in the fields of aerodynamics and electronics. Additional numerical models were built by Mr. Giulio Biscarini, a fluid-structure interaction expert. *piezoTsensor* was thoroughly tested over a period of 12 months in wind tunnel at the UNIFI-CRIACIV (the Inter-University Research Center for Building Aerodynamics and Wind Engineering in Florence). The electric circuit was designed with the collaboration of Dr. Marco Balsi of the Sapienza University of Rome. The final design was carried out together with SystemDesign srl, an Italian startup company.

Figure 2 shows the sensor prototype and its components.

Table 1. Work packages of the project development and timeline

Task/WP	Task Name		Month	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24
1	Numerical modelling		Planned																								
			Actual	*325%*																							
2	Prototyping		Planned																								
			Actual	*200%*																							
3	Experimental Testing		Planned																								
			Actual	*75%*																							
4	Final Design & Prototype		Planned																								
			Actual	*100%*																							
5	Business Plan		Planned																								
			Actual	*450%*																							
6	Intellectual Property Rights		Planned																								
			Actual	*100%*																							
7	Marketing		Planned																								
			Actual	*100%*																							
8	Management		Planned																								
			Actual	*100%*																							
			Kick off Meeting												Midterm Review												Final Review
Planned																											
Actual																											

Figure 2. *piezoTsensor* prototype inside its box

Modeling activity and prototyping

The sensor has been tested extensively and specific aspects have been optimized, starting from the aerodynamic fin form, the materials, and the electronic circuit. Several testing steps have been successfully concluded, focusing on the energy harvesting optimization, including the testing of different harvesting circuits. Numerous numerical models have been developed both in FEM (Fig. 3) and CFD (Fig. 4), and different prototypes have been prepared (Fig. 5).

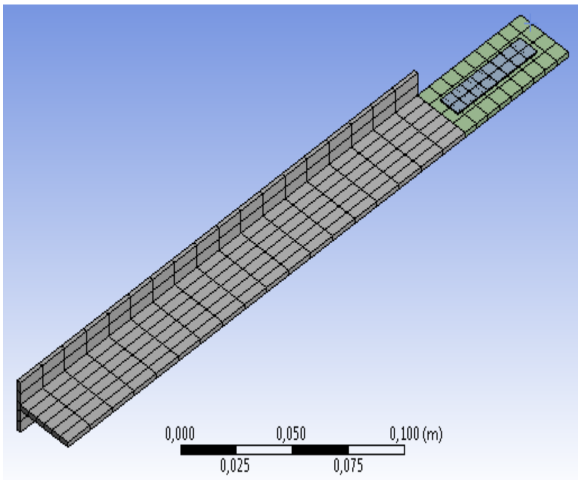

Figure 3. *piezoTsensor* FEM model

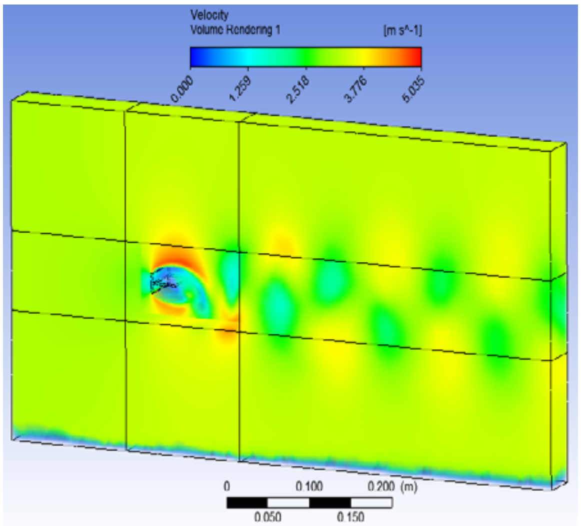

Figure 4. *piezoTsensor* CFD model

Figure 5. *piezoTsensor* prototype

For more information regarding the numerical modeling activity, the reader is referred to Petrini *et al.* 2014 and Biscarini *et al.* 2016.

As can be seen, the final configuration of *piezoTsensor* is composed of three elements:

a. A fixed end-support that is composed of aluminum
b. A piezoelectric bender composed of Kampton and a piezo-ceramic material
c. An aerodynamic fin composed of balsa wood

Piezoelectric component selection criteria

The choice of the piezoelectric element is a critical aspect for this project. It was based on a number of criteria (fundamentally three) that were set a-priori from StroNGER. The criteria are resumed as follows:

a. The piezoelectric component has to meet certain conditions with the *piezoTsensor* scope and conception (dimensions and bending capacity).
b. The delivery of the components was critical, since StroNGER needed to anticipate the prototype realization and the wind tunnel testing
c. The after sales support and the possibility to establish and extend a collaboration with the manufacturer.

Eventually, the PI Ceramic P-876K015 DuraAct Patch Transducer was chosen, due to the specific technical characteristics, the delivery time and the after-sales considerations.

Prototype assembly

Considering the materials selected for the final configuration of the prototype and the expected sensitivity of the prototype behavior with respect to the mass distribution along the aerodynamic fin, StroNGER inquired for a recognized expert in the assembly of aerodynamic components in balsa wood, considering that the latter is capable of developing sustained vibrations without suffering strength damage.

The final choice of the assembler was a local assembler of wood airplane scale models and the proximity of the chosen assembly laboratory to the StroNGER headquarters (20 km) allowed StroNGER to control directly the assembler capacity and machinery, to constantly overview the assembly activity and to decide small changes directly on-site.

For example, a significant decision was taken on-site, in collaboration with the assembler regarding the geometry and configuration of the aluminum base. In particular, the attachment of the base to the bender was decided to be pinned, something that was not entirely defined in the previous stages.

Due to the complexity of the power extract module emerged by the investigation, the assembling of such circuit was assigned to two external experts who worked independently each other:

- Dr. Balsi of the Sapienza University of Rome
- Dr. Formisano, of SystemDesign s.r.l.

Relevant aspects and technical characteristics connected to the power extract module and considered in the start of the module development are:

- The correlation between the damping and the obtained electrical power;
- The advantages of using a power manager that maximize the electrical energy extracted from the device.

Following the presentation meetings, Dr. Balsi proposed to design an electrical circuit and to perform wind tunnel experiments in order to understand the electro-mechanical coupling behavior, and he indicated the electronic components to be acquired in order to assemble the first circuit prototype. Dr. Formisano instead, suggested to characterized the piezoelectric bender to design the circuit in a second phase

After the first wind tunnel tests conducted including the effect of the circuit an optimization study focusing on the best choice of components and assembly for minimizing the power losses, the final design of the circuit for energy harvesting, data acquisition and wireless transmission was conducted by an additional external assignment to Systemdesign s.r.l.

Wind tunnel testing

The initial planned strategy regarding the experimental tests was to start with a single consistent experimental campaign based on the results obtained by the numerical analyses. During the development of these numerical analyses, StroNGER realised that an alternative strategy regarding experimental tests was preferable: it was chosen to subdivide the experimental test campaign in two subsequent steps. Initially, preliminary tests for assessing the best aerodynamic configuration were planned. The necessity to conduct this kind of tests have been decided also due to the fact that the reliability of CFD analyses have been recognized to be lower than initially expected. The results provided by this first set of experimental tests is of value since they can be used to calibrate the numerical models and then to increase their level of reliability to the initially expected one. In a second phase, the originally planned (extended) experimental campaign was carried out on the basis of the device configurations obtained by the calibrated numerical models.

Regarding the choice of the wind tunnel facility to conduct the experimental tests, three options have been investigated:

- a wind tunnel facility belonging to the esa network. The feasibility of this option has been proposed by BIC Lazio. From the investigations carried out, it resulted that a facility with the specific requested characteristics (boundary Layer wind tunnel operating at very low flow velocities) was not available.

- the wind tunnel facility of University of Genova.
- the UNIFI-CRIACIV- Centro di Ricerca Interuniversitario di Aerodinamica delle Costruzioni e Ingegneria del Vento (Inter-University Research Center for Building Aerodynamics and Wind Engineering) wind tunnel facility at University of Florence.

After a cost estimation provided by to the last two facilities above, the final choice was to proceed with the testing at the CRIACIV wind tunnel facility in Florence.

Evolution of the model configuration

The evolution of the model configuration is an important aspect of the numerical analysis performed by StroNGER, and led to a configuration that gave very promising results in later testing. In particular, three different aerodynamic fin shapes have been developed and tested:

a. A circular cylinder shape
b. A rectangular cylinder shape
c. A T-shaped cylinder shape

At the end, the T-shaped cylinder shape was chosen due to its far better performance over a broad flow range. The following paragraphs describe the evolution of the models.

<u>Circular cylinder model evolution</u>

StroNGER at the start of the project started numerical analyses on a configuration characterized by a rectangular aerodynamic FIN. This hypothesis for the FIN was based on corroborated literature and experience gained by StroNGER also before the project commence. At a certain point, a significant feedback was received by aerodynamic experts at the INVENTO 2014 conference in Genova, where StroNGER presented results from the initial configuration (Petrini *et al.* 2014). On the basis of this feedback, StroNGER investigated different shapes and materials, in order to enhance the vibrations of the model. The result was a model with a T-shape aerodynamic FIN in balsa wood.

The consulting activity assigned by StroNGER to UNIFI-CRIACIV, led to a further change in the shape of the FIN. The most promising shape was found to be a circular section shape aerodynamic FIN, again in balsa wood.

An additional modeling activity led to the definition of the dimensions of the FIN shape.

<u>Rectangular section shape model evolution</u>

The original idea was to choose the length side ratio L/D = 1. This hypothesis for the geometry of the FIN was based on corroborated literature and experience gained by StroNGER also before the project commence.

Following Investigations made by Dr. Biscarini, the length side ratio was increased to 3 in order to avoid instability phenomenon as galloping. However, after further investigation was chose the length side ratio of 3.5 in order to avoid problem related to the strong variation of the Strouhal number for length side ratio between 2.8 and 3.3 that make very cumbersome the determination of the vortex shedding frequency.

<u>T-section shape model evolution</u>

Initially, based on corroborated literature and experience gained by StroNGER also before the project commence was chosen to design an H-section shape. However, after further investigation was chosen to change geometry to a T-section shape.

Due to the lack of literature information about the fluid dynamics behavior of this shape was chosen to design the prototype based on the information obtained by the CNR-DT 207/2008 and numerical analysis.

The sensor has been tested in (simulated) real conditions inside wind tunnel (Fig. 6), demonstrating the energy capacity over a broad flow range typical of HVAC tubes (3-6 m/s^2). Figure 7 shows the power/flow law.

Figure 6. *piezoTsensor* wind tunnel testing

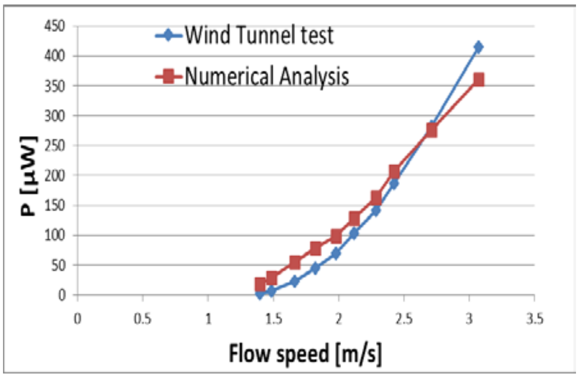

Figure 7. *piezoTsensor* wind tunnel testing

In a close to production form, the sensor is equipped with the following parts:

- Piezo Systems Inc Std QM 303 piezoelectric patch
- Microchip MRF89XA multi-channel FSK/OOK transceiver
- Measurement Specialties HTU21D digital temperature and humidity sensor with custom components

It is foreseen that some additional cost-saving will occur for the production version using gross-market components. Figure 8 shows the final design of the sensor casing and of the communication dongle.

The sensor has already been studied for easy and not-invasive installation inside HVAC tubes, by means of a magnetic base, using common tools, while the cable free operation further facilitates the installation.

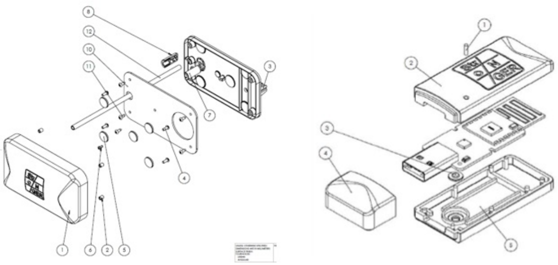

Figure 8. Sensor and usb dongle components

Market approach

Unique selling proposition and market potential

The developed sensor will be the first mass market energy harvesting sensor based on wind flow excitation, if not one of the very first commercially available vibration energy harvesters. Vibration energy harvesters have been studied thoroughly in the last years, but none of them has been tied to a specific application as in this case. The principal innovation of the sensor is that it produces more power than sensors already in the market, and it is designed specifically for airflow environments, typical of HVAC tubes. This will be the key marketing strength of the product, since it can be a game-changing asset. The entrepreneurs are positive that this will remain a key asset of the product until and after its commercialization.

The unique proposition lies to the fact that:

- Existing sensors are mains-powered or autonomous. The latter, use either batteries or an EH module that harvests small amounts of energy, principally using the temperature differential or solar cells. The proposed sensor harvests a higher amount of energy from air flow, and thus has a higher autonomy, something that can lead to a higher sampling rate, and as a consequence, to further reduction in the HVAC energy consumption.
- Regarding the specific application (in HVAC systems), the above mentioned commonly implemented EH methods (based on temperature differential or solar cells) are not efficient since they require specific conditions that are not always present in HVAC systems: for example, solar cells-based EH systems imply the exposition of the cells to the solar or artificial light. In this sense, the proposed sensor is more appropriate since it generates energy just from an intrinsic characteristic of HVAC systems (airflow inside the ducts).

The principal competitors identified in HVAC and business automation ambient are:

- EnOceanTM ECT 310 Perpetuum
- POWERCASTTM P1110 Powerharvester Receiver
- Distech ControlsTM SR65 AKF - Duct Temperature

These sensors are powered by thermal differential or light cells. EnOceanTM ECT 310 Perpetuum for example, is used for powering battery-less EnOceanTM radio modules by Thermal Energy. In Table 2, a brief comparison of the specific piezoelectric harvester is provided with two principal competitors based on EH from temperature differential and solar cells. The comparison is not straightforward, since competitor EH sensors have a very low intermittency due to the lower energy production. The sensor's integration inside an HVAC system is straightforward, since in the HVAC duct, the airflow circulation is continuous.

From an initial comparison, the harvested power of the sensor is much higher than the competition, harvesting 10-15 times more energy (in the order of 2-4 mW for HVAC flows), while the price is foreseen to be higher than the competition, something that reflects the relative advantages.

Since self-powered wireless sensors are retailed as a single product to be integrated in the WSN during the design phase of the HVAC and its control system, StroNGER will enter in the market of such sensors as an innovative and efficient device. Focusing on the market value chain (Fig. 9), the producers of Humidity and Temperature sensors represent the first element of the chain. These sensors are a solid part of technologies for smart buildings. Two pertinent examples of these technologies are the wireless network architecture for the data acquisition and the energy harvesting modules for autonomous wireless sensors, which is precisely the location in the value chain of this sensor. These technologies are integrated in HVAC automatic control systems with the goal to optimize the building consumption, which is one of the targets of Building administrators and owners.

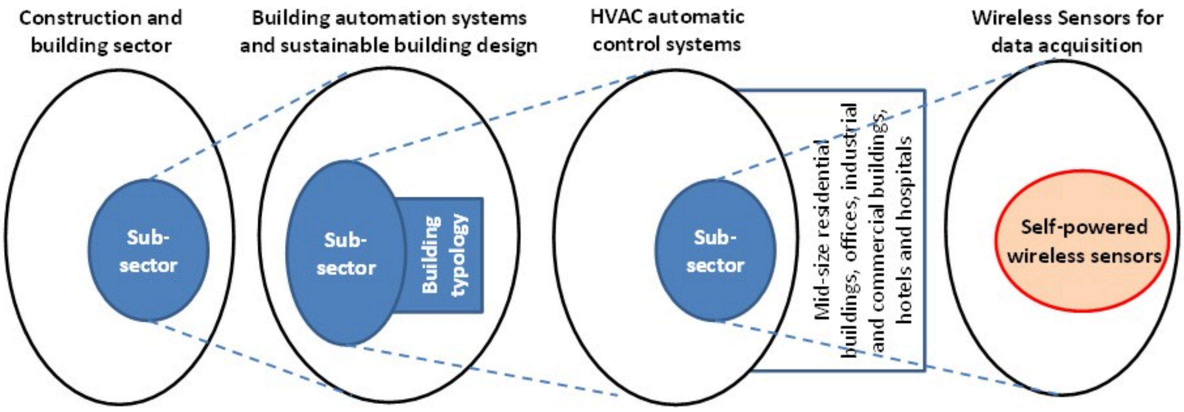

Figure 9. Market sectors

Table 2. Energy harvesting sensor comparison

	Piezoelectric EH	EH from temperature differential	EH from solar cells
Harvested Energy (µW)	200 µJ	20 µJ	20 µJ
External factors	NO	A temperature differential is necessary	Artificial light is necessary

Business model and pricing strategy
The sensor will be sold directly from StroNGER to the end-customer. StroNGER will focus on selected HVAC automation systems designers and installers to promote it. The key selling strategy will be on the technical advantages of the sensor compared to those already in the market. In this sense, it is expected that a common ground approach will be preferred (on technical/scientific basis) when approaching potential customers. The background checks on potential clients already performed will be constantly expanded and integrated, in particular before the commercialization phase. The starting price will be fixed on the basis of considerations regarding the manufacturing costs and the cost of competitor products. The sensor will be competitive priced, although it will not be on the low scale of similar products. In this sense, considering the significant advantages to existing sensors, it will be positioned on the higher end of the market. The aim is also to communicate the higher quality of the sensor (“Value Proposition”). The components of the sensor selected primarily on the basis of appropriateness.
The advantage of the sensor is that it is a relatively simple to manufacture product, based on a limited number of components: most parts are easy to find from different suppliers. The principal components are a StdQM 303 PiezoElectric patch from Piezo Systems Inc, an MRF89XA multi-channel Data transceiver from Microchip Inc. and a HTU21D digital temperature and humidity sensor with custom components from Measurement Specialties Inc. The software has been developed from SystemDesign.

IPR (Intellectual Property Rights)

StroNGER thoroughly carried out a patent search using a sector professional, and consecutively applied for a European Patent ((European Patent Application: EP2953259 - 2015-12-09). The principal claim is of a self-powered device of specific characteristics for the detection of environmental and/or structural parameters and for transmitting such data in wireless mode.

Marketing strategy
During the first two years, the principal marketing strategy of StroNGER will be to become recognizable in the HVAC automation systems scene (designers and installers).
In general, *piezoTsensor* marketing will follow two principal directions: entering an association of produces and selling directly to customers.

StroNGER with *piezoTsensor* will enter a consortium operating in smart systems and automation. In particular, among different associations, the ZigBee® Alliance has been chosen, for the advantages it offers (among else, open both to enterprises and research companies). StroNGER will participate in the alliance as "Adopter", and this will bring benefits also for what regards marketing and promotion activities.

A direct marketing approach will also be adopted for promoting *piezoTsensor*. Principal marketing will be conducted by direct contact or by emails (sending promotional letters and flyers), and will be tailored to the specific customer. It is expected that after the initial and successful implementation in projects, these will also serve as case studies for the future selling of the product.

In doing so, the following means will be implemented:

a. Direct marketing.

• Integration and improvement of the list of possible customers (HVAC automatic system designers and installers);

• Direct contact (by email, phone) of the above.

b. Participation and organization of information workshops (also within the ZigBee alliance).

c. Participation to international fairs, specific to the either the building sector, or to HVAC technology, or to building automation. The following fairs have been attended (spanning an arc of one year in the product development).

- Climatherm – Energy 2016 25 – 28 February 2016, Athens Metropolitan Expo "Together for an energy sustainable future", with over 15.000 visitors (businesses, technicians, researchers, engineers, architects, hoteliers etc.) featuring the latest trends, meet suppliers and useful business contacts
- Energy Harvesting & Storage Europe (Berlin April 28-29 2016), the biggest energy harvesting and building automation fair in Europe in 2016. It features big brands discussing their needs and experiences, new product launches, world first announcements and insightful analyst presentations.

Sales strategy

StroNGER will focus on selected HVAC automation systems designers and installers to promote the implementation of PiezoTsensor. The key selling strategy will be on the technical advantages of PiezoTsensor compared to similar sensors. In this sense, it is expected that a common ground approach will be preferred (on technical/scientific basis) when approaching potential customers. The sales strategy will be facilitated by the preparation of two documents:

a. A detailed internet website, with contact information (www.piezotsensor.eu)

b. A promotional flyer, where among else, advantages of *piezoTsensor* compared to similar products will be detailed.

The background checks on potential clients already performed will be constantly expanded and integrated, in particular before the commercialization of *piezoTsensor*.

As in the case of marketing, sales will be the responsibility of Dr. Gkoumas.

Risk analysis

A risk management process will run after the project to ensure that threats and opportunities remain up to date.

In the performed preliminary SWOT analysis (Fig. 10), the principal strengths, weaknesses opportunities and threats have been identified. During the project, some of the initial risks have been eliminated. For instance, the need to calibrate the aerodynamic fin is now neglected, since, testing have validated, that the sensor operates over a broad range of win flow.

The principal strength of *piezoTsensor* is that it produces more power than sensors already in the market. This will be the key marketing strength of the product, since it can be a game-changing asset. The entrepreneurs are positive that this will remain a key asset of the product until and after the commercialization of *piezoTsensor*. In the remote hypothesis that similar products enter the market with a similar advantage, StroNGER will revaluate its strategy focusing on other advantages (e.g. optimal integration of *piezoTsensor* in the HVAC system).

Other possible risk situations have been already identified. In particular, if selling *piezoTsensor* becomes more complicated for unforeseen reasons (e.g. market change) StroNGER will consider a modification of the *piezoTsensor* selling strategy. In particular, selling through a reseller could be considered.

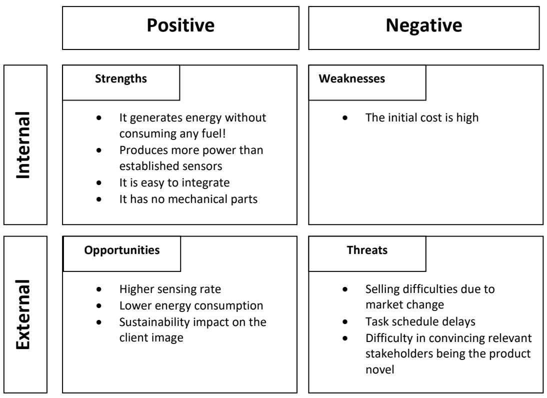

Figure 10. SWOT analysis for the commercialisation

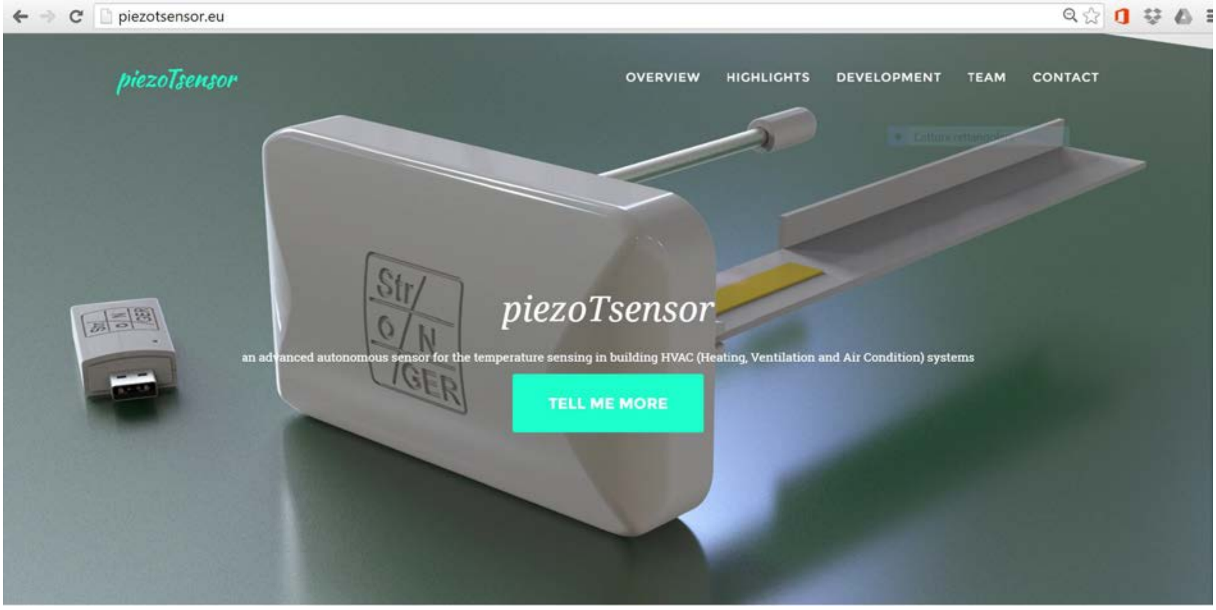

Figure 11. The www.piezotsensor.eu landing page

Web site development

A strong marketing point was the realization of a web-site. The domain www.piezotsensor.eu was acquired, together with web hosting space. Together with the domain, the email address: info@piezotsensor.eu was activated. The web page was prepared internally by StroNGER using state of the art methods and graphic tools, in particular bootstrap. Bootstrap is a free and open-source front-end library for creating websites and web applications. It contains HTML- and CSS-based (Cascading Style Sheets is a style sheet language used for describing the presentation of a document written in a markup language) design templates for typography, forms, buttons, navigation and other interface components, as well as optional JavaScript extensions. Bootstrap supports responsive web design. This means the layout of web pages adjusts dynamically, taking into account the characteristics of the device used (desktop, tablet, mobile phone). Bootstrap also adopts a mobile-first design philosophy, emphasizing responsive design by default.

The website was prepared focusing among else on:

- Precedence: The user's eyes is led through a sequence of steps, by specific use of colors, position of elements, size and design elements.
- Navigation: The site navigation is straightforward using the 1-page scheme.
- Typography: special fonts were used, among else, Font Awesome fonts (https://fortawesome.github.io) that give scalable vectors.
- Usability: the page adheres to standards for what regards navigation signals.
- Modularity: the webpages are scalable for different screens (from mobile phones, to tablets and large-screen home computers).

The page clearly illustrates the steps StroNGER took for the development of the project, both before and after the ESA funding. The page is integrated with a contact form for potential customers.

The page adheres to the StroNGER brand-image colors (using as a basis the StroNGER color, RGB 0 204 153), and using variations obtained through specific design tools (e.g. http://www.color-hex.com). Figure 11 illustrate in part of the web site potential.

Acknowledgements

The realization of a multidisciplinary project as the one described in this paper requires the collaboration between different disciplines and different authors. Even though the project is finished under the ESA BIC umbrella, the entrepreneurs are committed in promoting the project in further commercialization or research activities.

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