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

Konstantinos Gkoumas, Francesco Petrini, Stefania Arangio, Chiara Crosti, Franco Bontempi

an advanced autonomous sensor for the temperature sensing in building HVAC (Heating, Ventilation and Air Condition) systems

StroNGER – vision

"Start Up Innovativa"
ai sensi della legge 221/2012

"…. to provide, through innovation, advanced products and services that help save energy, for sustainable buildings."

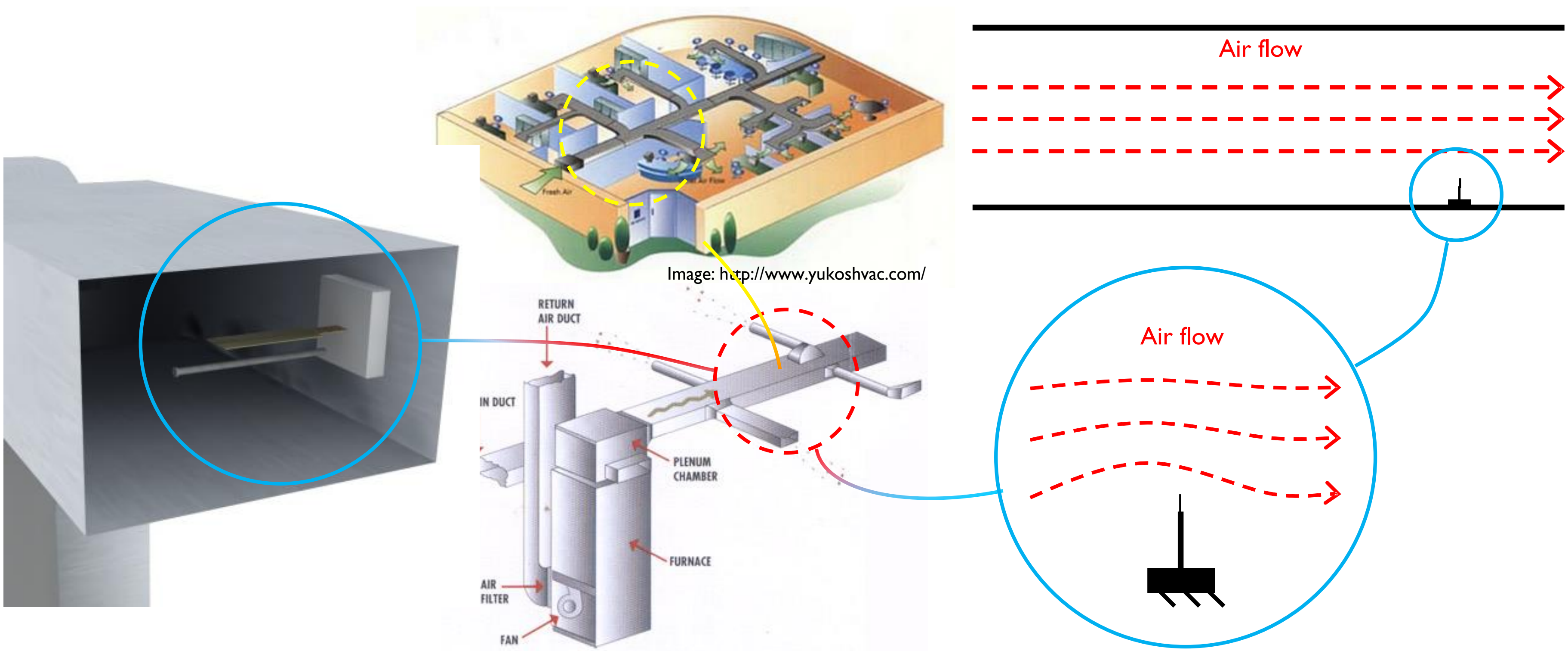




December 2013: ESA BIC Lazio (European Space Agency Business Incubator Center Lazio) winner of a 50.000€ grant for the space technology transfer.

Engineering: 10+ years of experience Entrepreneurship?

An advanced sensor for the optimum energy management in building HVAC (Heating, Ventilation and Air Condition) systems.



piezoTsensor implementation scheme inside an HVAC duct

piezoTsensor – market: value chain

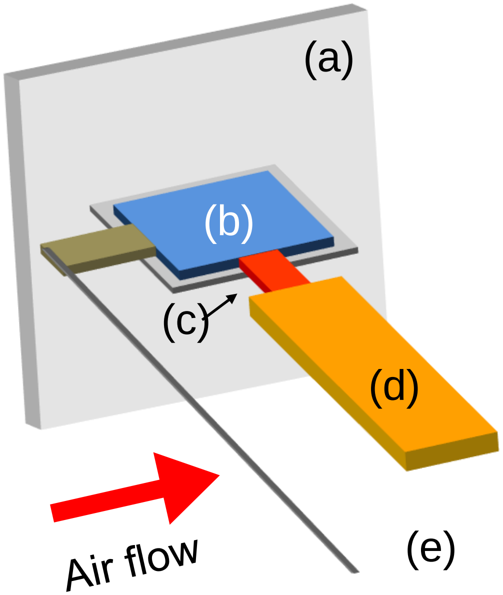
Image from enocean-alliance®
http://www.enocean-alliance.org

Producers of Humidity and Temperature sensors → Technologies for smart buildings companies → HVAC automatic control system producers and designers → Building administrators and owners

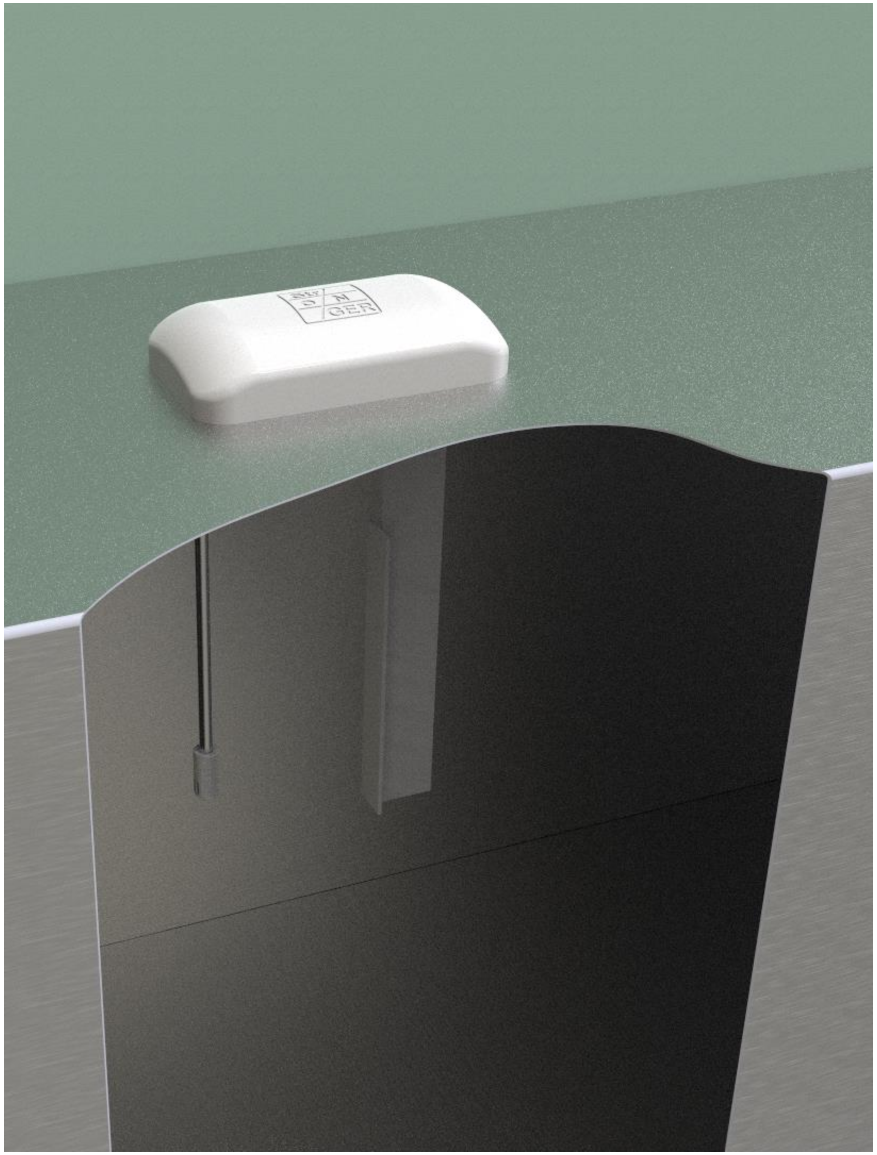
Essentially, ***piezoTsensor*** consists in an **Energy Harvesting** (EH) device that uses a **piezoelectric bender** and an appropriate customizable **aerodynamic fin** that takes advantage of specific air flow effects (principally **Galloping** and **Vortex Shedding**) for producing energy. The sensor is completed with a **temperature probe**.

***piezoTsensor* scheme**

a. Steel plate (support)
b. Sensor transmitter module
c. Piezoelectric bender
d. Fin
e. Temperature probe



piezoTsensor – Unique Selling Proposition



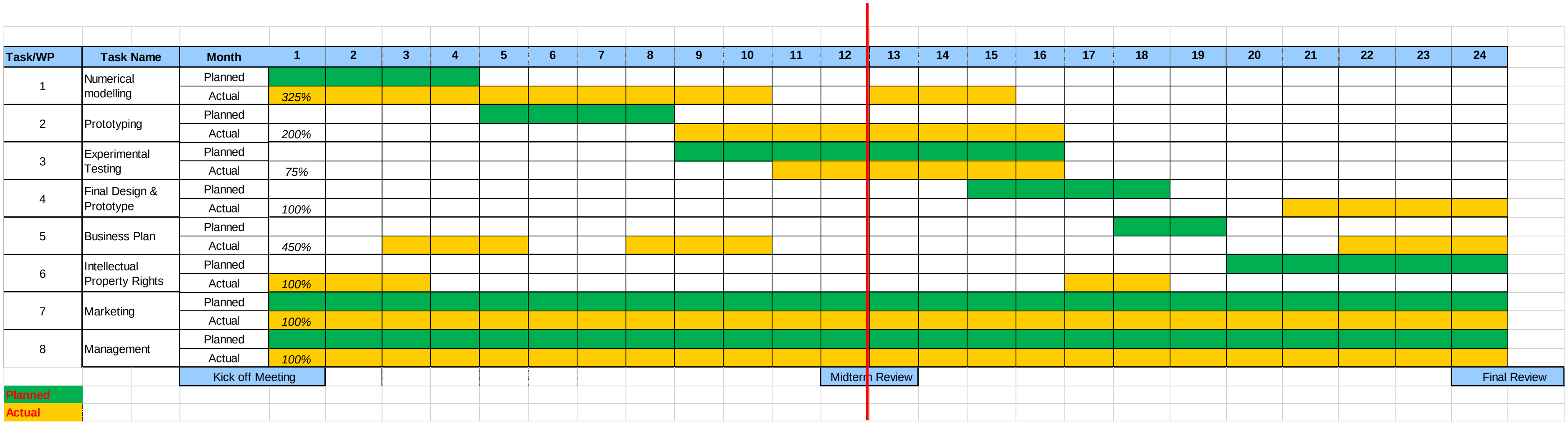
- *piezoTsensor* harvests a **higher amount of energy** from air flow, and thus has a higher autonomy, something that can lead to a higher sampling rate.
- *piezoTsensor* generates energy from an **intrinsic characteristic** of HVAC systems achieving an optimal integration.
  - **Competitors**
    - EnOcean™ ECT 310 Perpetuum
    - POWERCAST™ P1110 Powerharvester Receiver
    - Distech Controls™ SR65 AKF - Duct Temperature

Final Term Review

June 6 2016

Updated Gantt chart – months 1-24

The Gantt chart has been updated to reflect progress, with certain tasks re-arranged to resolve problems with over-allocated tasks



TASKS

1. *Numerical modelling*
2. *Prototyping*
3. *Experimental testing*
4. *Final design and prototype*
5. *Business plan*
6. *IPR*
7. *Marketing*
8. *Management*

16 Deliverables

46 Annexes

Updated Gantt chart – months 1-12

The Gantt chart has been updated to reflect progress, with certain tasks re-arranged to resolve problems with over-allocated tasks

Task/WP	Task Name	Month	1	2	3	4	5	6	7	8	9	10	11	12
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	

Planned
Actual

Updated Gantt chart – months 13-24

The Gantt chart has been updated to reflect progress, with certain tasks re-arranged to resolve problems with over-allocated tasks

Task/WP	Task Name	Month	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%											

Mid term Review — Final Review

Planned

Actual

TASK #1 Numerical modelling - months 1 to 10 and 13 to 15 (a total of 13 months)

Objectives

The goal of this task was to develop the necessary numerical models.

Important points:

- *In-Vento Conference 2014* (June 2014): feedback on the aerodynamic shape of the fin section
- calibration after wind tunnel testing

Sub-tasks

a. FEM and CFD models development. The necessary FEM models and some CFD models were developed in this subtask.

b. Definition of the prototype configuration (piezo-mechanical parts) based on the results obtained by the above mentioned modelling activity.

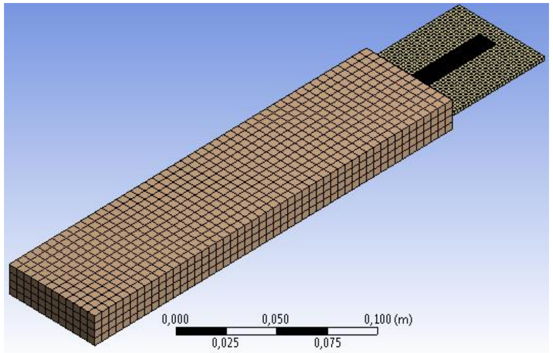
Output

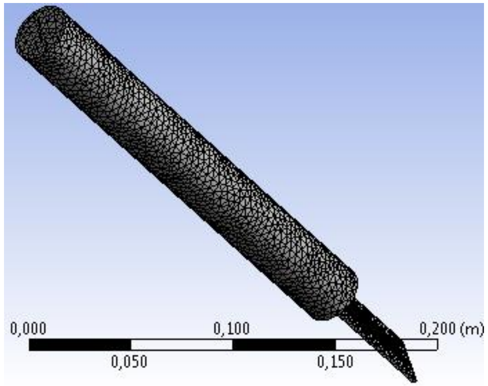
- **#1a** numerical and CFD modelling

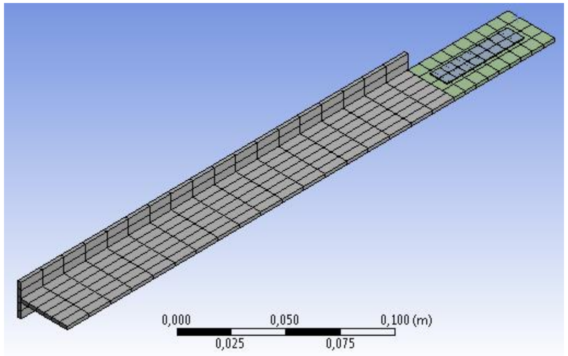
- **#1b** definition of the prototype configuration (piezo-mechanical parts).

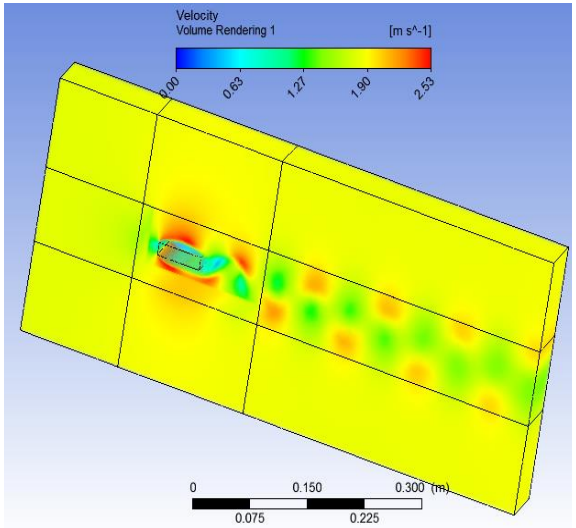
- **#1c** FEM and CFD modeling (rectangular and T-section geometry).

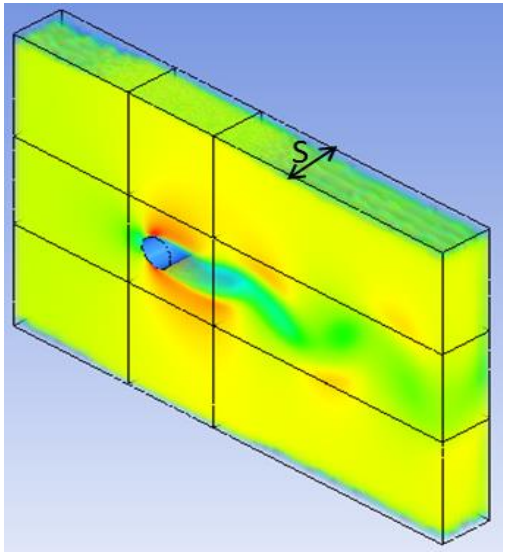
TASK #1 Numerical modelling - months 1 to 10 and 13 to 15 (a total of 13 months)

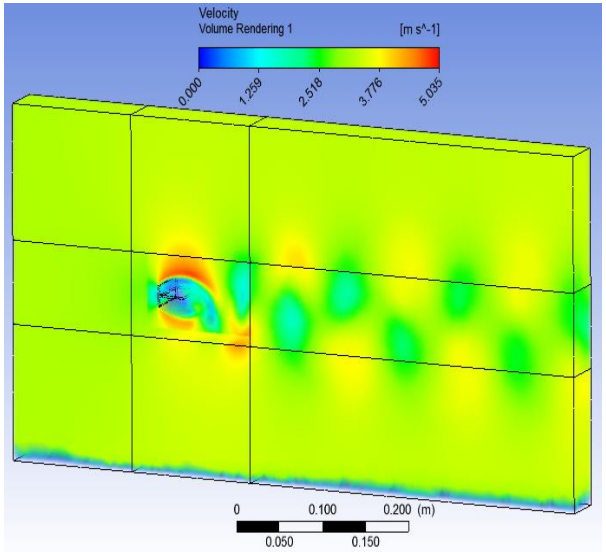












TASK #2 Prototyping – months 9 to 16 (a total of 8 months)

Objectives

Define the final configuration of the prototype and arrive at the assembly of the prototype for the experimental testing.

Important points:

- Parts of the prototype were acquired on the basis of the outcome of **Task #1**. Several different prototypes have been assembled based on three different aerodynamic shapes for the fin. This working prototypes were used for wind-tunnel testing in **Task #3.**

Sub-tasks

a. Parts selection and acquisition.

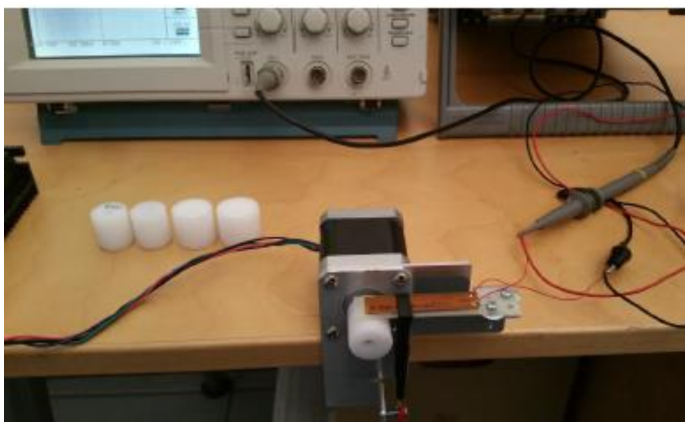
b. Prototype assembly.

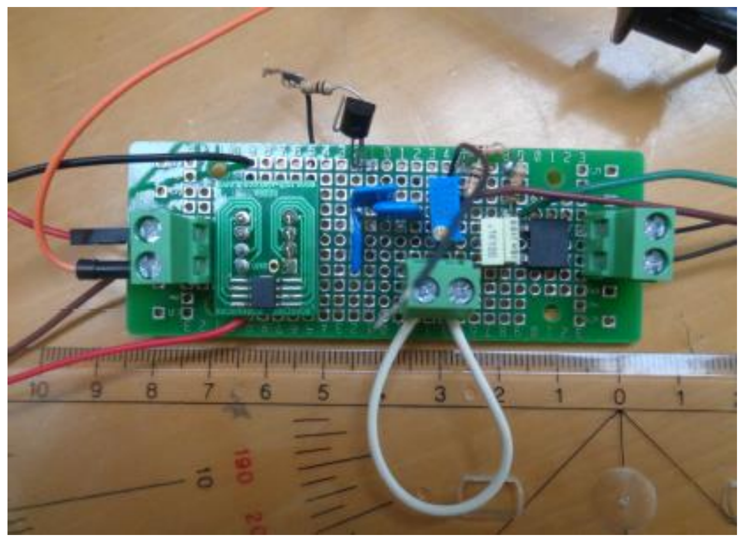
c. Power transfer module assembly.

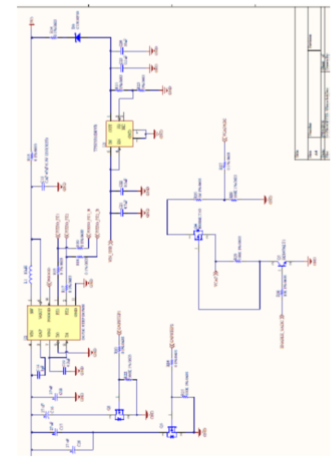
Output

- **#2a** Piezoelectric component selection from technical sheets.
- **#2b** A set of complete working prototypes for experimental testing.
- **#2c** Electromechanical component characterization and definition.

piezoTsensor – task 2







TASK #3 Experimental testing of the working prototype – months 11 to 16 (a total of 6 months)

Objectives

Objective of this task was to assess the effective energy harvesting potential of the *piezoTsensor* working prototypes in laboratory conditions. Two kinds of experimental tests were performed:

i) shaking tests

ii) wind tunnel tests

Important points:

- The T-shape fin section proved to be the best choice.

Sub-tasks

Testing of different prototypes. Power extraction assessment. HVAC duct simulation.

Output

- **#3a -** *CRIACIV* preliminary wind tunnel testing report.
- **#3b -** *CRIACIV wind tunnel testing report*: electro-mechanical investigation.
- **#3c -** *CRIACIV wind tunnel testing report:* HVAC duct report.

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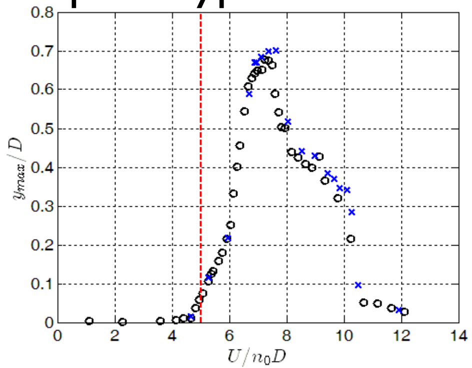
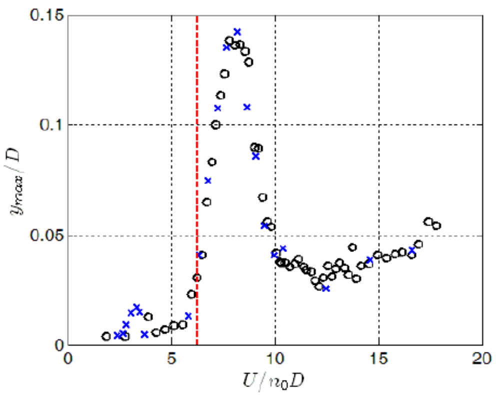
Mechanical Response of the prototypes

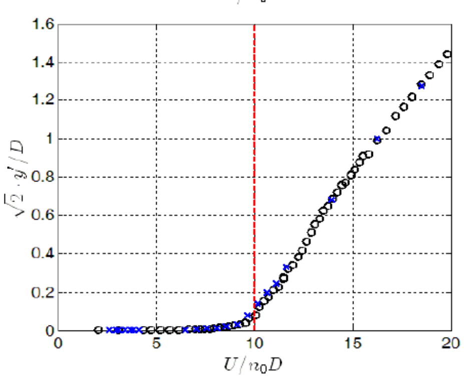
Circular shape



Rectangular shape



T-section shape



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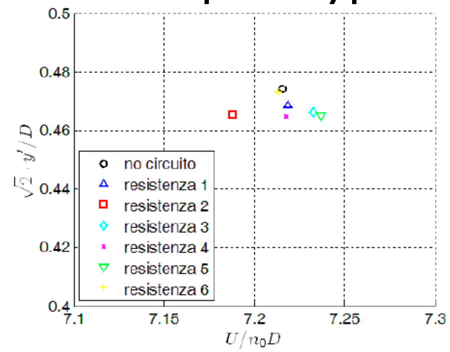
Centro di Ricerca Interuniversitario di Aerodinamica delle Costruzioni e Ingegneria del Vento

Normalized dynamic response of the model, varying the reduced wind velocity.

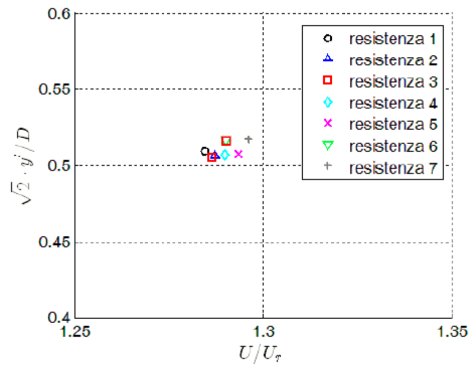
- Circles: first testing series (increasing values with wind speed)
- Crosses: second testing series (decreasing values with wind speed)
- Dotted red line: reduced speed equal to 1/*St*, assuming a value of *St* = 0.2 for the Strouhal number.

Electro-Mechanical Response of the prototypes

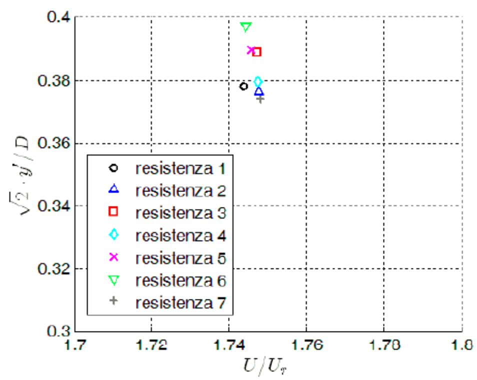
Circular shape



T-section (single PZT patch)



T-section (double PZT patch)

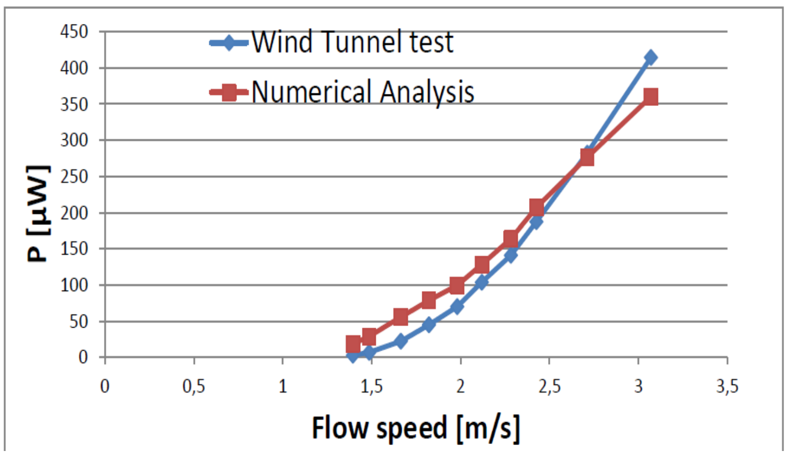


CRIACIV

CENTRO DI RICERCA INTERUNIVERSITARIO DI AERODINAMICA DELLE COSTRUZIONI E INGEGNERIA DEL VENTO

LEFT: mechanical response of the prototypes at different values of the electrical resistance.

BELOW: power/flow velocity law for non optimized circuit – T-section shape prototype.



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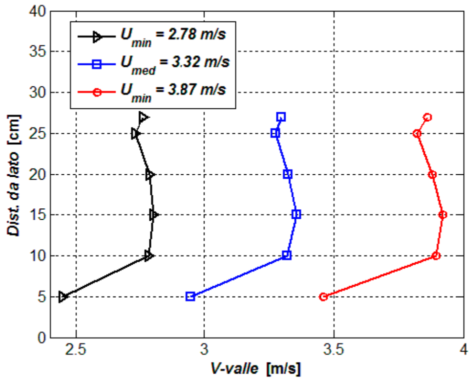
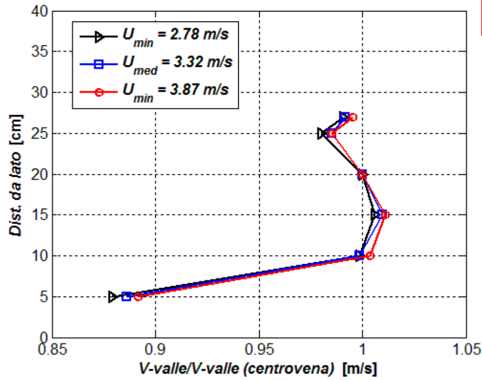
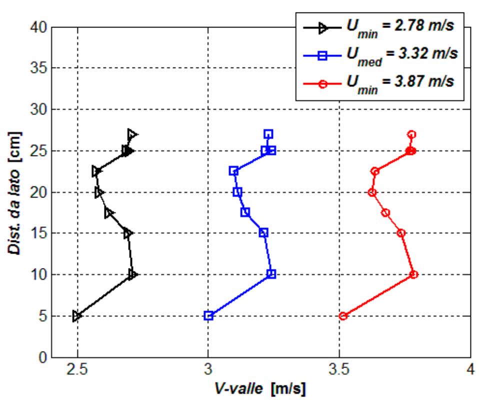
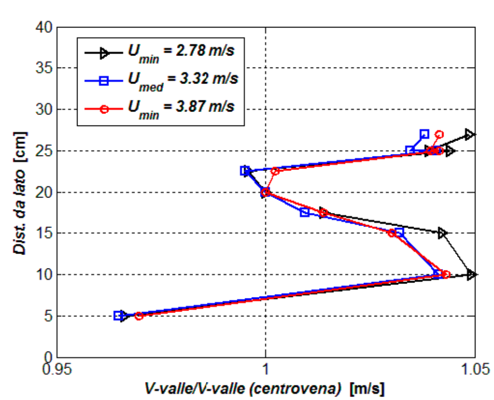
Flow disturbance

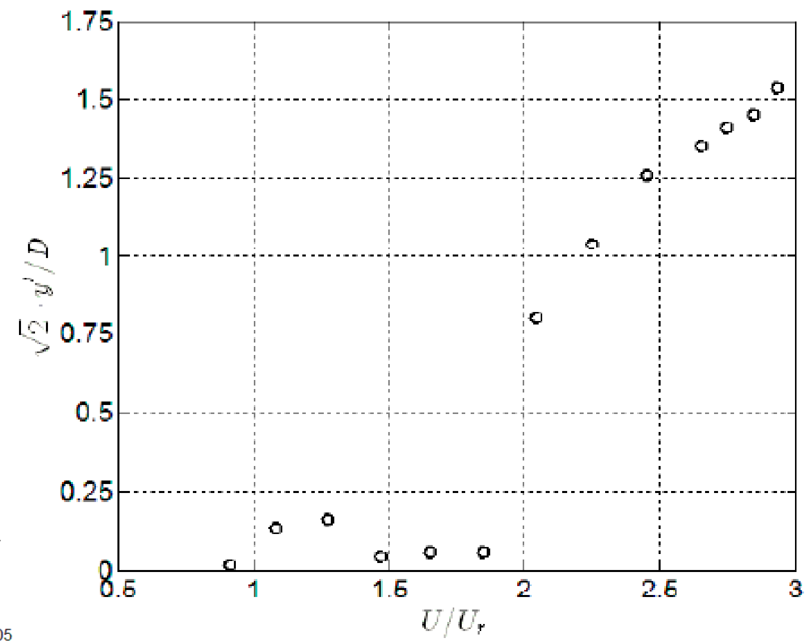








Response of the prototype



TASK #4 Final design and prototype – months 21 to 24 (a total of 4 months)

Objectives

Obtain the final design of *piezoTsensor*

Important points:

- Final configuration of prototypes for use in HVACs.
- Obtainment of working prototypes.

Sub-tasks

a. Integration of the electronic components (Wi-Fi, electric circuit, capacitor, temperature probe) to the EH part and software development.

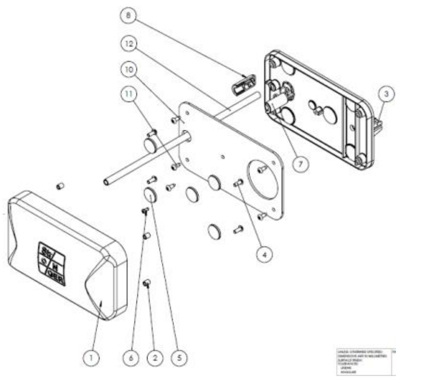
b. Choice of the battery/capacitor scheme and optimization of the electronic circuit.

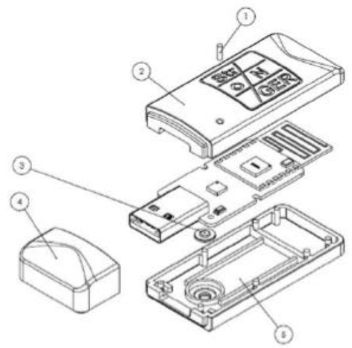
c. Calibration and fine tuning by FEM.

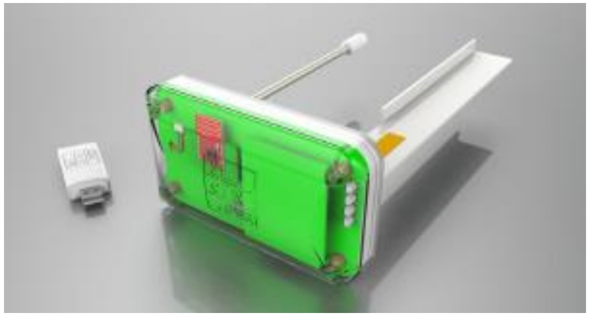
d. Final design, including 3D renderings and final parts selection and acquisition (partly developed by an external assignment).

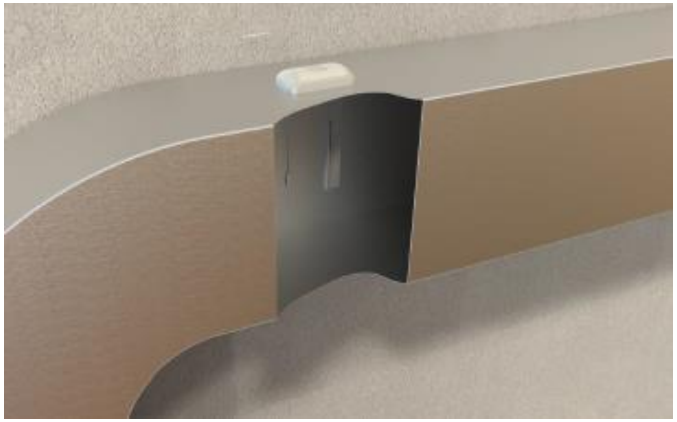
Output

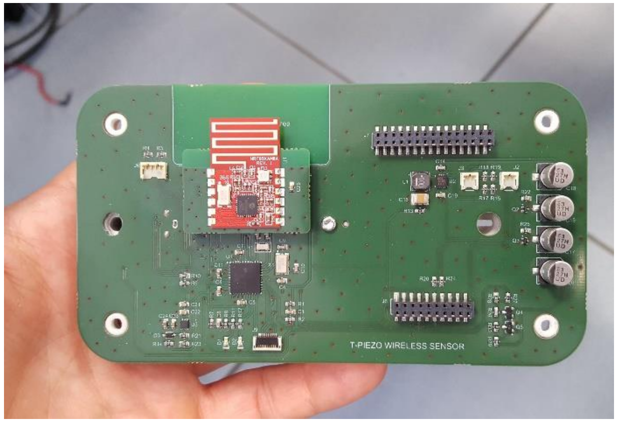
- **#4a** - *Final Configuration of piezoTsensor.*










T-PIEZO WIRELESS SENSOR

TASK #5 Business plan – months 3-5, 8-10 and 22 to 24 (a total of 9 months)

Objectives

Objective of this task was to update the business plan of the project, on the basis of four pillars:

- Training - for the participation in investment activities.
- Schematization - preparation of a graphic representation of the business plan.
- Funding opportunities - participation in funding opportunities and competitions.
- Update - StroNGER defined and updated a comprehensive business model, on the basis of performed market analysis and interviews with industry experts.

Important points:

- Major improvement of communication capacity and business training.

Sub-tasks

The four pillars reported above, form a single task.

Output

- **#5a** *Business Model update* reports the major aspect of the activity for Task **#5**.

Key Partners*

- Physik Instrumente (PI), on piezoelectric components
- Officina mec. Traini Giovanni on prototype parts
- Marco Balsi (Sapienza University of Rome - DIET) on EH pcb design and testing
- SystemDesign on EH pcd and wireless trasmision module hardware and firmware development
- CRIACIV Firenze on wind tunnel testing
- SystemDesign on industrial design

Key suppliers

- 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

Key activities

- Numerical Modelling
- Prototyping
- Experimental test
- Final design and prototype
- IPR
- Marketing
- Production readiness

Key resources

- All StroNGER partners are from the academy in the Sapienza University of Rome
- StroNGER received financial support through the fund "FILAS - POR FESR LAZIO 2007/2013 - Support for the research spin-off"
- *piezoTsensor* development is supported from the European Space Agency (ESA) through the fund for the space technologies transfer
- StroNGER has an European patent pending on *piezoTsensor* (European Patent Application: EP2953259 - 2015-12-09)
- StroNGER will apply for a trademark registration for *piezoTsensor*

Value proposition

- *piezoTsensor* consists in an Energy Harvesting device that uses a piezoelectric bender and an appropriate customizable aerodynamic fin that takes advantage of specific air flow effects (principally Vortex Shedding and galloping) for producing energy. The sensor is completed with a temperature probe, an EH module and a wireless module.
- *piezoTsensor* implementation helps reducing the energy cost, having enough energy for a high frequency temperature data transmission.

Customer relationship

- CRM and CK will be handled internally by a specific person in the StroNGER team, who will review and analyze all the information
- social media and technology will be activated to engage with customers
- www marketing will be principally used
- After sales consulting and training

Channel

- Direct one-to-one contact
- Direct contacts in energy and building automation fairs.
- Indirect contacts with partner and network linked operators.

Customer segments

- Customers are principally from building automation systems and sustainable building design in the construction and building sector.
- Direct customer are the designers and planers of HVAC automation systems.
- Other customers are retail building automation megastores

Cost structure

The principal costs are human recourses (design, marketing, astersale), material and production with savings related to economies of scale.

Revenue streams

Customers will purchase the product, consulting and aftersales service. Pays are on a 60 day basis after sale.

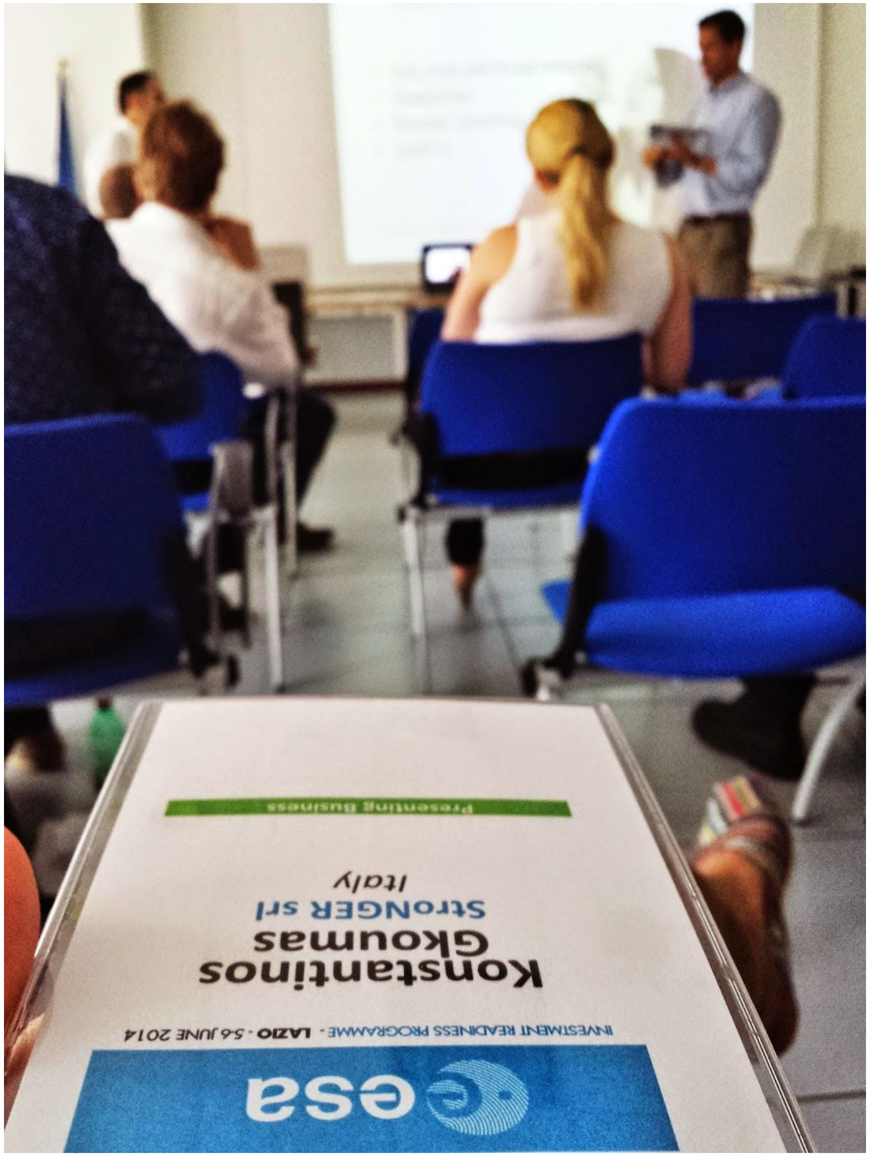
Training events

European Space Agency (ESA) Investment Readiness Programme (IRP), Lazio - June 5/6

- one of the 5 ESA IRPs held in 2004

ESA IRP aims to help early-stage entrepreneurs increase their likelihood of acquiring seed-level or venture capital funding.

Rick Salmon (http://ricksalmon.com) the program leader, worked with the participating entrepreneurs, representing 9 companies, to fine-tune business models and sharpen business propositions.



TASK #6 Intellectual Property Rights – months 1 to 3 and 17 to 18 (a total of 5 months)

Objectives

Objective of this task was to assess the eligibility of *piezoTsensor* for an Italian patent and, in the case that the eligibility is granted, to initiate the procedure for obtaining both a national and European patents.

Important points:

- In the original plan, the initial thought was to apply directly for a European patent. The process changed after consulting with experts (including ESA BIC Lazio).

Sub-tasks

a. Assessment of the eligibility and application for an Italian patent.
b. European patent application.
c. Further developments after the response from the Italian and the European Patent Offices. StroNGER will reply in June and December 2016.

Output

- **#6a** Italian patent application
- **#6b** European patent application

piezoTsensor – task 6

Verbale di Deposito Domanda di Brevetto per Invenzione Industria
numero domanda: RM2014A0002

Camera di Commercio Industria, Artigianato e Agricoltura di ROMA

Verbale di Deposito
Domanda di Brevetto
per INVENZIONE INDUSTRIALE

Numero domanda: RM2014A000291
CCIAA di deposito: ROMA
Data di deposito: 05/06/2014

In data 05/06/2014 il richiedente ha presentato a me sottoscritto la seguente domanda di brevetto per Invenzione Industriale.

ROMA, 05/06/2014 — L'Ufficiale Rogante

Diritti di Segreteria	15,00 EURO
Bollo Virtuale	20,00 EURO

Pagina 1 di 4

(19) Europäisches Patentamt / European Patent Office / Office européen des brevets

(11) EP 2 953 259 A1

(12) EUROPEAN PATENT APPLICATION

(43) Date of publication: 09.12.2015 Bulletin 2015/50

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(21) Application number: 15170907.8

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Designated Validation States: MA

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(54) DEVICE MADE OF PIEZOELECTRIC MATERIAL HAVING A FIN FOR HARVESTING ENERGY FROM AIR FLOWS

(57) The subject of the present invention is a device that is able to harvest energy from air flows present in either open and closed environments, from natural or artificial sources. The invention basically consists of a piezoelectric element appropriately attached to an aerodynamic appendage specifically sized in shape and mechanical characteristics for exploiting a specific effect of the flow of air (in particular, one of the effects referred to technically as "vortex shedding", "flutter", or else "turbulent-flow-induced vibrations") for the production of electrical energy. In the example of embodiment referred to in the present description, the device is mainly conceived as an element of a wireless building automation network integrated with a temperature sensor, for specific applications within air-conditioning ducts in which the aforesaid vortex-shedding phenomenon is exploited.

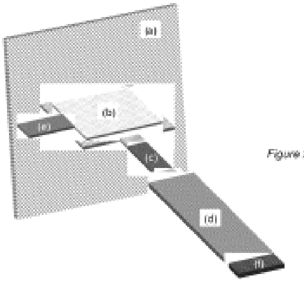

Figure 2

EP 2 953 259 A1

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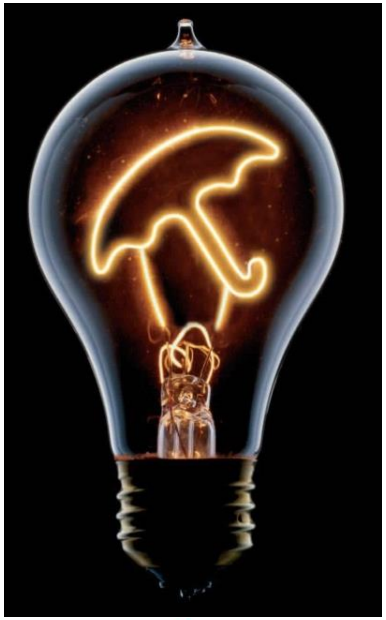

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Ministero dello Sviluppo Economico
DGLC- UIBM

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TASK #7 Marketing – months 1 to 24 (a total of 24 months)

Objectives

- Evaluate the potential market.
- Develop an efficient product concept and product image for *piezoTsensor.*
- Individuate partnerships for the distribution, in particular within EN Ocean Alliance.
- Develop a brochure and a web-site of *piezoTsensor.*
- Carry out direct marketing actions (direct contact with the customer).
- Focus on key market players in order obtain an active interest on the product.
- Continuous monitoring of the market evolution.

Sub-tasks

a. Analytical market analysis - *months **1** to **3***.

b. Monitoring of the market - *months **4** to **16** and **13 to 16***.

c. Market approach - *months **21** to **24***. See deliverable **#7c.**

d. Partnerships - *months **21** to **24***. See deliverables **#7d**.

Output

- **#7a** *piezoTsensor analytical market analysis;* **#7b** *Market monitoring: contacts and interviews;* **#7b** *Website;* **#7c** Possible partnerships pursued by StroNGER.

Table 1. Direct competitors

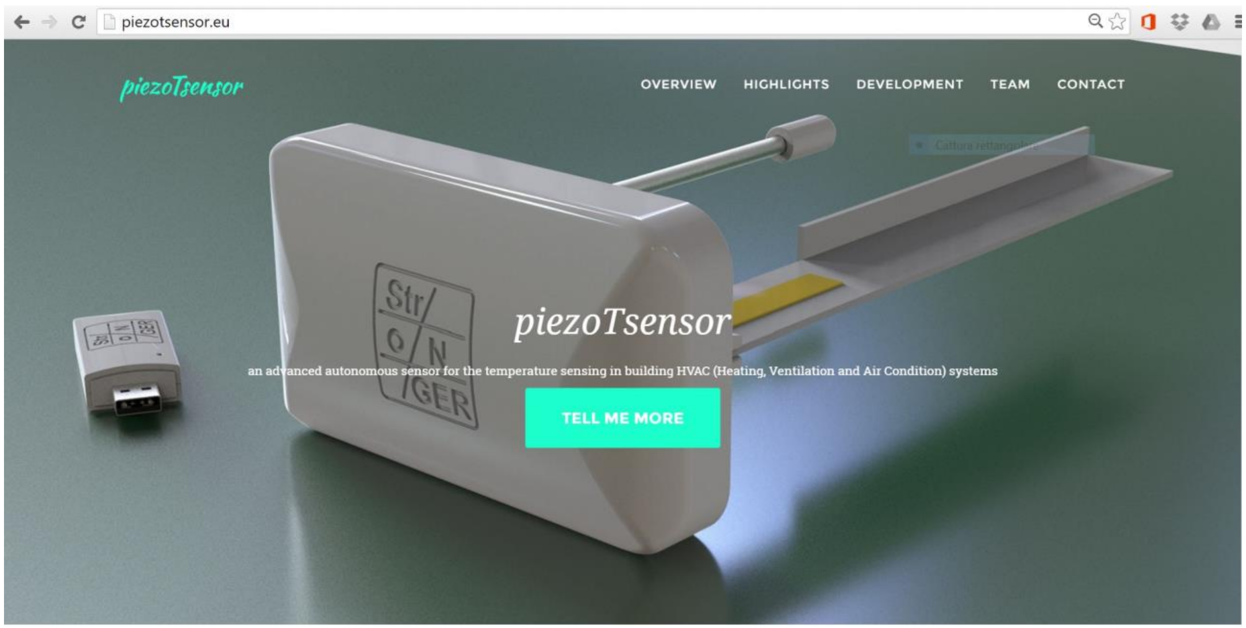
	Product	Description	Price (€)	OUTPUT Power (Watt/s=J) or operating current (A) or elctric potential (V)	Integration potential with HVAC (1-low; 5 – high)	Ease of installation HVAC (1-low; 5 – high)	Maintenance and life time (1-low; 5 – high)
EnOcean (Termokon)	SR65_315 AKF	*	150	dv>= 3.6 V (requires batteries) ?? µW @200lux	4	2 (requires light) From the technical manual: "minimum illumination of 200lx should be guaranteed at the mounting place for at least 3 to 4 hours every day regardless whether there is artificial light or daylight (The health and safety at work act requires a minimum illumination of 500lx for office workplaces)" "When using collimated artificial light the angle of incidence on the solar cell should be not too steep" "The sensors should preferably be mounted with the solar cell in window direction, whereas a direct sun radiation should be avoided. An occasionally direct sun radiation would lead to falsified measuring values with the temperature detection." "The illumination should not exceed 1000lx in the long term."	4 operating time approx. 5 to 10 years,
	SR65 TF	**	140	dv>= 3.6 V (requires batteries) ?? µW @200lux	4		4 operating time approx. 5 to 10 years,
StroNGER	piezoTsensor		240	dv=15 V (peak) 230 µW @flow V=3.5 m/s	3	4	??

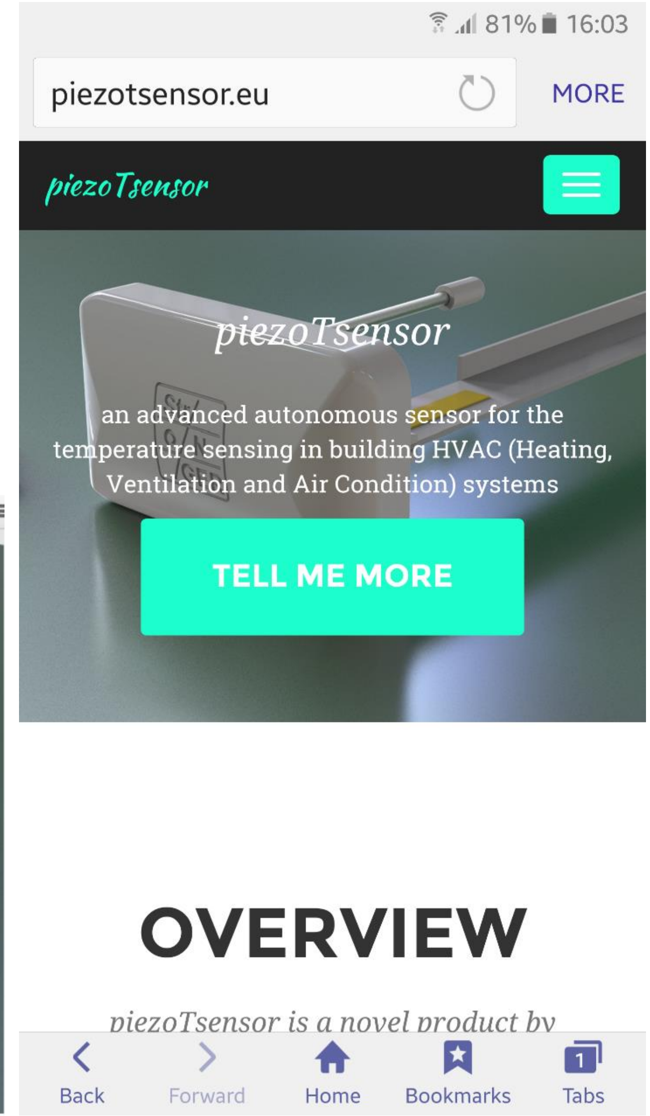
Application

Battery and wireless airduct sensor for temperature control in connection with the receiving interfaces SRCx and highergraded control systems Detection of measuring values via the highergraded control system. Transmission to receiver by means of radio telegrams according to EnOcean standard. With integrated temperature sensor and **solar energy storage** for maintenancefree operation.

Dynamic responsive website based on the bootstrap framework

www.piezotsensor.eu





Events

IDTechEx Energy Harvesting & Storage Europe Conference and Exhibition in Berlin

Events

EU Brokerage Event
on KET* in Horizon 2020

Focus on (*) Key Enabling Technologies - nanotechnologies, advanced materials, advanced manufacturing and processing | Conference and Bilateral/B2B meetings 12th May 2016 - Mainz - GERMANY | Calls 2017

EU Brokerage Event on KET* in Horizon 2020, Thursday, 12th May 2016 at the Favorite Parkhotel, Mainz, Germany (made possible only after an invitation by BIC Lazio).

ENERGY HARVESTING & STORAGE EUROPE

Energy Harvesting and Storage Europe 2 Day Conference and Exhibition in Berlin (DE) on April 28 and 29 2016.

Contacts

- Prof. Saibal Roy (Head of Micropower Systems & Nanomagnetics, Tyndall National Institute).
- Martin O'Connell of the Tyndal National Institute.
- Chris Bowen (ERC Advanced Investigator in Novel Energy Materials and academic in EH at the University of Bath).
- Stephane Sage (sales engineer at CEDRAT Technologies).

TASK #8 Management - months 1 to 24 (a total of 24 months)

Objectives

To manage all the tasks and the activities of the project, to conduct periodical reviews of the tasks and to report the progress of the project.

Sub-tasks

a. Identify and keep up-to-date human resources and contactors for different tasks.

b. Settle different issues (financial, technical) and control the milestones.

c. Manage the finance.

Output

A continuous updated management plan

Lessons learned

piezoTsensor is the first product developed by StroNGER, which is fundamentally a company providing engineering services. For this reason, *piezoTsensor* represents a milestone for StroNGER.

a. The StroNGER team had to perform a **market analysis** for *piezoTsensor*. This was particularly difficult, considering as stated above that StroNGER principally provides engineering services and is not a sales company.

b. Defining **marketing strategies** was the second challenging issue for StroNGER. In particular, at the start of the project the question was raised whether it would be separate energy harvesting device (to be sold as a sensor component) or an integrated product (sensor). StroNGER developed internally many marketing related tasks that represent completely new experiences.

c. A last issue relates to a technical part. The first analyses were not enough to clarify some **scientific and technical aspects**, and more precisely, the form of the aerodynamic fin, and initially, a cylindrical shape was chosen. Only the last aerodynamic campaign at the CRIACIV wind tunnel clarified these aspects, and led to using a T-shaped part, which is proved to have numerous advantages.

Details of the support received from ESA experts

During the 24 months, **160 expert hours** were used with ESA BIC Lazio specialists (Business Incubation support).

- Formally, **22 progress meetings** were carried out (on monthly basis). In the meetings participated for ESA BIC Ms Pasqualina Cedrone, while on many occasions, also ESA BIC director Mr Roberto Giuliani participated. These meetings were integrated with Skype calls on more frequent basis.
- Most of the support from ESA BIC experts was aimed to the areas that StroNGER was weak, in particular **business planning** and **go-to-market actions**.
- ESA BIC Lazio's contribution to the preparation of StroNGER on these aspects and its constant involvement was fundamental for the project development.

Business contacts established for the project development

Company	Person	Area
Physik Instrumente (PI)	Gianluca Poli	Piezoelectric components
Officina mec. Traini Giovanni	Giovanni Traini	Aerodynamic fin assembly
Sapienza University of Rome - DIET	Marco Balsi	Electric circuit development
Aeroelastic modelling expert	Giulio Biscarini	Numerical modeling and testing
SystemDesign	Ciro Formisano	EH pcd, wireless transmission module hardware and firmware development, industrial design
CRIACIV Firenze	Gianni Bartoli Claudio Mannini Antonino Marra	Wind tunnel testing
-	Dimitris Mantas	Consultant on HVAC
Nonsolodesign Studio	Angelo Ricchiuti	Industrial design
ESAC srl	Salvatore Cataldi	Consultant on HVAC

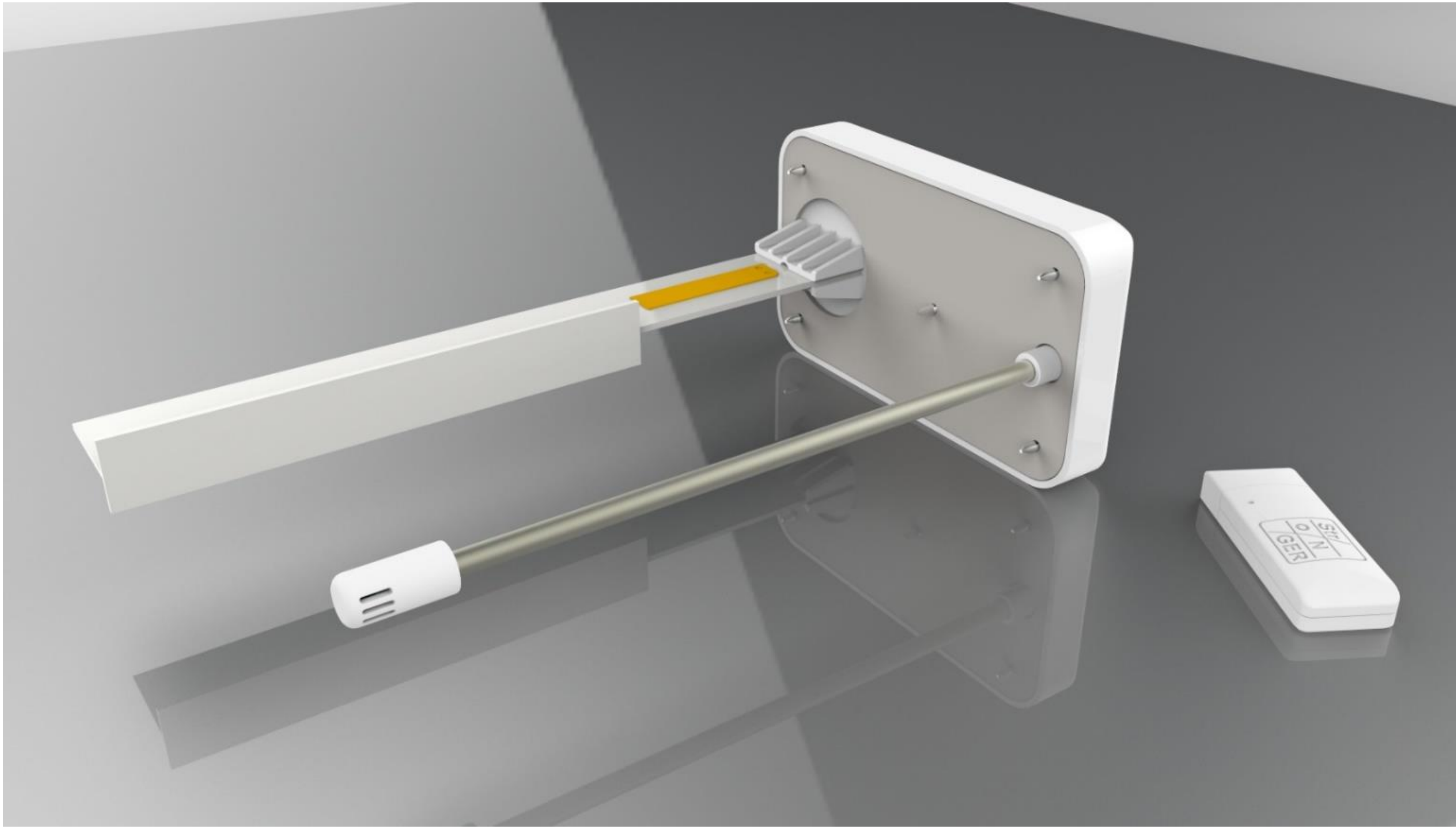
- StroNGER has involved a specialist to pursue **European funding**. StroNGER and applied for a **Horizon 2020 SME Instrument phase 2** in the deadline set for **September 7 2016** to obtain additional financing for *piezoTsensor* to optimize specific aspects. (e.g. material, application fields).
- **A demonstration will take place** in due time in the offices of ESA-BIC Lazio. After that, we plan to demonstrate the product in different companies in Europe to establish possible business partnership.
- In view of a production phase, the **material of the prototype fin bender will be updated**, moving from balsa wood to a more durable and cheap material of similar characteristics.
- StroNGER plans to **conclude the IPR activity**
- In the **long run**, StroNGER will extend the original business idea of *piezoTsensor* in different fields of application (e.g. implementation in road or railway tunnels and bridges for monitoring purposes).


esa
business
incubation
centre
Lazio


ESA BIC Lazio
MIDTERM REVIEW REPORT
Company: StroNGER s.r.l.
(Structures of the Next Generation Energy harvesting and Resilience)
Project: piezoTsensor

piezoTsensor – final review

piezoTsensor - testing



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Ferri, S., Gkoumas, K., Petrini, F. and Bontempi, F. (2014) “Flow-induced energy harvesting: conceptual design and numerical analyses of a piezoelectric bender for smart building applications”, Proceedings of the 3rd International Workshop on Design in Civil and Environmental Engineering, Technical University of Denmark, Denmark, August 21-23, 2014 Lotte Bjerregaard Jensen & Mary Kathryn Thompson Editors, pp. 146-156, ISBN 978-0-9894658-3-0

Gkoumas, K. (2012a). “Energy harvesting in bridges and transportation infrastructure networks: state of art, recent trends and future developments”, IABMAS 2012 - The 6th International Conference on Bridge Maintenance, Safety and Management, Stresa, Lake Maggiore, Italy, July 8-12

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Gkoumas, K., Petrini, F., Arangio, S., Crosti, C. “Energy harvesting for the sustainability of structures and infrastructures”, The Fifth International Conference on Structural Engineering, Mechanics and Computation (SEMC 2013), September 2-4, Cape Town, South Africa

Petrini, F., Gkoumas, K., De Gaudenzi, O. (2012a). “Wind energy harvesting in civil engineering systems”, Joint Conference of the Engineering Mechanics Institute and 11th ASCE Joint Specialty Conference on Probabilistic Mechanics and Structural Reliability (EMI/PMC 2012), Notre Dame, USA, June 17-20

Petrini, F., De Gaudenzi, O., Gkoumas, K. (2012b) “An energy harvesting application in a long span suspension bridge”, 3rd International Symposium on Life-Cycle Civil Engineering (IALCCE 2012), Vienna, Hofburg Palace, Austria, October 3-6

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