New generation of generic synchronized wireless sensors for shm

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ABSTRACT

PEGASE (generic expert platform for embedded wireless applications) is the trade name of a generic wireless sensor platform designed and built by University Gustave Eiffel since 2008. The PEGASE concept is essentially based on a generic vision of its hardware and software capabilities. Hardware genericity is ensured by a principle of plug-in motherboards and daughterboards. The PEGASE motherboard integrates the most common functions of typical data logger systems with specific wireless capabilities and robustness for outdoor field applications: providing computing, power management, multiple I/O and wireless communications, time synchronization. This first-generation PEGASE has been designed in house and sold by a third-party industrial company in thousands of units since 2008. As electronics is a fast-moving field, a second version[2] in 2016 was designed to mitigate the problems of computing power (ram, storage, etc.) and a third one in 2018 incorporating absolute time-stamping[1] [3]of acquisitions has been industrialized. Time-stamping enables data acquired by different sensors to be merged and flight times to be calculated. They are therefore used in a wide range of SHM applications, such as acoustic monitoring of bridge cables, strain gauge monitoring, vibration monitoring, etc.

In 2023, the fourth generation of the PEGASE was developed, its electronics not only more powerful, with the addition of a real-time core, a new generation of wi-fi, more storage... But software's improvements have also enabled it to go even further in the field of synchronization. In fact, in addition to absolute time stamping of acquisitions, the PEGASE 4 platform enables in-phase acquisitions. As a result, 2 PEGASE cards with nothing in common will acquire data with an offset of less than a hundred nanoseconds. This new hardware and software design is also accompanied by a new daughter board. The addition of these, together with new synchronization and phase acquisition methods, are used in fields such as guided waves and acoustic emission. Finally, the BSP (board support package) and the software to be installed on the PEGASE board (driver for the various daughter boards, tools, sdk...) are intended to become open source. In this way, third parties can use the boards and the software embedded on them to carry out their own instrumentation cases. In this paper we will present and discuss the new functionalities of this fourth generation. Perspectives will also be addressed.

1 INTRODUCTION

The advancement and introduction of novel numerical techniques for Structural Health Monitoring (SHM) and Non-Destructive Testing (NDT) necessitate the collection of field data for their validation. When creating a digital twin, for instance, real-world data is crucial to validate the model. As a result, there is a need to develop data acquisition systems that are not only high-performing but also sturdy and dependable. In the case of large-scale structures like bridges, railways, and high-voltage lines, the installation of autonomous wireless systems is imperative, presenting three key challenges:

- Ensuring minimal power consumption in the acquisition system to enable energy autonomy.
- Incorporating specific algorithms within the acquisition system to transmit only pertinent data to users and prevent the overload of the communication interface's bandwidth.
- Given that data is collected as a function of time (f(t)), it is vital to synchronize the time base of various systems to effectively merge the acquired data."

Following this assessment, the SII laboratory has commenced the development of a generic data acquisition platform to tackle these challenges. The aim is to accommodate as many use cases as possible while necessitating minimal hardware and software reconfiguration.

2 Bridge wire fault detection : PEGASE 1

In 2008, PEGASE 1 (figure 2) board was invented and created in response to a demand for bridge cable surveillance, with the goal of detecting and locating breaks in the individual wires that make up bridge cables. The PEGASE concept revolves around the creation of a board with generic hardware and software. The generic hardware is achieved through a combination of a motherboard containing processing and communication components and various daughter cards, each capable of performing acquisitions at different frequencies and levels of precision. On the software side, generality is achieved through the presence of libraries that enable the use of daughter cards with high-level functions and basic programs that perform key sensor functions, such as communication management, sensor synchronization, configuration downloads, and data transmission to a server.

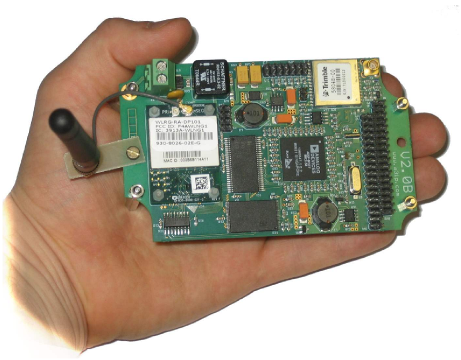

Figure 1: PEGASE 1 mother board

Figure 2: CASC

In our CASC (figure 2) application (Acoustic Control for Cable Surveillance), cable break detection is based on the following principle (figure 3): when a tensioned wire ruptures, the release of energy generates an acoustic wave that propagates along the cable, on both sides of the break point. Sensors, evenly distributed along the cable, detect this wave by comparing it to a threshold and timestamping its passage. Each sensor that detects the wave's passage transmits this information to a supervisor. The supervisor is aware of the relative positions of the sensors (L12, L23, etc.) and can calculate the time differences between detections by different sensors (Δ12, Δ23). This allows it to determine the location of the break. In the example depicted in Figure 20, a break occurred between sensors C1 and C2. Sensors C1, C2, and C3 detected the passage of the acoustic wave and send timestamped data to the supervisor, who calculates the distance X between the break point and sensor C2 using an equation.

$$X = 1/2 * (L23 - V * -T2 - T3)) \qquad (1)$$

with

$$V = L12/(T1 - T2) \tag{2}$$

The speed of mechanical wave propagation in a bridge cable is typically around 5000 m/s to 6000 m/s.

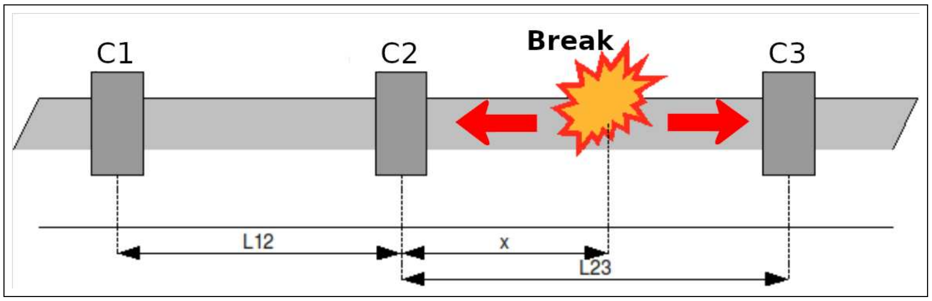

Figure 3: CASC

An error of 1 microsecond in wavefront detection results in an error of approximately 5.5 cm when locating the break. PEGASE 1 enables sub-microsecond precision in wavefront detection. This temporary precission on two sensors having nothing in common was the difficulty encountered in carrying out this instrumentation.

3 Locating lightning strikes on high-voltage lines : PEGASE 3

An application (GDS figure 6) similar to CASC has taken the PEGASE concept further in its event timestamping capability. This application involved detecting and locating an electrical wavefront in a high-voltage power line, which could be generated by lightning strikes. Following the motherboard-daughter-board principle and updated electronics, PEGASE 3 (figure 3) was designed to address this challenge. With an electrical wave's propagation speed in a wire at approximately 20,000 km/s and a required localization accuracy of 10 meters, the absolute timestamping precision for the wavefront had to be within 50 nanoseconds.

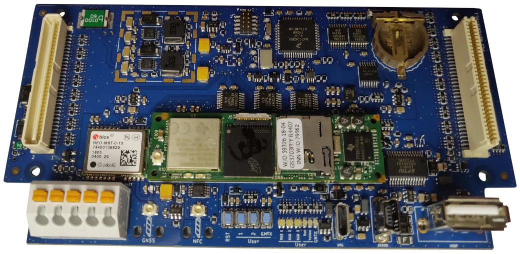

Figure 4: PEGASE 3 mother board

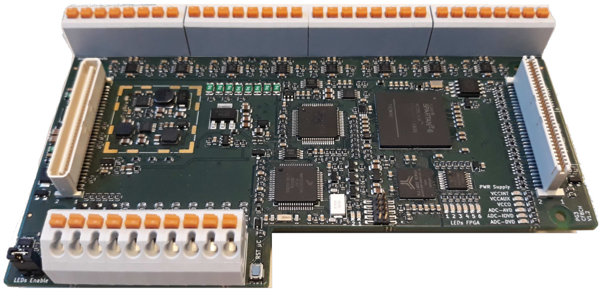

Figure 5: 8-channel daughterboard

Using an FPGA coupled with a GNSS receiver enables achieving this level of precision, with the GNSS receiver generating a pulse per second (PPS) signal. Consequently, every second, the Linux operating system on the PEGASE 3 board retrieves the internal operating frequency of the FPGA, along with the error in the PPS signal provided by the GNSS receiver. These data facilitate the recalculation of the actual second observed by the FPGA and the reevaluation of the timestamp of an event that occurred during that second.

$$T_i = 10^{-3}.qErr1_{ps} + \frac{timeCounter_i}{f_i}.(10^9.1_s - 10^3.qErr1_{ps} + 10^{-3}.qErr2_{ps}$$

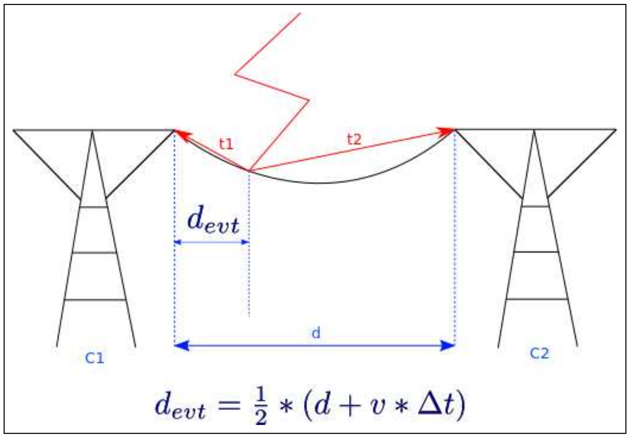

Figure 6: GDS

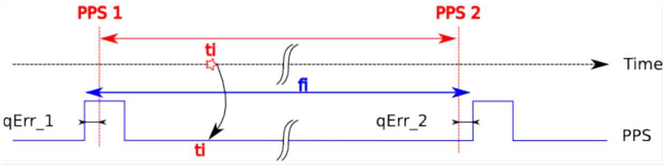

Figure 7: Exemple of date's recalculatting.

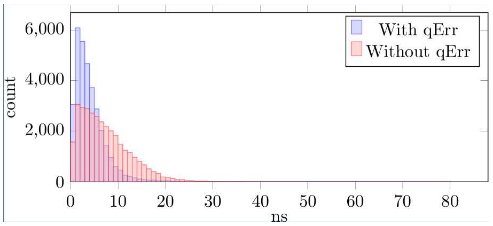

Figure 8: Interval in nanoseconds between two PEGASE 3 with and without qErr.

Using this algorithm, out of 30,000 digital wavefronts, the timestamping error between two cards is 95% below 10 nanoseconds.
One of the problems with this method is that it can only detect an electrical front, but some faults on high-voltage lines simply involve a change in the phase and amplitude of the 50hz.

4 Locating ground faults on high-voltage lines :PEGASE 4

Another possible fault, aside from lightning, on high-voltage power lines is a ground fault. Such a fault causes a distortion (in phase and amplitude) of the voltage and current on the three-phase network (see Figure 9). Following these measurements, impedance calculation algorithms enable the localization of the ground fault location.

Two factors contribute to the algorithm's increased precision:

- The accuracy of the sampling frequency, which is 2000Hz in this case.
- The acquisition phase difference between the two different sensors.

The new hardware configuration and the algorithms implemented on the PEGASE 4 board(figure 10, as well as the FPGA, have led to an improvement in these factors. Figures 11 and 12 depict the exact moment when a sample is acquired by two PEGASE 3 cards (Figure 11) and two PEGASE 4 cards (Figure 12).

Out of 200,000 samples, here are the results obtained regarding the sampling frequency accuracy:

	PEGASE 3	PEGASE 4
F mean	2003,202 Hz	1999,997 Hz
F min	2003,181 Hz	1999,874 Hz
F max	2003,21 Hz	2000,078 Hz

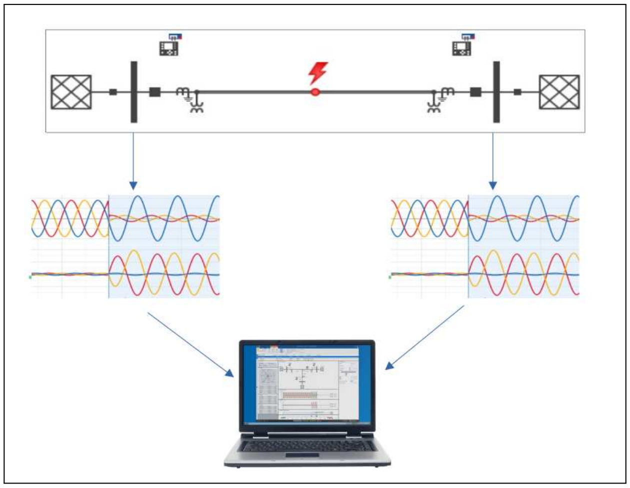

Figure 9: Détection remise à la masse du réseau

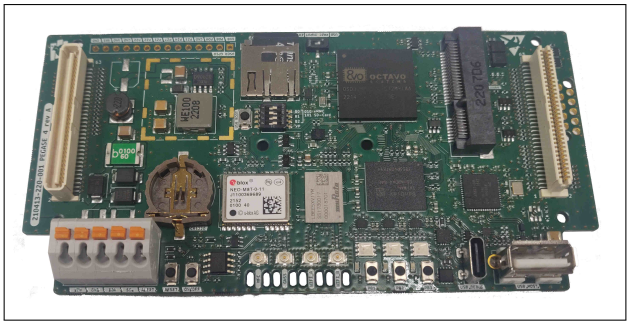

Figure 10: PEGASE 4 mother board

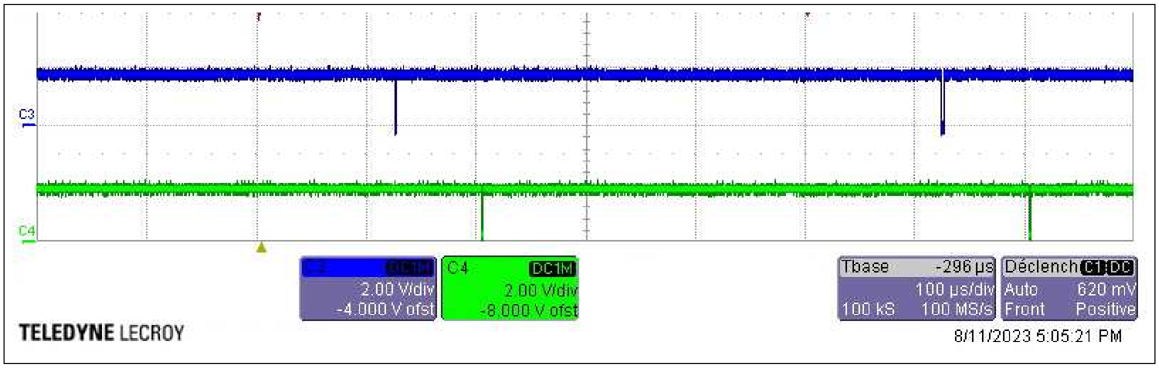

Figure 11: data ready of 2 PEGASE 3

As well as the phase difference between two cards:

	PEGASE 3	PEGASE 4
delay min	-496 uS	-128,9 nS
delay max	495 uS	90,7 nS
delay SD	202 uS	29,06 nS

In addition to the improvement in sampling frequency and phase difference, the power consumption and CPU time required for the same application have been reduced on the PEGASE 4.

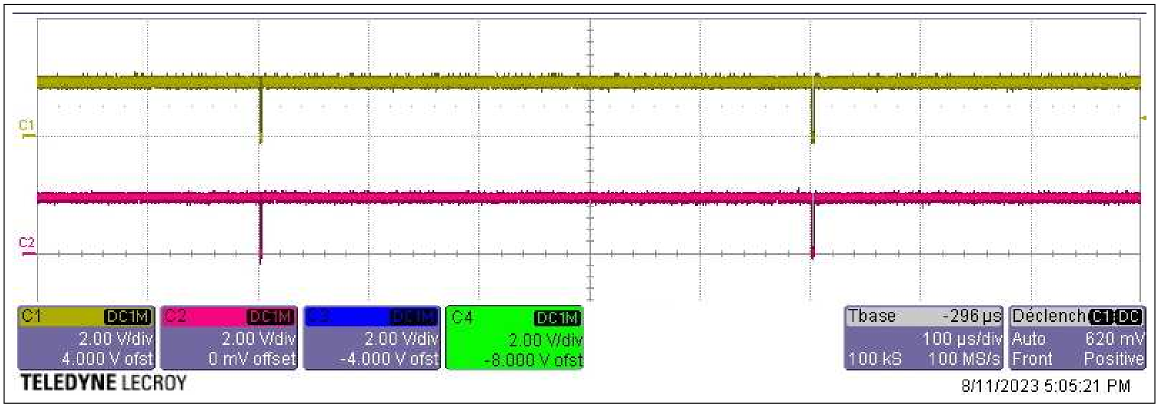

Figure 12: data ready of 2 PEGASE 4

	PEGASE 3	PEGASE 4
% de cpu utilisé	15.6%	2.3 %
Consommation	3.64 W	2.44W

In the PEGASE 4 system has brought about significant improvements in several key aspects of its operation. In particular, substantial gains have been achieved in terms of sampling frequency accuracy. Additionally, the phase difference between two cards has been significantly reduced. These improvements result from a new hardware configuration and the implementation of advanced algorithms on the PEGASE 4 board in collaboration with an FPGA. Furthermore, these enhancements have been realized while reducing power consumption and the CPU time required for the same application, thereby enhancing the system's capacity to provide accurate and efficient measurements. It is worth noting that the PEGASE 4 board's Board Support Package (BSP) and the embedded algorithms that have yielded these results will be open source and reusable by all, fostering collaboration and innovation in this field.

5 conclusion and prospects

In summary, the development and implementation of robust data acquisition systems are essential in the context of Structural Health Monitoring (SHM) and Non-Destructive Testing (NDT) to validate novel numerical methods and ensure precise results. The challenges posed by large-scale structures, such as bridges, railways, and high-voltage lines, demand autonomous wireless systems that offer low power consumption, efficient data transmission, and precise synchronization. The PEGASE project, from its inception with PEGASE 1 to the latest PEGASE 4, has been at the forefront of addressing these challenges. The success of these endeavors is evident in the enhanced accuracy and reduced time required for event timestamping, as well as the open-source nature of the BSP and algorithms, which encourages collaboration and innovation across the field. As technology continues to evolve, PEGASE's legacy in advancing data acquisition for SHM and NDT remains a valuable asset in ensuring the safety and reliability of critical infrastructure.

Several perspectives are being considered to enhance PEGASE for future instrumentation:

- Synchronization capabilities are currently reliant on the use of a GNSS receiver. However, the sensor is not yet resilient in the event of a GNSS signal loss. Efforts have already been undertaken to compensate for potential GNSS signal loss or, in another scenario, to manage the receiver's shutdown to conserve energy[4].
- The PEGASE board could be designed to predict the long-term meteorological aging of its sensors, especially during extended instrumentation periods, such as over a 5 to 10-year duration.

REFERENCES

[1] Vincent Le Cam, Arthur Bouche, and David Pallier. Wireless sensors synchronization: an accurate and deterministic gps-based algorithm. In IWSHM 2017-11th international workshop on structural health monitoring 2017, 2017.

[2] Vincent Le Cam, Michael Döhler, Mathieu Le Pen, and Laurent Mevel. Embedded modal analysis algorithms on the smart wireless sensor platform pegase. In IWSHM 2013-9th International workshop on structural health monitoring (Proceedings), volume 1, pages 1210–1217, 2013.

[3] Mathieu Le Pen, Arthur Bouché, Ivan Guéguen, Michael Döhler, Laurent Mevel, and Vincent Le Cam. Phased and synchronous sampling between multiple smart network sensors for modal assessment of large structures. In IWSHM 2019-12th International Workshop on Structural Health Monitoring, pages 1–9, 2019.

[4] David Pallier, Vincent Le Cam, and Sébastien Pillement. Energy-efficient gps synchronization for wireless nodes. IEEE Sensors Journal, 21(4):5221–5229, 2020.