An Autonomous Early Warning System Concept for Real-Time Remote Monitoring of Critical Structures

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ABSTRACT

Over the years, Structural Health Monitoring (SHM) and related concepts that focus on monitoring & managing the health of critical structures have gained vast popularity, especially considering the rapid growth and implementation of industry 4.0 approaches in the industrial manufacturing, production and operational environments. However, the implementation of SHM, which is clearly defined by the industry pain-points, have not risen on-par with the expectations of the end users. We believe that this gap could be associated with the following key points, *a.* the challenges in collecting, handling and analyzing the data collected from the sensors used for monitoring the health of these structures; *b.* the lack of SHM implementation concepts that establish an added value in rapid decision making and c. the lack of clear V&V approaches that establishes the technological maturity. Although the currently available state-of-the-art sensors are capable of collecting and communicating the sensor data, the complexity in data handling on the edge in combination with selection of the appropriate communication protocol hinders its value for industrial implementation. In addition, in a lot of cases, we observe that the available solutions for remote sensor connectivity do not correspond to the power and connectivity requirements of the end-user. This establishes the need for revisiting the implementation concept of SHM in the upcoming digital future.

In this paper, we propose an autonomous early warning system based on smart sensors and the Internet of Things (IoT) for real-time remote monitoring of critical structures. We address the challenges associated with collecting, handling, and analyzing data from sensors used for structural health monitoring (SHM) and highlight the need for a digital, real-time, and reliable sensor solution. Our approach uses novel intelligent sensors, developed and provided by IPR as part of our joint collaborative effort, with edge-computing and an efficient and low data rate (due to data pre-processing and compression into meaningful “digests") wireless communication infrastructure for data collection and new methodologies for data integration & data analysis. We elaborate on the relevant pain-points faced by end-users across several industries, including infrastructure, aerospace, railway, and marine. We describe our autonomous early warning system concept, focusing on its technical capabilities and how it compares with the needs and requirements of end-users. We also discuss our V&V approach, which focuses on the added value of cross-industry innovation and aims to generate innovative solutions and new business cases for SHM across industries. Overall, we believe that our pain-point first approach and our proposed concept can generate vast amounts of experiences and data

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necessary to establish SHM as a fundamental and necessary concept for estimating the structural integrity of critical structures. By leveraging smart sensors and the IoT, we can provide real-time monitoring and early warning systems that can help prevent catastrophic failures and improve the overall safety and reliability of critical infrastructure.

FROM PAINS TO GAINS

Although SHM has been an active discussion topic in different industries over the past few decades, only a few SHM technologies have been able to achieve the required readiness levels for implementation. We think that the limited implementation of SHM could be associated primarily with a technology-first approach as opposed to a pain-point-first approach. In other words, we foresee an increase in business cases as well as related technological breakthroughs if pain-points of the end-users are placed first when identifying an SHM-based solution. Some of the relevant end-user inputs are compiled in Tables I and II.

TABLE I. RELEVANT PAIN-POINTS FROM END-USERS

Industry	Some Relevant Structural Pain Points	
Wind turbines	• Accidental damages during transportation or installation. • Added weight, vibration and structural damages due to ice formation.	• Bolt loosening (vibration--> structural damage). • Weak towers and weak foundations (structural damage). • Noise on operating turbines (structural damage).
Bridges and Infrastructure	• Operational failure due to excessive strains, temperature & humidity fluctuations. • Vibrations resulting from wind fluctuations & earthquakes.	• Ice formation on cables leading to added static & dynamic loads. • Formation & propagation of damages due to load redistribution resulting in abrupt failures.
Aerospace	• Operational failures due to undetected defects during the manufacturing process. • Accidental failures caused by tool drops or equivalent. • Costs and time for performing structural tests.	• Weight and increased frequency of structural repair. • Costs due the need for unscheduled repair & maintenance. • Costs due to aircraft ground-time (aircraft unavailability). • Operational failures due to extreme loads.

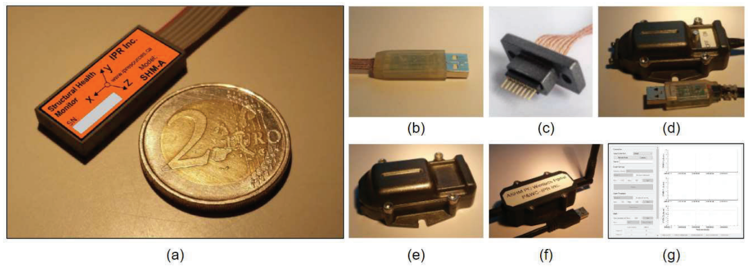
Before discussing the technology in question, the list of pain-points provided in Table I, would help assist the readers in understanding the motivation behind the technology selection. In addition, Table II, which details the wishlist of end-users who are using conventional monitoring systems for monitoring their critical structures, provides an insight to the end-user needs. These tables are a compilation of feedback and requests we have gotten from end-users and details those key-points relevant in the context of this article.

TABLE II. SHM WISH LIST OF END-USERS

Capabilities of the conventionally used SHM solutions	• High TRL, • Low mass, • Sensor flexibility • Low cost per sensor • Analog output • Very high wiring effort (cost) • Single parameter measurement	• High power requirements • Bulky DAQs (scaled solution) • Single use sensors • No edge processing • External noise to be compensated • Low fatigue life (sensor)
SHM wish-list from end users	• Low mass • Small form factor • Digital output • Multi-parameter measurement • Programmable sensors • Simple UI • Edge processing • Low power consumption • Simple DAQ • Cloud-based (optimized IoT)	• Wireless implementation • Autonomous operation • Plug & play and not plug & pray. • Machine Learning & Artificial Intelligence • Reusable sensors • Lower scaled solution costs • Infinite fatigue limit of the gauge • Self-calibration

AUTONOMOUS SMART MULTI-SENSORS FOR SHM

Considering the end-user requirements, one of the key qualities we had identified for a SHM system is its customizability. This is especially important when considering cross-industry implementations. With the advancements in Internet of Things (IoT), Machine Learning (ML) and Artificial Intelligence (AI), an SHM system that can be adapted both from a sensing as well as from a connectivity point of view would be an ideal candidate for the next generation of SHM solutions [1]. One such solution that was identified is a sensor solution developed by IPR Innovative produced Resources Inc. [2]. Over the past three years, Testia and IPR have been conducting several activities to refine & validate this innovative solution. Although the technology was developed primarily for the aviation sector, a cross-industry implementation strategy was undertaken to accelerate the learnings due to the increased testing opportunities. A snapshot of the system along with its components can be seen in Figure 1. In essence, each Autonomous Structural Health Monitor (ASHM)/ intelligent sensor has three strain channels *(Rosette; +/-3000 microstrains; up to 1000 Hz)*, three acceleration channels (*3-axial, range from +/-2 to +/-16g; up to 5000 Hz*), and three environmental assessment channels (temperature - *-60^0 to 115^{0}C at 1 Hz*, relative humidity - *0-100% at 1 Hz*, and barometric pressure - *300-1100 hPa at 1 Hz*). Each channel, or any combination of inputs from them, can be virtually routed to a processing module for data processing, significantly reducing the amount of data to be transmitted (e.g. setting thresholds, calculating Fast Fourier Transforms, Rain-Flow processing for fatigue assessment etc.). Moreover, the ASHM's quick response time enables it to provide timely feedback on events that could lead to a safety issue or even prevent a catastrophic failure.



Legend			
(a)	ASHM-A	(e)	Autonomous Wireless Battery operated RF Transceiver, 916 MHz
(b)	UART-USB 2.0 Converter	(f)	Wireless Transceiver, 916MHz, USB
(c)	8-pin Connector	(g)	Dashboard
(d)	Battery/USB Cable Housing 2x3.6 LiPo Primary Batteries		

Figure 1. ASHM system and components

The ASHM's low power consumption (100 ASMS will consume less than 1 Watt of energy), low weight (100 ASMS will weigh less than 1 Lbs), and universal interface option (UART, CAN, USB, RS-232, RS-485) allow it to work autonomously or be connected to a network, IoT, or PC. All communication protocols are encrypted. In our very first iteration, the following three configurations were identified, combining the end-user requirements along with the system capabilities. These three variants: variant A (*with ASHM-A, UART-USB connector and dashboard*), variant B *(with ASHM-A, 8-pin connector, battery/ USB cable housing and dashboard*) and variant C (*with ASHM-A, 8-pin connector, autonomous battery, wireless transceiver/ PC and dashboard*) were identified as sufficient for conducting feasibility tests by our end-users. While variant A catered to the end-users' needs for laboratory tests (primarily for users to get familiar with the device & the data output), variants B and C were used for field tests. *Variant A* is a smart sensing unit that connects directly to a PC via USB. It allows users to configure the sensor, set processing algorithms, and visualize data output using a dashboard. *Variant B* is a system with autonomous data preprocessing and logging capabilities. It includes a housing for a battery, enabling complete autonomous operation. With a 3.6V, 1250 mAH battery, it can operate autonomously for 50 days while collecting one data set every 5 minutes. However, it requires a USB connection to download logged data or modify sensing configurations. *Variant C* includes a wireless transceiver and a battery. It can send data to a server or cloud, providing full visibility to the end-user. Collaborating with Connected Ops GmbH, their cloud solution was used to collect and visualize the data from the edge device. With a single computer, a sensor, a USB 4G stick, and a 30,000mAH battery, an operation of approximately 150 days was achieved. If three sensors are connected per computer, the operational lifetime would be 54 days using the same battery. Extending the lifetime can be achieved by sending pre-processed data only or programming the computer to sleep and wake up for low-frequency measurements. The usability and practicality of the listed variants were evaluated through various validation activities to assess the performance of the ASHM system.

ASHM SYSTEM VALIDATION TESTS

To evaluate the scope of capabilities, the ASHM system was tested for several use-cases across different industries. The following section provides an overview of some of the tests conducted along with some significant outcomes.

Monitoring of Aerospace Structures

To verify the performance of the sensor, two different field-tests were conducted. The first use-cases focused on the capability of the sensor (variant A) in detecting and locating impact damages on thin aircraft structures (shells). The data from the sensor was then compared with conventional accelerometer data. Figure 2 (left), shows the sensors mounted into the structure using a simple double sided tape.

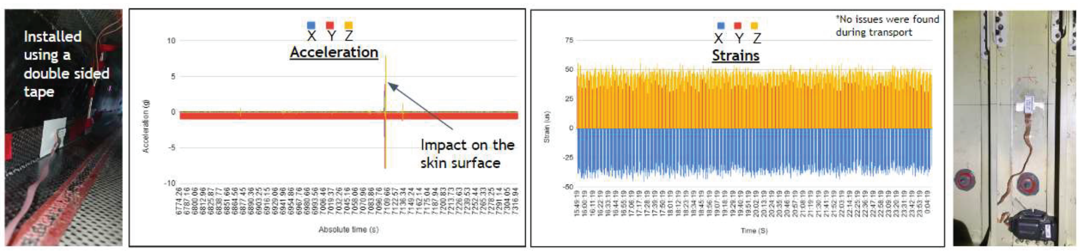


Figure 2. (Left) impact test on a thin aerospace component; (Right) autonomous ASHMS for monitoring the transport of critical structures.

The main-motivation for using a double sided tape was to evaluate the handling capability of the sensors for plug & play use. From the previous tests using conventional sensors, mounting on a double sided tape had sometimes led to the sensors being dislodged due to the impact energy on the thin shells. The behavior of the ASHM sensor in such a situation was also to be studied. Although several impacts of different energies were made on the structure, we show an impact (8 g) captured by the sensor in Figure 2 (left). Not only did the sensor pick up the impact accurately, it also managed to withstand the impacts without being dislodged.

The second use-case, on the contrary, was to monitor a critical section (hot-spot) during the transport (movement) of a large structure with a low measurement frequency. The autonomous sensor along with the battery module can be seen attached (glued) to the component of interest in Figure 2 (right). The sensor, monitoring the 3-axis strains was programmed to operate autonomously during the transportation period. The sensor was programmed to sleep and wake up every minute to capture the strains and to store the same on board. The data from the sensor was collected after 2 weeks and processed. The test provided an assurance to the end user that there were no extreme strain spikes during the test period and the same was validated using conventional measurement techniques.

Monitoring of Bridges

Based on the end-user requirements, the use-cases for monitoring bridge infrastructure can be broadly classified into two (based on the expected loads). The first monitoring scenario is a low-frequency (every few minutes), but long duration measurement (up to a few months) and the second scenario requires a high-frequency (1000s of Hz) but relatively shorter duration measurements (up to a few weeks). To validate the capability of the sensors, two different sensor variants were installed onto two different landmark bridges in Hamburg (see Figure 3 (a), 3 (b) and 3 (e)). One of these bridges was a traffic bridge, while the other was a railway bridge. For the traffic bridge, the sensor variant B was programmed and installed for autonomous operation (one data point every 5 minutes). More details on this test can be found in [3]. For the railway bridge, on the other hand, a high-frequency variant of the sensor (variant C) was connected to an edge device and a 4G dongle (see Figure 3 (e)). Data was collected & sent to the Connected Ops cloud for storage and visualization. The goal of the evaluation campaign was to compare sensor outputs to a conventional strain gauge and assess the comparability of strains caused by loads from trains on the bridge. Figure 3 (e), shows one of the sensors installed on a critical location of the bridge (along with acceleration data showing train passages). The different acceleration amplitudes correspond to trains running on the near and far track, respectively (in comparison to the location of the sensor). In order to validate the performance of the sensor, the strain measurement made by the sensor was compared with a conventional strain gauge. Figure 3 (f) shows strain values measured by both the sensor types. The measured strain values can be seen to be a very close match. Temperature drifts were observed (and corrected during post-processing) but could be eliminated through strain sensor calibration.

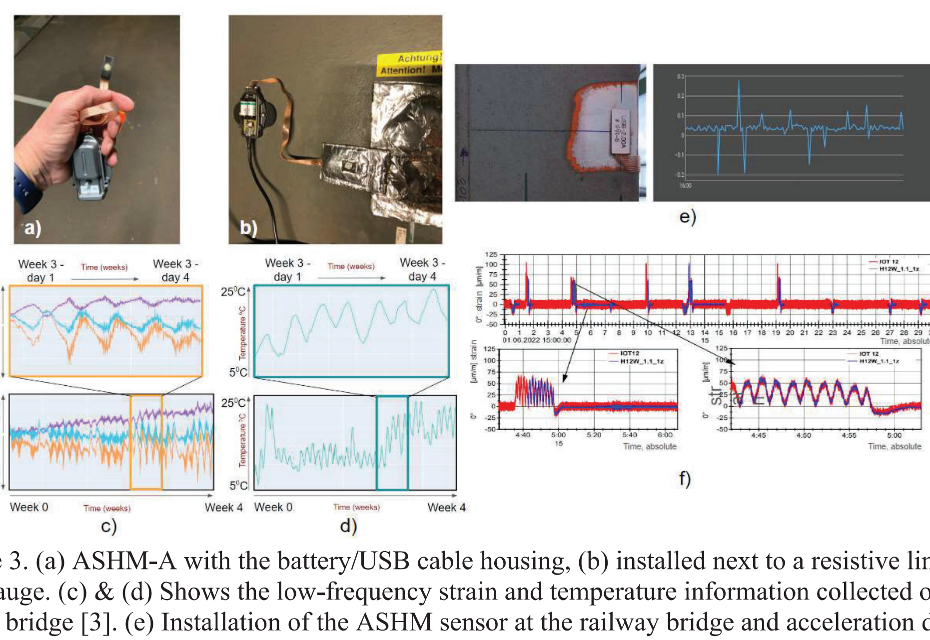


Figure 3. (a) ASHM-A with the battery/USB cable housing, (b) installed next to a resistive linear strain gauge. (c) & (d) Shows the low-frequency strain and temperature information collected on the traffic bridge [3]. (e) Installation of the ASHM sensor at the railway bridge and acceleration data showing trains passing over the bridge and (f) comparison of strains measured by the ASHM sensor (red) and a conventional sensor at a critical location on the bridge.

Overall, the ASHM sensor data was found to be comparable to the conventional strain sensor, providing additional information including accelerations and environmental readings. The next step involves using the collected data to set thresholds on the edge (ASHM), limiting data collection, and providing early warnings to the end-user.

Monitoring of Wind Turbine Blades

One of the key requirements from the end-users for the wind turbine blade inspections was related to the measurement of acceleration during operation (which is especially relevant due to increasing blade lengths). In addition, constraints related to availability of power and connectivity are also critical to be considered, especially for turbines located in remote locations. In order to cater to these use-cases, the sensor (variant C) was further developed to not only remotely transmitting raw data onto a cloud, but also to be able to store data on the edge, in case of any connectivity issues and to re-sync the data back on the cloud, once the network is available again. This was established with the help of the Connected Ops team. In addition, the possibility for the sensor to directly communicate with the turbine on the edge was also established, in order to further speed up the decision making process. Recent tests conducted on a blade in a controlled environment, resulted in millions of data points, and have shown comparability with the conventional sensors. Further tests are underway to further verify and validate the usability of the sensors in an non-controlled setting, which would then expose the ASHM to external factors such as lightning strikes, dust, humidity and high vibrations.

VALIDATION & VERIFICATION STRATEGY - TESTIA

One of the main advantages of the cross-industry implementation strategy is the possibility of using the know-how and experiences gained in each of these industries and combining them. Such a combined pool of knowledge and experience would not only help in generating new business opportunities, but also reduce the overall time for qualifying and/or certifying a new solution for a specific industry. This is the strategy we follow at Testia to improve and enhance cross industry collaborations, which essentially results in the development of new and unique use-cases for a given SHM sensor and/or system (see Figure 4).

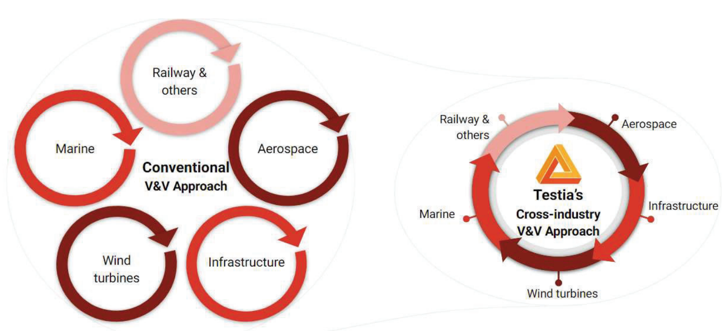


Figure 4. Testia's V&V approach

These use-cases, either similar in terms of implementation or fairly diverse, could help in understanding the operating boundaries of an SHM solution. Such information, then, could be useful and applicable for various industries, which could provide insights into what the technology is capable of achieving and also potentially result in identifying new scenarios and use-case for which these technologies could be used. Figure 4, below illustrates the essence of our strategy aimed at increasing cross-industry collaborations, which creates new business cases and potential technological breakthroughs in the near future.

CONCLUSIONS AND NEXT STEPS

In this article, we propose a strategy based on a pain-point first approach to evaluate technologies for successful SHM implementations. By understanding the end-user needs in the aerospace, wind turbine and the infrastructure (bridge) industries, we identified customizability as a key quality for SHM systems. We present the results from studies performed using an autonomous structural health monitor to address industry-specific challenges. The initial sensor variants and some significant highlights from the measurement campaigns are discussed. Future iterations would introduce additional sensor variants including an autonomous or CAN Bus powered configuration (*ASHM-A, 8-pin connector and UART-CAN 2.0, CAN FD battery*) and a miniature configuration with battery power and global cellular connectivity. These custom solutions along with smart data analytics, aim to create a plug & play system for multiple industries. In addition, a V&V approach was proposed, which would enhance reliability and promote broaderSHM adoption & enhance cross-industry collaborations.

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