Smart Autonomous Sensor Network for Multilevel Damage Identification

R. Loendersloot

Mechanics of Solids, Surfaces and Systems – Dynamics Based Maintenance,
Engineering Technology, University of Twente, P.O. Box 217, 7500AE, Enschede, The
Netherlands, r.loendersloot@utwente.nl

Abstract

If there is anything industrial applications can learn from nature, then it is flexibility and adaptiveness. Humanity has invented, designed and implemented an increasingly complex set of technological solutions to achieve more, make life more easy and reach further than our natural capacity allows us. However, only recently developments started to hand over the control to systems. While not disregarding the potentially negative sides of this, the concept of autonomous operation systems does exhibit a significant positive contribution to for example monitoring systems. Control of these systems includes the decision on what to monitor when and how and ultimately which action is to be taken based on the outcome of the monitoring. Normally, this is a task assigned to humans, which are generally considered as trustworthy and sufficiently flexible to recognize out of the ordinary responses. The objectiveness of the human judgment is however a weak point and the inability to recognize new, yet unknown outliers in a signal is increasingly pushed back by new technologies to resolve or circumvent this issue. Bringing this line of thought to the application of an actual application of a damage identification system for a safety critical composite structure, results in the concept of a smart autonomous sensor network using piezo-electric sensors. The use of piezo-electric sensors is crucial, due to their chameleon characteristic: they can be used as sensor, actuator and harvester. Focusing on the first two functionalities, a given set of piezo-electric transducers (PZTs) is embedded in a composite skin stiffener structure, which is excited by an operational, vibrating condition. In normal mode, the transducers measure the dynamic response of the system. Depending on several possible triggers, such as time, an impact event or anomaly identification based on the dynamic response, the mode of operation switches to a specific form of active, for example, Vibro-Acoustic Modulation (VAM) or acousto-ultrasonic (AU) measurement at a specific location in the network. All without human interference: all decisions on what to do when and how are taken by the control unit of the network. Ultimately, the outcome of the analysis of the system includes an operational control action, such as stopping the system (shut down) or limiting the maximum power. A leaner version simply issues a warning to the user that a specific component needs attention.

Keywords : Autonomy, control, sensor networks, Piezo-electric sensors

1. Introduction

The strong awareness in the current society of the way materials and resources are used, has introduced a focus on the operational phase of products and systems. Materials are used more efficiently, resulting in light weight structures yet also designed with more narrow margin with respect to their maximum capacity. Materials are also used for a longer period, avoiding waste of materials.

Using materials and designing structures closer to their performance limits, calls for monitoring systems. The currently available technologies allow for the use of large amount of sensors – and therefore this is applied by some. The low prices of sensors and data acquisition systems, including data storage further stimulated the use of many sensors. Data-driven methods are then applied to discover trends. However, this does not always provide the answers the user was looking for. As a counter reaction, physical models are used to understand the behaviour of the structure and select sensors and analysis techniques based on the physics [1]. This however, is limited to what can reasonably be modelled. The approach of monitoring could benefit from considerations originating from a completely different perspective: inspiration coming from nature.

Physical structures, in their broadest sense, are typically considered as passive entities. This inherently implies a certain rigidity, which in fact is contradictive with the nature – in some way the actual physics. The development of sensing technologies and the electronics behind it, have initiated the concept of "Internet of Things" (IoT) [2], converting structures to more active entities. With IoT a variety of possibilities can be explored for systems to communicate and interact with humans and take actions by itself, thus becoming more 'alive'. However, the concept of IoT has not reached much more than being applied in consumer products, forming small, local networks, although the ideas and actual potential of the current state of technologies reaches much further. It may be argued that this somewhat bold statement is not true, as there are many examples of systems and structures that are being monitored, in some cases with a multitude of sensors. This, however, is something else than IoT, which takes the data collection a step further than measuring data from a single structure or system.

One important characteristic of IoT applications is that they do more than collecting data: they analyse the data and provide suggestions for further actions or even execute these actions. In this sense, systems are controlling actions of humans. Humans seem to accept that in some cases, yet not in all. Generally it is then argued (but quite often not true at all) that humans can make better decisions and should therefore be in control. An example in which full control is handed over to a system is the storm surge barrier "Maeslantkering" [3], which closes only and only if a predefined water level is reached. Humans would 'press the button' earlier, seeing the water level rise to extreme heights. However, the system only acts if rationally, not emotionally, necessary.

Another issue, for example related to self-driven cars, is related to liability: who is responsible in case an accident happens? Similarly, it is accepted to rely on measurement data acquired by a system in a decision process regarding for example the structural integrity of an aircraft component, but the final call on whether the component is approved for further use, is made by humans, not by machines.

It can be seen from this discussion that there is a certain reluctance to give control to systems in particular when human safety is concerned. It can be argued that this is not entirely just, when looking at the way humans collect data and take decisions themselves. The negative perception with handing over control to machines is understandable from a human point of view and the discussion on what is and what is not acceptable is broad with societal, philosophical, ethical and technical aspect. This discussion is far beyond the scope of this paper. However, what can be done and what should be done are two different things. Moreover, approaching the issue from another angle, to consider either the rigidity or full machine control of industrial structures as something negative is one, the question what would be a positive characteristic that can be added to a structure or system to lift this negative association is another thing. In fact this is a domain specific matter. In the domain of the structural health and condition monitoring, adaptiveness of the structure or system to react on its current state is characteristic with a high positive added value. The question to which level this type of control should be implemented will not be addressed: first the technical possibilities will be explored.

If there is anything industrial applications can learn from nature, then it is flexibility and adaptiveness. One possible route to push the developments in the direction of self-controlling systems is thus to adopt a "bio-inspired" approach. Being inspired by the way nature solves problems is one side of the coin, yet looking at it from a different angle, one could argue as well that the actions, response and decisions should be inspired by nature – or the environment to be more precisely; sensing the environment in a smart way, implies acquiring information from the environment – something humans, but also animals and even plants, do with a variety of methods.

In this paper, the focus will not be as much on the possible variety of sensors that could possibly be used, but it rather focusses on implementing a more flexible and adaptive processing of data from a given variety of sensors. This includes the way control can be implemented in a more generic way in such a system, making it a 'living' system, with a high level of autonomy.

2. Inspiration from nature

It is interesting at this point to look at solutions from nature on how to deal with large amounts of data. Consider for example the vast amount of visual information that is received by human eyes and transferred to the brain. The information density is far too high for real time processing – even given the fact a human brain still outperforms computer processors at this point – in particular when taking into account other data is simultaneously collected by other senses (e.g. taste is determined not just by receptors on the tongue, but also by visual information and scent). The data is strongly filtered by the brain, even to a point where too limited information is generated to take a deterministic decision. Processes that engineers would refer to as interpolation and extrapolation, are in place to provide the brain with sufficient information to take a decision – usually an action. Further incoming data, transformed to information in the same way, can then refine or further control the action.

A few observations are important: firstly, decisions are apparently taken based on estimates of the actual conditions, inherently accepting inaccuracies. Secondly, allowing a time sequence of estimates to control the actions, improves the robustness of the action – i.e. ensuring the right action is executed. Thirdly, the inaccuracy in the final action is significantly, even orders of magnitude, less than the inaccuracies made during the state estimations.

As a conclusion, the decision on actions is handed over to an in fact rather inaccurately operating diagnostic system, with a more or less loose control. And indeed, humans (and animals) can easily be tricked. There are many examples of this, resulting in a wrong action. This is generally accepted, as it concerns specific cases. Though not waterproof, a fail safe system design is adopted: it is accepted wrong actions are taken based on poor diagnostics of the situation, yet in most cases this has no serious consequences. This approach may seem to be inappropriate for many industrial applications, yet it may, when designed in the right way, help in taking decisions in complex operational conditions, with many disturbing environmental conditions.

3. Current state of monitoring

Over the past years, a rich variety of monitoring algorithms and techniques have been subject of research. In many cases, vibrations are used as 'interrogator': the structure is in some way or another excited, whereafter the dynamic response is measured, based on which a diagnose is made. As Worden et al. [4] state, damage identification always relies on a comparison between states (axiom II) – one of which usually being the reference case – and feature extraction using signal processing is an essential step in the identification process (axiom IV). The entire process of vibration based monitoring is graphically represented in Fig. 1 [5].

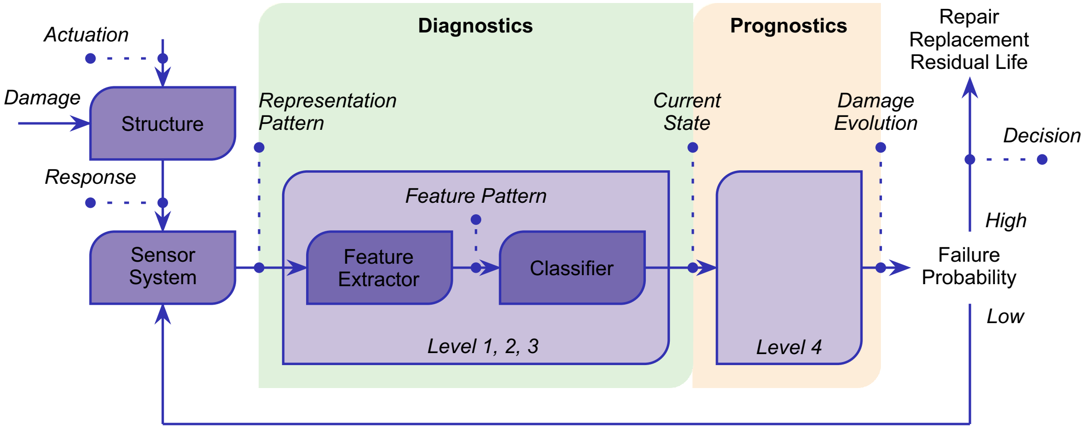

Figure 1 *: Schematic overview of the vibration based monitoring concept [5].*

The scheme depicted in Fig. 1 mainly applies to situation in which the state of a system is diagnosed. It may not clearly reflect the different levels of damage identification, generally defined as: detection, localisation, severity and remaining service life (the latter being part of the prognostic phase). Detection may be the sole purpose of a monitoring system. One could argue that this still fits with the terms used in Fig. 1, as the detection of an event such as an impact still requires the recognition of a specific feature in the response signal (e.g. a spike). After positive identification of such an event, the state is changed to "impacted", irrespective of the severity of the impact, or the potential loss of functionality. The severity is set to a value like "immediate action required" and the remaining life is reduced to zero.

Worden et al. [4] also point out that the frequency range of excitation and the size of the damage that can be identified are inversely related to each other (axiom VII). In addition, there is a link with the area of inspection: the higher the frequency, the smaller the region that can be inspected. The problems typically arise in large structures such as bridges, wind turbines and aircrafts. These systems are too large to monitor with a dense grid of sensors, where the density depends on the critical size of the damage that must be identified. Typical damages are fatigue cracks [6, 7] or delaminations [8–10]. Generally, a choice is made for either structural dynamics based (global) methods, or propagating waves based (local) methods, such as guide waves [11, 12].

A limited number of methods, e.g. Vibro-Acoustic Modulation (VAM) [13], mixes lower and higher frequency methods. A high frequency signal is modulated by a low frequency if damage is present in the structure, as it introduces nonlinear dynamic behaviour. Most authors [14,15] focus on the intensity of the sidebands, but this intensity depends on more than the damage severity: the dynamic response, local modes all influence the intensity of the sidebands as well.

Part of the motivation of the choice for either a global or a local approach depends on the expectations of the monitoring system. In many cases, a detection is judged to be sufficient. Indeed, this is a first and important step in for example the aerospace industry, in which certification is an important factor and to some extent – but rightfully – slows down the implementation of new technologies.

Another axiom (number III) of Worden et al. [4], suggests that event detection and localisation can be done using unsupervised learning modes, while the estimation of the severity can – generally – only be done using supervised learning modes. The logic behind this, is that an event in general will cause a specific change in the signal that can easily be categorised as an anomaly: an outlier with respect to the normal response. As a simple example, an impact will cause a short peak in the response of an accelerometer or strain gauge, allowing it to be classified with high confidences as an outlier. The consequence of the impact – for example a delamination – will cause a much more subtle change to the (dynamic) response of the system. It will result in a local reduction of the bending stiffness [16] and hence a change of the natural frequencies This change is generally of the same order of magnitude as the variation due to environmental or operational conditions (see also [4]). Hence, the extent of the damage cannot be determine with a high level of confidence, unless more specific patterns in the response are learnt to and subsequently recognised by the monitoring system.

This again supports the concept of a flexible and adaptive system, in which different methods are combined to increase the confidence of a specific diagnosis, or increase the performance level of the diagnostic analysis. This is in particular valid for prognostics.

Looking beyond the limitations of current inspection and monitoring technologies, new sensor technologies do offer an interesting perspective for combining different methods and thus implement smart monitoring of structures. Key is to bridge the gap between local and global oriented methods by providing a new level of autonomy to monitoring systems. The following steps need to be included at least:

1. Combine methods of different frequency ranges; creating complementarity
2. Combine data from different types of sensors; sensor complementarity
3. Use and develop sensors with either a wide operational range, or a high flexibility in operational modes, or a combination of these characteristics
4. Create (local / distributed) networks of sensors, including the communication between different parts of the network
5. Develop smart solutions for local energy generation to support the autonomous operation of the network

The author does not claim that this list is complete, however it is judged to be a sufficient list. These topics will be further elaborated in the next section, including the concept of bio-inspiration.

4. The concept of "bio-inspired" monitoring systems

As argued, handing over the control to a system is a difficult issue, requiring a high level of robustness. Once again comparing it with the manner in which the human brain processes data and takes decisions, a more loose approach is proposed. At the same time, a high level of flexibility must be introduced. New information may need to be collected rapidly, based on the outcome of an earlier analysis. The outcome of the additional analysis further controls the action or decision taken and reduces the risk of a wrong decision based on the first analysis only.

Differently phrased, the first analysis may result in a number of false positives. The number of allowable false positives is inversely related to the number of true negatives. The true negatives are to be reduced, while the number of false positives stays within reasonable limits. Thus allowing the first analysis to generate a high number of false positives, implies a low number of true negatives. Subsequent steps then only have to filter the false positives (as much as reasonably possible) from the positive outcomes of the damage identification process.

Effectively, handing over autonomy to a network of sensors, implies that 'brain capacity' needs to be included in this network. A distinction can be made between master and slave elements. Slave elements are sensors and actuators, simply receiving signal from the structure or sending a signal into the structure respectively.

Master elements play a much more active role and can process data and / or control actions to be executed by slaves. This hierarchy is important and possibly multilayered: masters can also be slaves of masters at a higher hierarchic level of the network. Typically, a so-called sensor node is used as master element. Such a sensor node contains a processing unit, a data communication unit, a power supply and a number of sensors can be connected to it.

An example of a layered hierarchic system is shown in Fig. 2. Local sensors and global sensors are indicated. Local sensors communicate with the local masters, in the example the processing nodes. The global nodes are directly connected the more central controlling node, which is positioned higher in the hierarchy than the processing nodes. Furthermore, an arbitrary set of the local sensors is appointed as actuator by a control action (see also section 4.2). Finally, the arrows indicate the direction in which the signals flow. Note that data communication can be either wired or wireless.

4.1 Method complementarity

As discussed in section 3., different methods are developed for different frequency ranges and with different objectives. Registering the global vibrations of a structure provides information on the overall loading of the system. It can be used to estimate accumulation of fatigue damage [1, 17], but also for impact detection [18] and impact localisation [16]. Other methods act more locally [8–10, 13, 19], but have the potential to provide more detailed information. These methods are complementary in the sense that the latter can add more details to the first class of methods. Another form of complementarity is using impedance measurements to assess the condition of the sensors itself [20, 21]. This information can be used to classify an observed anomaly either as sensor fault or as potential damage.

The main challenges in terms of development is the execution time: A modal analysis may take time windows that are substantially longer than the time windows needed for

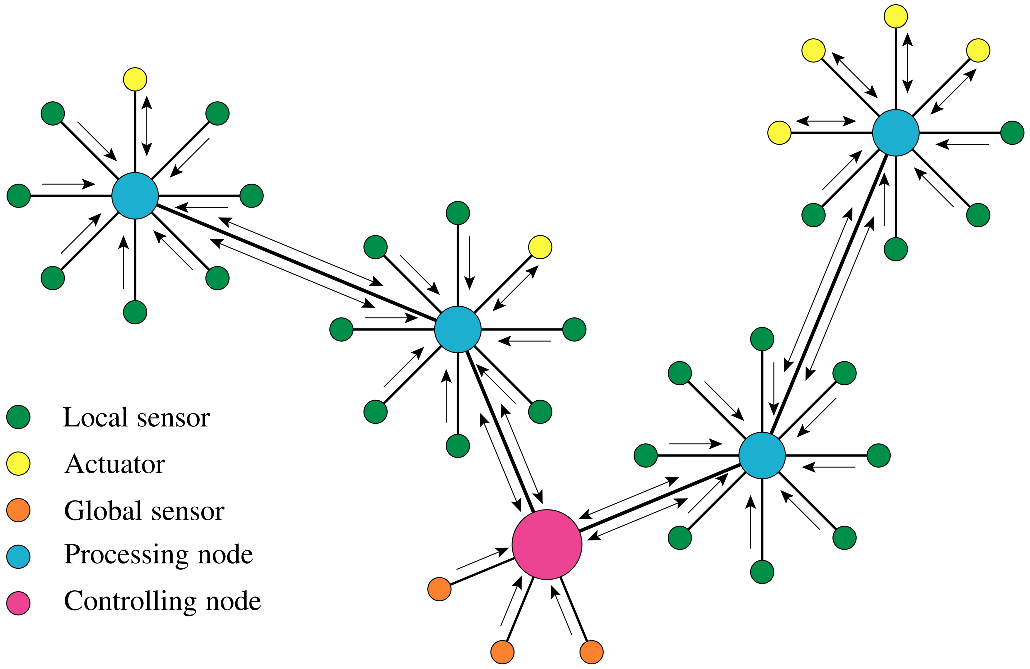

Figure 2 *: Sensor network with various types of sensors (local and global) and two hierarchic levels of master nodes. The arrows indicate the flow of signals.*

wave propagation methods, the total time for the signal processing and analysis can be much longer for the latter.

4.2 Sensor complementarity

The use of PZT transducers has a number of advantages. The main advantages is that the transducers can be used as sensor and actuator, and their role can be changed at any moment without changing the hardware. They can even be used in harvester mode (see also section 4.5). Furthermore they can be easily integrated in the structure [22]. This flexibility fits well with the concept of a smart, autonomous monitoring system. This means for example that the role of the local sensors (green and yellow circles in Fig. 2) can be changed from sensor to actuator, simply by instructions from a master element (the magenta controller node).
In line with the way humans sense their environment, a collection of various types of sensors can be used to enrich the information acquired. The concept is that either the information from one sensor improves the accuracy of another (e.g. temperature compensation of sensors) or the combined information from various sensors provides a better estimate of the current state (e.g. mode shape reconstruction based on a combination strain gauges and accelerometers readings).

4.3 Sensor development

A variety of sensors is available, while new and better sensors are still being developed. Following the IoT approach, a multitude of sensors should flock a structure. Typically, small sensors are preferred, to limit their interference with the structure itself. MEMS are a convenient solution in terms of their ability to make themselves scarce. However, their capabilities in terms of for example sensitivity and resolution may be insufficient for a specific application. Moreover, the transmission of data from the sensor to a central node may be a limiting factor. A compromise must be found in terms of performance and (power) consumption, and in terms of embedding options and connectivity.

Another example of relevant sensor development can be found in the application of optical fibres. They have a good reputation regarding the possibilities to integrate them in (primarily composite) structures, though their size is an issue [23,24] as well as the effect of the manufacturing process of composite on the performance of the fibres [25]. The advantages of multiplexing and the broad frequency spectrum that can be dealt with must further be balanced by the fact they can only be used as sensor and require a relatively bulky (laser-)light interrogator.

4.4 Distributed sensor networks

The network shown in Fig. 2 can be classified as a distributed sensor network. A basic example of such a network of sensors is elaborated in the thesis of Dzulqarnain [26]. A number of sensors was used to collect the dynamic responses of small pedestrian or cycle bridges at the University of Twente campus. A trade-off between local processing and data transmission was investigated. The main question is to define the minimum amount of information that is needed, which includes the sub-questions which data should be processed and stored locally, which data should transmitted, in both directions, between the slave and the master node. The possible solutions are restricted by the available power and (local) processing capacity and require a balanced design of functionalities [27,28].

4.5 Power consumption and local energy harvesting

A recurring element in the smart autonomous networks is the power consumption. On the one hand, the issue is to reduce the power used by the various elements in the distributed network and on the other hand to increase or enable the local generation of energy. As mentioned in section 4.4, the system design of the network is a first step in terms of efficient use of energy resources.

Generating energy locally (energy harvesting) can be done using for example piezoelectric transducers. The energy that can be generated by PZTs is limited and sophisticated electrical circuits are required to harvest these low amounts of energy instead of losing them in the circuit itself [29, 30]. Although limited successes have been reported, this topic does need a substantial amount of research before it can successfully be implemented. In particular if actuation (e.g. of guided waves) is included, as this is relatively power demanding.

The larger the application gets, the more options are available. Voice coils [31], solar panels and wind turbines [32] are possible solutions. Although miniaturisation may still be an issue, these solutions have a high degree of maturity.

5. Conceptual Design

In the previous section, the elements of a smart autonomous sensor network were discussed. Here a possible lay-out of such a system is presented, focussing on the use of vibration based methods and (primarily) PZTs. The flow chart is shown in Fig. 3.

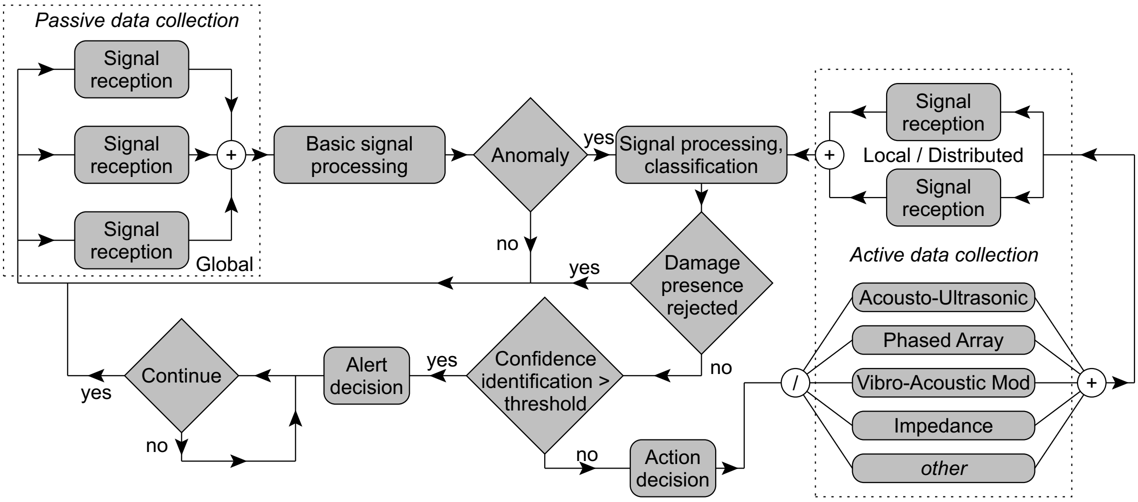

Figure 3 *: Possible flow chart for a smart autonomous sensor network.*

An important distinction is made between passive and active data collection. Despite using (mostly) the same transducers, the way of using them is adapted to the momentary needs. Starting from the left top of the flow chart, the system can be considered to be in a passive waiting mode. Signal are received by the sensors and the readings are evaluated by the processing nodes (see Fig. 2). The system remains in this mode as long as no anomaly is detected. Once an anomaly is detected, signal processing (again by the processing nodes) is applied to extract more detailed information (higher level features) from the signal, based on which the anomaly is either classified as a potential impact or damage or as a meaningless event. This does not imply that it is certain the anomaly indeed is caused by an impact or damage. In fact, it may reject the anomaly even if it results from an actual impact, as long as that impact has e.g. an energy content below a specific predefined threshold. The anomaly is not rejected if there is no conclusive result from the signal processing analysis.

If sufficient information is present, implying the confidence of positive identification is higher than a certain threshold, then it is known *if* there is damage and if so *which* action should be taken. This can be an action like stopping the machine or sending an alarm to a central control unit.

In case the damage cannot yet be identified with sufficient accuracy (again, the desired accuracy level entirely depends on the application), another action decision follows. This decision is for example made by the control node in Fig. 2, based on the information it received from the processing nodes in the same figure. The action is in this case the choice of the local interrogation method that will be applied and by which subset(s) of nodes (grouped around processing nodes). This action may include the role of a transducer changes from sensor to actuator. Again, the sensor readings are analysed (signal processing & classification), thus re-entering the loop of damage identification and action decisions. the process is then repeated until a final decision can be made (or must be made).

Most of the elements to realise a smart autonomous sensor network are in principle present (see section 4.). The most important elements in this flow chart that need attention are the action decision blocks. Based on a global event detection and localisation analysis, the decision on which subset(s) of sensors should be involved in a subsequent action is fairly easy. However, the choice which method to execute is more complicated. It can be a preset order, based on the performance of the methods. An acousto-ultrasonic method can for example be used to analyse the exact location and damage extent in a specific region, increasing the localisation and size of damage estimation, while a phased array method analyses a specific point in this same area. Alternatively, the choice can be made dependent on sensor readings or processed results reported by the processing nodes, pointing in a specific direction. Although the confidence may not be sufficient for a definite conclusion, it may be sufficient to point to a specific method to be used.

A parameter to take into account as well is the momentarily available power: the amount of available power may rule out the use of specific methods. Finally, a consideration may be the time needed to execute a specific action in relation to the estimated time until a decision must be made.

It may not be necessary to choose the most accurate method. A quick and flexible decision may be more important. Bear in mind that humans take decisions based a sometimes crude interpretation of the actual situation, which in the far majority of cases does not result in problems. On the contrary, it allows for fast decisions rather than stalled decision making which is in fact often worse than a suboptimal decision.

6. Concluding remarks

Bio-inspired monitoring systems are not alive yet. The desire to realise autonomous sensor networks is there and the conceptual ideas have matured significantly over the past years. This paper has shown a possible lay-out of such a system and the most important challenges were identified. More research is required on a number of fields, yet the most important are:

- Power consumption of network elements has to be reduced as much as possible
- Local energy harvesting methods need more maturity and the amount of energy that can be harvested needs to be boosted
- Algorithms should not solely be developed to maximise performance in terms of identification, but also in terms of energy consumption and processing time

Finally, it is suggested that applying a more loose control strategy, provided executed properly, is more promising than applying a rigid, deterministic control strategy. The latter has the false appearance of being better.

A final remark on this paper is that the author does not claim to have hard proof of these concepts, but rather sees a discussion evolving from the concepts addressed in this paper. Evidently, future work will focus on the implementation of these concepts in an attempt to collect proof or refine the ideas – the latter may even be a more likely result than obtaining sound proofs.

References

[1] T. Tinga and R. Loendersloot. *Predictive Maintenance in Dynamic Systems*, chapter Physical Model Based Prognostics and Health Monitoring to enable Predictive Maintenance, page *under review*. Springer, 2018.

[2] A. Bassi, M. Bauer, M. Fiedler, Th. Kramp, R. van Kranenburg, S. Lange, and S. Meissner. *Enabling Things to Talk – Designing IoT solutions with the IoT Architectural Reference Model*. Springer, 2013.

[3] Wikipedia. https://en.wikipedia.org/wiki/maeslantkering. online, 2018 (last edit).

[4] K. Worden, C.R. Farrar, G. Manson, and G. Park. The fundamental axioms of structural health monitoring. *Proceedings of the Royal Society*, 437:1639–1664, 2007.

[5] T.H. Ooijevaar. *Vibration based Structural Health Monitoring of Composite Skin-Stiffener Structures*. PhD thesis, University of Twente, 2014.

[6] M. Venterink, R. Loendersloot, and T. Tinga. The detection of fatigue damage accumulation in a thick composite beam using acousto ultrasonics. In *Proceedings of the first HEAMES conference, London, UK*, page 10 pages, 2018.

[7] R. Loendersloot, M. Venterink, A. Kruse, and F. Lahuerta. Acousto-ultrasonic damage monitoring in a thick composite beam for wind turbine applications. In , editor, *Proceedings of the European Workshop on Structural Health Monitoring*, volume Accepted, page 12. -, 2018.

[8] R. Loendersloot, I. Buethe, P. Michaelides, M. Moix Bonet, and G. Lampeas. *Smart Intelligent Aircraft Structures (SARISTU): proceedings of the final project conference*, chapter Damage Identification in Composite Panels - Methodology and Visualisation, pages 579–604. Springer, 2015.

[9] M. Moix Bonet, B. Eckstein, R. Loendersloot, and P. Wierach. Identification of barely visible impact damages on a stiffened composite panel with a probability-based approach. In F.K. Chang and A. Guemes, editors, *Proceedings of International Workshop on Structural Health Monitoring*, page 8 pages. Lancaster, Pennsylvania: DEStech Publications, 2015.

[10] M. Moix Bonet, B. Eckstein, and P. Wierach. Probability-based damage assessment on a composite door surrounding structure. In *Proceedings of European Workshop on Structural Health Monitoring*, pages 1–9. NDT-net, 2016.

[11] Z. Su, L. Ye, and Y. Lu. Guided lamb waves for identification of damage in composite structures: A review. *Journal of Sound and Vibration*, 295(3-5):753–780, 2006.

[12] Z. Su and L. Ye. *Identification of Damage Using Lamb Waves From Fundamentals to Applications*, volume 48 of *Lecture Notes in Applied and Computational Mechanics*. Springer, 2009.

[13] T.H. Ooijevaar, M.D. Rogge, R. Loendersloot, L. Warnet, R. Akkerman, and T. Tinga. Vibro-acoustic modulationbased damage identification in a composite skinstiffener structure. *Structural Health Monitoring*, 15(4):458–472, 2016.

[14] N.C. Yoder and D.E. Adams. Vibro-acoustic modulation utilizing a swept probing signal for robust crack detection. *Structural Health Monitoring*, 9(3):257–267, 2010.

[15] A. Klepka, W.J. Staszewski, R.B. Jenal, M. Szwedo, T. Uhl, and J. Iwaniec. Nonlinear acoustics for fatigue crack detection - Experimental investigations of vibro-acoustic wave modulations. *Structural Health Monitoring*, 11(2):197–211, 2011.

[16] T.H.Ooijevaar, L. Warnet, R. Loendersloot, R. Akkerman, and T. Tinga. Impact damage identification in composite skin-stiffener structures based on modal curvatures. *Structural Control & Health Monitoring*, 23(2):198–217, 2016.

[17] C. Boller. *New Trends in Structural Health Monitoring*, chapter Structural Health Monitoring Its Association and Use. Springer, 2013. ISBN 978-3-7091-1389-9 (Print) 978-3-7091-1390-5 (online).

[18] F. Ciampa and M. Meo. Impact detection in anisotropic materials using a time reversal approach. *Structural Health Monitoring*, 11(1):43–49, 2011.

[19] M. Moix Bonet, P. Wierach, R. Loendersloot, and M. Bach. *Smart Intelligent Aircraft Structures (SARISTU): proceedings of the final project conference*, chapter Damage Assessment in Composite Structures Based on Acousto-Ultrasonics - Evaluation of Performance, pages 617–629. Springer, 2015.

[20] I. Mueller. *Inspection of piezoelectric transducers used for structural health monitoring*

systems. PhD-thesis, University of Siegen, 2017.

[21] I. Buethe, M. Moix-Bonet, P. Wierach, and C.-P. Fritzen. Check of piezoelectric transducers using the electro-mechanical impedance. In V. Le Cam, L. Mevel, and F. Schoefs, editors, *Proceedings of the 7th European Workshop on Structural Health Monitoring*, pages 748–755, 2014.

[22] D. Schmidt, A. Kolbe, R. Kaps, P. Wierach, S. Linke, S. Steeger, F. von Dungern, J. Tauchner, C. Breu, and B. Newman. *Smart Intelligent Aircraft Structures (SARISTU): proceedings of the final project conference*, chapter Development of a door surrounding structure with integrated structural health monitoring system, pages 935–945. Springer, 2015.

[23] N. Takeda, Y. Okabe, and T. Mizutani. Damage detection in composites using optical fibre sensors. *Proceedings of the Institution of Mechanical Engineers, Part G: Journal of Aerospace Engineering*, 221(4):497–508, 2007.

[24] R. Di Sante. Fibre optic sensors for structural health monitoring of aircraft composite structures: Recent advances and applications. *Sensors*, 15(8):18666–18713, 2015.

[25] K.S.C. Kuang, R. Kenny, M.P. Whelan, W.J. Cantwell, and P.R. Chalker. Embedded fibre bragg grating sensors in advanced composite materials. *Composites Science and Technology*, 61(10):1379–1387, 2001.

[26] A.R. Dzulqarnain. Distributed processing for operational modal analysis of bridge infrastructures using wireless sensor. MSc-thesis, University of Twente, 2017.

[27] P. Zand, K. Das, E. Mathews, and P.J.M. Havinga. *19th IEEE International Conference on Emerging Technologies and Factory Automation (ETFA'2014)*, chapter A Distributed Management Scheme for supporting energy-harvested I/O devices, pages 1–10. IEEE Industrial Electronics Society, 2014.

[28] V.R.K. Ramachandran, A. Sanchez Ramirez, B.J. van der Zwaag, N. Meratnia, and P.J.M. Havinga. *Proceedings of the IEEE Ninth International Conference on Intelligent Sensors, Sensor Networks and Information Processing, ISSNIP 2014*, chapter Energy-efficient on-node signal processing for vibration monitoring, pages 1–6. IEEE, 2014.

[29] F. Da Silva Souza, N. Oki, J.V. Filho, R. Loendersloot, and A.P. Berkhoff. Accuracy and multi domain piezoelectric power harvesting model using VHDL-AMS and SPICE. In *Proceedings of IEEE Sensors*, page 3. IEEE International, 2016.

[30] A.F. Gomez Casseres Espinosa, A. Sanchez Ramirez, L.F. Combita Alfonso, R. Loendersloot, and A.P. Berkhoff. Development of a piezoelectric based energy harvesting system for autonomous wireless sensor nodes. In V. Le Cam, L. Mevel, and F. Schoefs, editors, *7th European Workshop on Structural Health Monitoring*, pages 205–212, 2014.

[31] A.C. Waterbury. *Vibration Harvesting using Electromagnetic Transduction*. PhD-thesis, University of California, Berkerly, 2011.

[32] R. Loendersloot and N. Mostafa. Implementation of a complete vibration monitoring system on irish rail bridge. Deliverable H2020-MG 2014-2015 636285 D1.5, University of Twente, 2018.