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Automatic Reliability Assessment of Data Paths in Component-integrated Sensor Networks

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The integration of sensor networks (SNs) into large-scale structural components enables the monitoring of operational loads and resulting structural responses area-wide for the whole part. During the development phase of these components, Finite Element Models (FE-Models) of operational loads can be used to find suitable sensor positions and network configurations for this task. Since the network components can't be replaced after manufacturing due to the integration inside the part, the assessment of the SNs system reliability is important. Because finding a network configuration which fulfills the reliability requirements can be a time-consuming task, an automatic reliability assessment for a sensor network aids during the development. In this paper, an algorithmic solution for the automatic calculation of the system reliability is presented. The calculation is based on an analyzation of the data paths and the creation of a reliability block diagram (RBD). In order to show the applicability of this algorithm, it is tested on exemplary scenarios in a case study.

Keywords: Sensor Network, Data Paths, System Reliability, Reliability Block Diagram.

1. Introduction

For the last years, a trend to increasing product sizes can be observed, like e.g., the growth of wind turbine diameter shows (Behrens et al. 2014). Since the growth of these products leads to higher material costs, principles for lightweight constructions are used. Avoiding oversizing for weight-savings makes it necessary to monitor the structural components of products. For example integrated sensors can fulfill this task (Gao et al. 2014). Furthermore, from a product development point of view, the sensor integration allows to gather data about operational loads, which helps developing the next product generation, estimating the components residual life and to schedule maintenance actions (Lachmayer et al. 2014; Mozgova, Yanchevskyi, and Lachmayer 2018; Waldhauser et al. 2022). An exemplary sensor network (SN) is shown in Fig. 1, where an airplane wing is monitored. In this example, the data gathered at the sensor nodes is sent via transmission links from one node to another to a sink node at the root of the wing. One possible resulting data path from one node to the sink is illustrated in Fig. 1.

The reliability of a SN's data collection is, among others, determined by the sensor nodes position, for example due to cyclic loads. Finding such positions can be based on Finite Element Models (FE-Models) of a structural component (P. Wang, Youn, and Hu 2010).

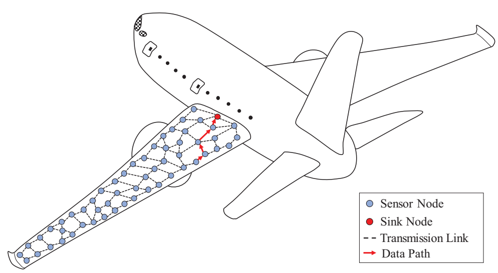

Fig. 1. Exemplary representation of a sensor network consisting of sensor nodes, a sink node and transmission links

To ensure a data collection for the whole product use-phase, the reliability of the SN has to be assessed during the development. This is due to the fact that non-destructive changes in the network configuration can't be made after integrating the network components into the part. To find possible weaknesses regarding the SN's system reliability, the data paths have to be analyzed individually. Such analysis allows the network designer to investigate how changes in the network configuration affect each data path and how this in turn affects the system reliability of the SN.

Since the analytically reliability modeling of the data paths can be very time consuming, especially when many iterations are needed to find the right network configuration, the automation of this process can help finding network configurations, fitting the specified reliability requirements for the whole system (Jesus et al. 2018).

We address this issue with an algorithmic solution to assess the system reliability of a SN by its data paths. For this purpose, the paper is organized as follows. Section 2 gives an overview on related work on the reliability assessment of sensor networks. In Section 3, the algorithmic solution for the automation of this task and its implementation in Matlab are presented. To show its applicability, a short case study and its results are presented in Section 4. Last, Section 5 concludes this paper with a summary and gives an outlook for future work.

2. Reliability assessment of data paths

The data acquired by sensors in a sensor network (SN) is send along specified data paths from one sensor node to the next. How the data paths are chosen depends on the transmission protocol. For example, the data is sent from each sensor node to the sink node directly, when a DIRECT protocol is used. In contrast, when a FLOODING protocol is used, the data is sent hop by hop from one sensor node to another until it arrives at the sink node (Dâmaso, Rosa, and Maciel 2014). Both protocols are illustrated in Fig. 2, where the data path from sensor node 1 to the sink node S is shown.

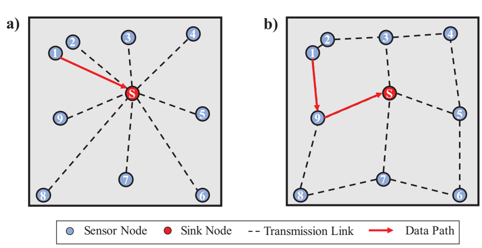

Fig. 2. Data paths in a sensor network resulting from the use of the a) DIRECT and b) FLOODING protocol

However, in the literature different ways of assessing the reliability of a SN by its data paths can be found. Since in some applications, a SN is repairable, some publications assess the networks' reliability and availability by using Markov chains or Petri nets (Jesus et al. 2018; Li and Huang 2017). However, since we focus on component-integrated and, due to that fact, not repairable SNs, these methods for reliability analysis are not considered further.

Another way of reliability analysis is described by (Gurupriya and Sumathi 2022). Since sensor nodes in Wireless Sensor Networks (WSNs) are battery powered, the battery capacity determines the lifetime of the nodes, they analyze each data path in the network regarding the energy consumption for data transmission. This approach allows to choose most suitable network configurations regarding the number of nodes, the transmission range and the transmission protocol, since the energy consumption along each data path is analyzed. On the other hand, this approach does not consider any redundancy in data acquisition, when two sensor nodes are close to another and measure similarly. Furthermore, failure due to degradation because of cyclic loads is not considered in this approach.

The approach of (Lin et al. 2010) assesses the system reliability of a SN by dividing it into sub-networks and derive a set of series and parallel sub-systems. For this task, the SN is denoted as a graph $G = (V, E)$ with a set of nodes V and a set of edges E connecting these nodes. The graph is divided into sub-graphs G_i and sets of edges $E_{p,i}$, so the networks system reliability is calculated as

$$R_G(t) = \prod_{i=1}^{n} R_{G,i}(t) \cdot \prod_{i=1}^{n} R_{E_{p,i}}(t). \tag{1}$$

The approach of dividing the SN like that allows to assess its system reliability regardless the number and position of nodes or transmission links. A disadvantage of this approach is that information of the reliability of each data path is not directly available, since the sets of sub-networks and their links cannot represent these paths directly.

This issue is overcome by the approach of (Dâmaso, Rosa, and Maciel 2014). In their work, a sensor network is divided into different regions. A region is a set of nodes, sensing the same physical phenomenon. For example, in Fig. 2, the nodes 1 and 2 are close to each other and are possibly sensing the same phenomenon. So, in the next step the data paths for transmitting the sensed information are modeled for each region. This a key aspect about this approach, since it allows to analyze the reliability for different used transmission protocols. Furthermore, it allows to consider redundancy due to sensing the same data and due to different data paths from the sensor node to the sink. These advantages are used for the reliability assessment by modelling each data path as a RBD and combining them to a RBD for the whole region. Each RBD has the sensor nodes and the links between them as elements, since the links might also fail due to data jam or loss, like investigated in (Korkmaz and Sarac 2010). This procedure is shown in Fig. 3, where the sensor nodes 1 and 2 form a region, from which data is sent along the paths A and B to the sink node. Since both nodes are sensing the same phenomenon, their data paths form a parallel configuration in the Region Model with the sink node as series element at the end, because the data is gathered there.

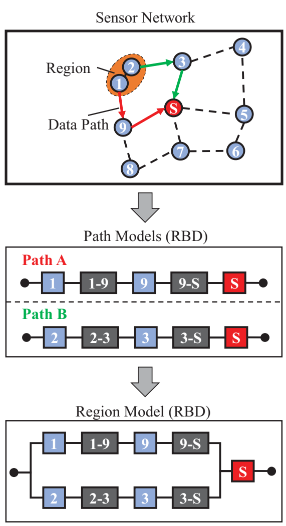

Fig. 3. Method for creating a RBD for sensing regions according to (Dâmaso, Rosa, and Maciel 2014)

After creating the region models, (Dâmaso, Rosa, and Maciel 2014) use them to investigate different transmission protocols reliability, regarding their energy consumption. However, this approach does not specify, how regions could be identified if specific sensors, for example strain gauges, are used. Furthermore, the region reliability is only addressed regarding the lifetime of the sensor energy. This neglects the influence of cyclic loads, which has an influence on the network reliability, when a constant energy supply is given. Last, the authors don't combine region models to a network model, which is necessary to assess the system reliability of the whole network.

To overcome these issues, an algorithmic solution based on the approach of (Dâmaso, Rosa, and Maciel 2014) is presented and implemented in Matlab.

3. Algorithm for automatic reliability assessment of component-integrated sensor networks

When data of operational loads should be monitored with a component-integrated sensor network (SN), consisting for example of strain gauges, existing Finite Element Models (FE-Models) from the component development can be used to find positions for sensor placement (P. Wang, Youn, and Hu 2010). To assess the reliability of the SN automatically by analyzing the data paths in it, the methodology of (Dâmaso, Rosa, and Maciel 2014) is used as basis for the algorithmic solution in this paper.

The algorithmic approach in this work to assess the reliability of a SN by its data paths can be divided into three main steps:

1. Sensor network configuration,
2. Region analysis and
3. Reliability assessment of the network.

The procedure of this algorithm is illustrated in Fig. 4. In the first step, the user has to specify, which positions the nodes have by their x, y and z coordinates and which node is the sink node. The positions are important, since data paths can be generated just for sensor nodes in range of one another. So, in this step the transmission range from one sensor node to the other is defined, too. Furthermore, the transmission protocol is selected, which defines how data is sent from a sensor node. Based on that, an adjacency matrix is created, which specifies the nodes and their connections in the SN. Using this adjacency matrix, a graph is created and plotted with the nodes and their links. Afterwards, the shortest path from each node to the sink node is found. To find the shortest path, Dijkstra's algorithm is used, since it is often used for routing in SNs (Sharma, Chandra Saini, and Bhandhari 2012).

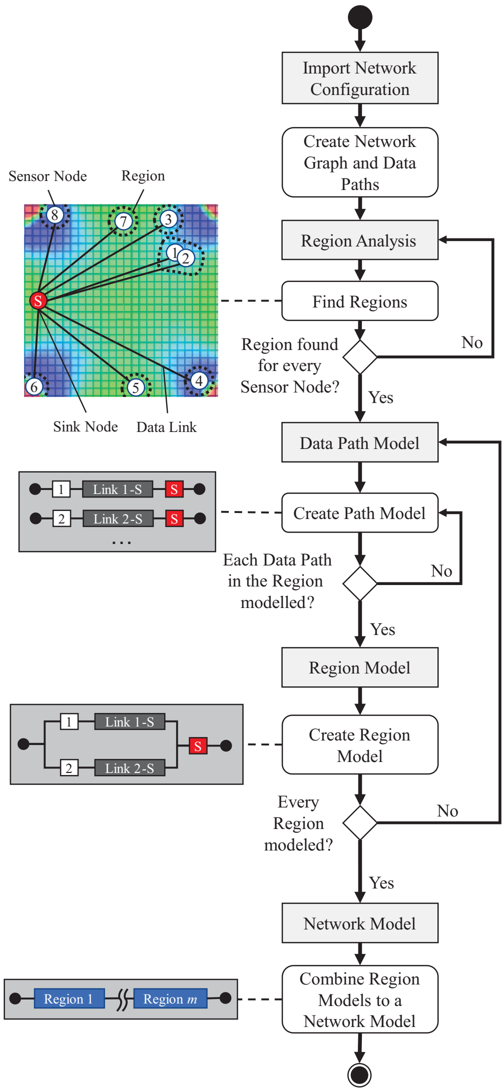

Fig. 4. Algorithm for automatic reliability assessment of sensor networks based on their data paths

In the second step, the idea of region models is taken up from (Dâmaso, Rosa, and Maciel 2014). To do so, the data from a FEM simulation is needed. Based on the coordinates of the elements in the simulation and the resulting strains in each element, a strain value is assigned to the nearest sensor node. For this task, a for-loop with *i = 1 to n*, where *n* is the number of sensor nodes, starts to assign the strain values to each sensor node *i*. If two or more sensor nodes are close to one another, which can be specified by the user with a radius around the sensor nodes, and the strain values are equal or the difference is less than the measuring tolerance, they form a region.

In contrast, if two sensors are close to one another but are sensing different strains, they do not form a region. The result of this analysis is a vector of regions with redundant measuring sensor nodes and a vector of regions, where data isn't measured redundantly. In Fig. 4, for example, the sensor nodes 1 and 2 are close to one another and measure similar strains, so they form a region whereas all the other nodes form regions containing just one sensor node.

After this region analysis, the third part of the algorithm begins with the reliability assessment. To fulfill this task, a for-loop for *j = 1 to m* is used, where *m* is the number of regions. For each region *j*, the sensor nodes it contains are read out and the corresponding data paths from step 1 are assigned to them. This allows to create the reliability block diagram (RBD) for the data paths.

If the region consists of more than one sensor node, the process of modelling the data paths is repeated until a RBD is created for each data path in the region. When all data paths for the sensor nodes of a region are modelled, a RBD for the whole region is created. For example, in Fig. 4 the redundant measurement in the region of sensor node 1 and 2 results in a parallel arrangement with the sink node in series arrangement to them. The for-loop for this region modelling is stopped, when there is a RBD for all *m* regions.

Last the region models are used to form a network model, which is another addition to the method of (Dâmaso, Rosa, and Maciel 2014). In their work, the energy consumption is used for analyzing the networks lifetime and is calculated for one region. To assess the reliability of the whole SN $R_{SN}(t)$, all Region Models are combined in a serial arrangement. This is due to the fact that each region has to work, to ensure the monitoring of the component at all the specified positions. Therefore, a failure of one region would lead to a failure of the whole SN. So, the $R_{SN}(t)$is than calculated as the product of all *m* region reliabilities $R_{Reg}(t)$, as shown in Eq. (2).

$$R_{SN}(t) = \prod_{j=1}^{m} R_{Reg,i}(t) \quad (2)$$

4. Case Study

The algorithm described before is tested with a Matlab App in a case study with two exemplary scenarios. In the following, the demonstrator part as well as the used network configurations and the results are described in detail.

4.1. *Demonstrator*

As a use case, we consider a curved plate (500 x 500 x 3.5 mm), made of carbon fiber reinforced plastic (CFRP). Such a plate could be used, for example, as segment of an airplane fuselage. HEX4 elements are used to discretize the geometry for finite element analysis (FEA). These elements are chosen to model the layers of the CFRP. Furthermore, it ensures a good resolution of the strains resulting from the bending along the thickness of the plate while keeping the overall number of elements reasonable for the simulation. To model the contact to other fuselage segments, we assume the plate as clamped along its edges. In the FE-model, the plate is loaded with a pressure of *60 kPa*. This load is chosen to model the pressure difference between the inside and the outside of a plane in *7 km* height with atmospheric pressure inside. The resulting maximum principal strains are shown in Fig. 5.

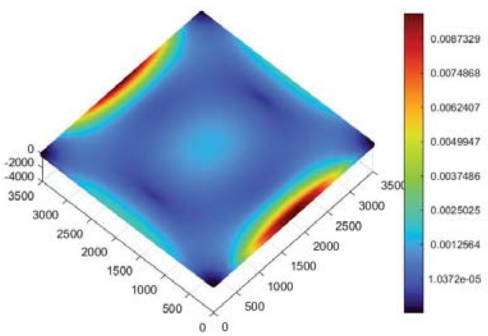

Fig. 5. Maximum principal strains for the load case of the CFRP-plate as demonstrator part

4.2. *Network configuration*

Besides the demonstrator of the case study, the structure-integrated SN has to be defined. In this case study, the SN is assumed as integrated close to the outer surface of the plate to measure higher strain values then close to the neutral fiber. So, the SN will be positioned between the first and second element-layer. For data transmission, the sensor nodes are connected with data cables in a topology, analog to the FLOODING transmission protocol of a wireless sensor network (WSN). For the connection, a transmission range is set to 1000 mm to ensure a good signal quality of the measuring signal. As sensors, we consider strain gauges with a measuring tolerance of 1.5 %, building up the sensor nodes.

Furthermore, a radius is defined, in which sensed strains might be of the same region. This sensing radius is set to 20 mm in this study. Using this information, the network topology can be plotted with the input of the node positions. Fig. 6 shows the network topology for the two exemplary scenarios in this case study as a two-dimensional plot. In this plot, the blue points depict the sensor nodes and the red point is the sink node. The coordinates of the nodes are similar in both scenarios, but the sink node is positioned differently, resulting in different data paths. Furthermore, sensor node 2 is positioned close to sensor node 1 in scenario a) and close to node 21 in scenario b).

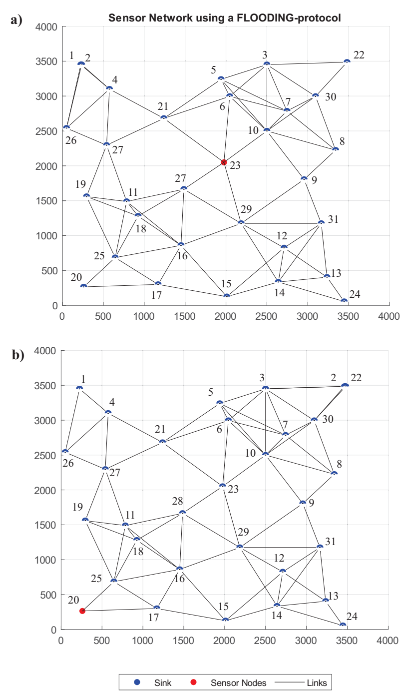

Fig. 6. Topology of the two exemplary sensor networks in the case study as a two-dimensional plot

4.3. *Results*

After configuring the SN and simulating the FE model, the algorithm is used for the reliability assessment. So, the region analysis is started as described in Section 3. Based on the assigned strains, the algorithm detects sensor node 1 and 2 as redundant in scenario a). In contrast, the node 2 and 22 are not identified as redundant in scenario b), even though they are positioned as close to each other as node 1 and 2 in scenario a). This shows, that the region analysis works well, based on the strains from the FE-simulation.

To finally assess the SN's system reliability, the user has to specify the Weibull parameters describing the reliability of the sensor nodes, links and the sink node. In this case study, we consider a shape parameter $b = 1$ for the components, since electronic parts often have a constant hazard function. For the scale parameter, a value of $T = 1*10^6$ *hours* is assumed, like in (Lin et al. 2010). This results in the plots shown in Fig. 7 for scenario a) and scenario b).

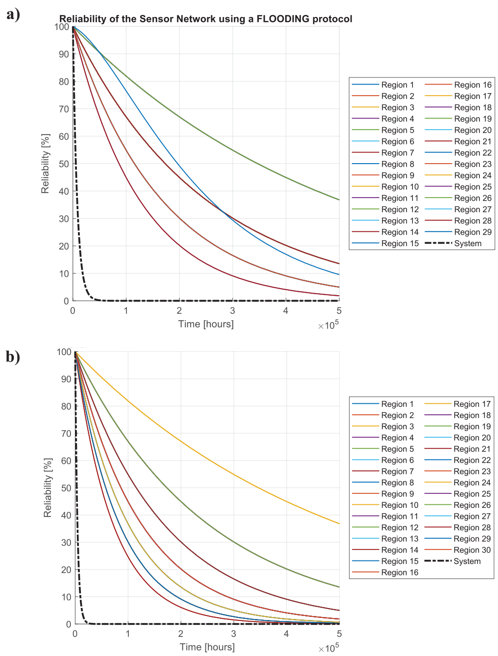

Fig. 7. Result plot of the reliability of each region and the whole SN with the configurations of scenario a) and b)

In both scenarios, the resulting curves for the reliability of each region look similar. However, one can see the slightly different curve progression of Region 1 in Fig. 7 a) because of the redundancy of sensor node 1 and 2. Furthermore, a lot more curves overlap in this scenario a) due to data paths of same length, resulting from the position of the sink node. This results in a higher system reliability than in scenario b). For example, the system reliability falls to a value of 10 % 8517 hours earlier than in scenario a).

However, both scenarios show regions with a higher reliability than others, which is equal in both scenarios. These are regions, where the sensor nodes are directly connected to the sink node, resulting in less nodes and links which can fail in the data path and therefore it results in less blocks in an RBD. This shows, that in these scenarios a DIRECT protocol would lead to a higher system reliability of the SN, if the same Weibull parameters could be assumed.

Even though both scenarios lead to similar results regarding the reliability, it could be shown that the algorithm is applicable for different network configurations. This allows the user to investigate, which network design of different options is the most reliable and fulfills specified requirements.

5.Conclusion and future Work

The integration of sensor networks (SNs) into structural components allows to monitor their load cases during the use phase. This provides the product development with useful information for the next product generation. Before integrating a SN inside a component, the reliability of the SN has to be analyzed to check, if the chosen configuration satisfies the requirements. To fulfill this task, the literature provides different strategies. However, none of them were specific for strain gauges and took the strains of FE-models as possible criteria to find redundant measuring into account and calculates the reliability of a whole SN based on that. Due to that fact, we developed an algorithm based on (Dâmaso, Rosa, and Maciel 2014) to help engineers analyze the system reliability of a SN during the development phase. The algorithm is implemented in Matlab and its applicability is demonstrated in a case study with a CFRP-component's FEM data and two exemplary network configurations

In future works, the algorithm should be extended regarding its applications. At the moment, the algorithm can just take results from static FEM-simulations into account for finding redundant measurement regions. To integrate dynamic loads, it could be enhanced by analyzing results for different time steps while checking, if measurements differ at some point from one another, resulting in different measurement regions. Furthermore, an enhancement regarding the input of the Weibull parameters will be performed in future work. Since different strains and stress amplitudes will lead to different failure probabilities, this should be integrated in the next version of this algorithm. Furthermore, the parameters for the link reliability should be investigated for different transmission protocols and scenarios. Last, the algorithm should be extended for taking the degradation of measurement signals along the data paths into account. This would allow to estimate the measurement accuracy of the whole SN for different configurations.

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