A Review on Resilience in Current Sensing Technology

Patrick Kortenbusch[1,*], Eckhard Kirchner[1]

[1] Institute for Product Development and Machine Elements (pmd), Technical University of Darmstadt, Germany

** Korrespondierender Autor:*
Patrick Kortenbusch
Otto-Berndt-Straße 2
64287 Darmstadt
Germany
☎ *+49 6151 16 21180*
✉ *patrick.kortenbusch@tu-darmstadt.de*

Abstract

This paper provides a systematic literature review on resilience in sensing technology, addressing its potential to enhance the reliability of mechatronic systems, particularly in sensing components. The review investigates the current state of research, identifying key properties enabling resilience in sensing technology and assessing the limits of its implementation. It explores advancements in material resilience, algorithmic resilience, and resilient microelectronics, revealing progress and gaps in the field. The findings address the research question on how resilience can be implemented in sensing technology, providing insights for further research into its targeted design and application in product development.

Keywords

Resilience, Sensor, Sensing Technology, Systematic Review

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1. Motivation and Objectives

As automation continues to advance and safety and hazard regulations become more stringent, functional safety has gained significant attention within the engineering domain. Functional safety is a standardized concept with the objective of ensuring safe practices during the product life cycle. In functional safety, safety-relevant components are classified according to the effort that must be exerted in order to make them more reliable. As such, functional safety is a systematic approach to safety in product development. [1]

Resilience is a concept that has been gaining attention within this domain as a means of contributing to an increased reliability of mechatronic systems, especially sensing technology [2]. However, there is currently a lack of methods for a targeted implementation of resilience in metrology and in particular in sensing technology [3]. For this work sensing technology describes the data acquisition components and the components for data processing through software and hardware [4].

A systematic literature review following the PRISMA 2020 statement [5] is conducted to consolidate the current state of research on resilience in sensing technology, as well as the necessary properties and limits for its implementation. The subsequent results will help with answering the research question which is stated as follows: *How can resilience be implemented in current sensing technology?*

In this review current possibilities and limits of resilience in sensing technology are established. For that, currently existing resilient sensing technology is researched. Commonalities specific to resilience and sensing between different examples are investigated. In addition, resilient sensors exhibiting exceptional characteristics will be identified, and their resilience and sensing performance will be quantified. This information will be used to answer the research question and the review's results will provide a starting point for further research into targeted resilience. The fundamentals of resilience are presented in section 2. In section 3 the review's methodology is explained according to the PRISMA statement. In section 4 the review's results are analyzed. In section 5 the results are discussed, and an outlook is given.

2. Fundamentals of Resilience

This section will establish the fundamentals of resilience that govern this work. While resilience can be defined and used in different, potentially conflicting, ways [3], for this work the term will be used to describe the ability of a system or entity to withstand disruptive events that negatively impact the system's or the entity's functionality only temporarily [6].

For use in the technical domain, especially engineering and product development, resilience encompasses two conditions. Resilience requires the system to firstly, guarantee a mandatory minimum of functionality, even when disturbed, and secondly, recover the functionality to the initial level or beyond after the disturbance subsides or stabilises [7]. It is not necessary for the functionality to recover past the initial level, but it is very much possible for a resilient system to exhibit such a trait due to its ability to learn from past events and adapt to changing circumstances [8].

In the context of this work this means that resilient sensing technology can maintain the required function even after experiencing disturbances. Resilient sensing technology can recover from adverse conditions such as extreme temperatures or plastic deformation of a magnitude that would permanently destroy conventional sensing technology. In contrast to robust sensing technology, resilient sensing technology must experience a temporary decrease in functionality when sufficiently disturbed [9].

3. Methodology and Approach

The methodology used in this work accords with the PRISMA statement [5]. To that end, in section 3.1 inclusion and exclusion criteria are defined which govern the selection of reports.

Based on these criteria a search query is created and used to extract relevant records from scientific and technical literature databases in section 3.2. In section 3.3 these records are then screened by their title and abstract to identify those that match the criteria.

3.1. Inclusion and Exclusion Criteria

Initially, the scope of the reports, that were to be considered in the downstream processes, was defined. According to the research objective, records of interest are those that cover resilience in sensing technology. The definition of resilience that records are required to match was presented in section 2. Some records claim to cover resilience, but screening shows that their concept of resilience does not match the one stated above. Often systems are more accurately described by the term *robustness* [10] as the recovery can be considered instantaneously. These systems must be excluded during the screening process.

To focus on current and relevant developments, records are searched for only within the field of engineering and included in the downstream processes only if they were published between 2015 and 2025. We are also only looking at records published in English.

Another criterium is introduced to distinguish resilient sensing technology from systems that are made more resilient by the incorporation of sensing technology. If the sensing technology is not resilient, the record is excluded even if the system in which the sensing technology is integrated maintains some level of resilience.

Importantly, the discussed sensing technology must be a spatially concentrated system. Meaning that this study does not investigate distributed systems such as sensor networks or distribution systems. This is important as resilience in distributed sensor systems can be achieved even if a single sensor fails completely without the chance of recovery. This, for reasons stated above, is not expedient in achieving the objectives of this work.

Lastly, another criterium for inclusion in the study is that the recovery was performed by the examined system itself. While systems that fail in a way that requires external, potentially human, interference to recover from the disturbance and regain its functionality can, in accordance with the definition of resilience from section 2, be considered to be resilient, those are not an explicit part of this study.

Additionally, there are several exclusion criteria. To that effect, records that cover resilience in infrastructure or resilience from weather phenomena and natural disasters such as hurricanes, earthquakes and flooding are to be excluded. During prescreening, records from that domain showed methods to achieve resilience in civil engineering that are confronted with problems concerning build volume and transferability when applied to spatially concentrated sensing technology such as those used in the domain of mechanical engineering for the integration in machine elements [11, 12]. This excludes supply chain resilience and power infrastructure from this study.

Related to that, IT networks were also excluded from further research as these classify as infrastructure and distributed systems. There is a vast amount of research on resilience in sensing technology in cyber systems which mainly focuses on cyber security and cyber attacks such as DOS attacks or false data injections. [13] As these are not the target of this work they are excluded to increase the review's precision.

Resilience in healthcare and living beings, which is another comprehensive and intensively studied domain, was also excluded from this study. Prescreening showed that these records, while covering resilience and recovery in detail, lacked transferability to technical systems.

3.2. Search Query and Data Sources

The criteria presented in section 3.1 were translated into search queries that can be used to search selected databases for research that pertains to this study's objective. To achieve high precision and recall, the search query was iteratively optimized, using an iterative approach influenced by SCELLS ET AL. [14] Each iteration of the query was used to extract the output from Scopus. Scopus was chosen as the primary database as it contains a vast number of publications. A random sample was drawn from the output and analyzed for recall and precision. To converge on a suitable search query, a recall climbing approach was combined with a precision climbing approach. [15]

For that, two initial search queries were created, one broad query that aimed to include most pertinent records and one precise query that aimed to include mostly pertinent records. By iteratively broadening the precise query and narrowing the broad query the two approaches converged on a solution of which the analysis and tests showed that it was suitable for retrieving the final output from the database. That query is shown in table 1.

As a source of records Scopus, WebOfScience (WOS), TEMA, EBSCO and Proquest were consulted as these are databases that focus on records in the engineering domain. To that end, the final search query used for Scopus was translated and transformed according to the specifications and requirements set by the other databases. Where specific criteria could not be configured within a database’s filters, they were imposed manually after the search was executed. The resulting search queries are shown in table 1.

Table 1: Primary search string developed for Scopus and its adaptations for the other databases

Database	Search query
Scopus	(TITLE(resilien*) OR KEY(resilience)) AND TITLE-ABS-KEY(self* OR heal* OR recover* OR repair* OR continuity OR automat* OR autonom*) AND TITLE(sensor* OR detect* OR signal OR sensing OR monitor*) AND SUBJAREA(ENGI) AND (LIMIT-TO(LANGUAGE, "English")) AND NOT ABS(health* OR urban OR buildings OR "supply chain" OR "distribution system*" OR infrastructure* OR "natural gas" OR weather OR seismic OR "wireless sensor network*")
WOS	(TI=(resilien*) AND TS=(self* OR heal* OR recover* OR repair* OR continuity OR automat* OR autonom*) AND TI=(sensor* OR detect* OR signal OR sensing OR monitor*) AND WC=Engineering AND LA=English NOT TS=(health* OR urban OR buildings OR "supply chain" OR "distribution system*" OR infrastructure* OR "natural gas" OR weather OR seismic OR "wireless sensor network*"))
TEMA	*Global search*: (self* OR heal* OR recover* OR repair* OR continuity OR automat* OR autonom*) AND (sensor* OR detect* OR signal OR sensing OR monitor*) AND NOT (health* OR urban OR buildings OR "supply chain" OR "distribution system*" OR infrastructure* OR "natural gas" OR weather OR seismic OR "wireless sensor network*") *Title*: resilien* AND (sensor* OR detect* OR signal OR sensing OR monitor*)
EBSCO	(TI resilien* OR SU resilien*) AND (TX self* OR TX heal* OR TX recover* OR TX repair* OR TX continuity OR TX automat* OR TX autonom*) AND (TI sensor* OR TI detect* OR TI signal OR TI sensing OR TI monitor*) NOT TI health* NOT TI urban NOT TI buildings NOT TI "supply chain" NOT TI "distribution system*" NOT TI infrastructure* NOT TI natural gas" NOT TI weather NOT TI seismic NOT TI "wireless sensor network*"
Proquest	TI(resilien* OR resilience) AND TI(self* OR heal* OR recover* OR repair* OR continuity OR automat* OR autonom*) AND TI(sensor* OR detect* OR signal OR sensing OR monitor*) AND SU(Engineering) AND LA(English) AND NOT TI(health* OR urban OR buildings OR "supply chain" OR "distribution system*" OR infrastructure* OR "natural gas" OR weather OR seismic OR "wireless sensor network*")

3.3. Screening

After the records were extracted from the databases, as a first step duplicates were removed from the output. Afterwards the remaining entries were carefully screened to identify those that are in accordance with the criteria from section 3.1. The records were initially screened by their titles. If the title agreed with the criteria, the record’s abstract was screened. If the abstract agreed with the criteria, the record was cleared for analysis in the downstream process. A flow chart that visualizes the initial screening process is shown in Figure 1.

Out of the 603 records identified in the databases, 175 were duplicates and removed. The titles of 294 of the remaining 428 records did not agree with the criteria. Of the 134 records that agreed with the criteria 64 were excluded based on their abstract. 70 records remained for further analysis.

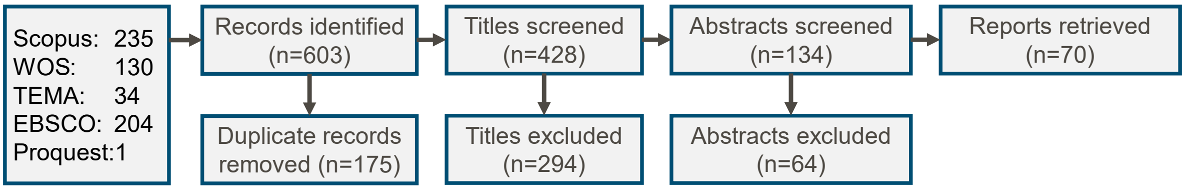

Figure 1: Flowchart of the systematic screening process

4. Results

The reports that were identified to be relevant in regard to answering the research question were analyzed. 58 of the 70 resulting reports can be grouped into one of the three components that make up sensing technology according to section 1. The 12 remaining reports are considered outliers and not presented further. 27 reports use resilient materials to measure physical quantities, 10 reports implement resilience in algorithms used for sensing and 21 cover microelectronic hardware that was modified to achieve resilient sensing. In this section these three categories are examined based on an assortment of matching reports. The reports selected for this section are those that best illustrate the solution space.

4.1. Material Resilience in Sensing Technology

Out of the 27 reports that were categorized to be describing components that achieve their resilience through material properties 18 are described as being capable of measuring strain, 13 are capable of measuring pressure or force and 9 are influenced by temperature. These make up the most prevalent measurement quantities in the data with some systems being able to measure multiple quantities. While most reports described sensors that used hydrogels as the resilient material [16], one report extra to the aforementioned categories covered a resilient photodetector based on a Molybdenum di-sulphide film on a silicon-nitride substrate [17].

Hao et al. who presented a resilient strain-sensor based on a hydrogel. The device was able to maintain relatively high sensitivity while experiencing strain of up to 1300% during stretching. This manifested in a gauge factor between 1.0 and 3.1 within the working range, implying suitable sensitivity for use as a strain gauge. The device was tested during 200 loading-unloading cycles during which it showed increased resilience to deformation. Slight increases in the relative electrical resistance were explained by the initial evaporation that hydrogels usually experience when exposed to a dry environment over an extended period of time. The device's resilience was shown when after 200 cycles the shape of the hydrogel remained stable at 100% strain. The resilience could be further improved by preventing or compensating the evaporation induced creep in the sensor's relative resistance. [18]

Yang et al. presented a hydrogel based resilient sensor that is highly compressible [19]. Due to an oriented manufacturing process creating an anisotropic material, the sensor is resilient to once-off compression of up to 99% in the direction of the orientation or repeated compression of 50% for up to 10,000 cycles. Between 0 and 80% strain the relative resistance increased linearly with the gauge factor benchmarking at 4.5 for 5% strain and 11.3 for 80%. The sensor showed a remarkable ability to regain its functionality and shape after being deformed. It was able to return to its original form during 500 compression recoveries. The sensor itself has a Young's Modulus between $1.68\ MPa$ and $2.06\ MPa$ within the test range enabling it to also detect the pressure differences occurring during human motions like finger joint rotations, elbow rotations or walking. Another report described hydrogel-based resilient sensors to even detect vocal cord vibrations that occur during human speech [20].

Additionally, due to the reliance on different gels (hydrogels, aerogels and ionogels) that are easily deformed but highly resilient to deformation, devices incorporating such materials are often used as wearable sensors. During use they then conform to the user's movement and measure different physiological quantities. In that way, PENG ET AL. presented a wearable sensor based on a hydrogel with the ability to conduct ions. These porous ionogel flexible sensors were used to successfully measure the user's pulse at 65 beats per minute. [21][22]

Fluorescent double network ionogels were presented by ZHAO ET AL. [23] These sensors offered a high sensitivity with a gauge factor of 3.13 at 800% strain and were able to withstand temperatures from $-30\ °C$ to $80\ °C$. They exhibit a fast reaction to stimuli with response times of $38\ ms$ and subsequent recovery times of $75\ ms$ allowing for repeated loading-unloading cycles. The single-walled carbon nanotube strain sensors by AHUJA ET AL. showed similar fast recovery times of $100\ ms$ when subjected to repeated strain loading [24]. GAO ET AL. presented a similar sensor with a recovery time of $97\ ms$ [16].

Exceptionally high gauge factors were achieved by HA ET AL. by augmenting an aerogel with multi-walled carbon nanotubes. Depending on the amount of carbon embedded in the aerogel, gauge factors of up to 625 at 13%-15% compression strain were achieved. While the carbon nanotubes improved the mechanical properties of the material, it could still be reversibly compressed by 90%. A reference material that was created without the carbon nanotubes experienced permanent deformation at even just 50% compression. [25]

The sensors in the reports covering sensors for force and pressure sensing offer a great sensing range with acceptable sensitivity. ZHENG ET AL. measured pressures at $-40\ °C$ in a range from 0 to $600\ kPa$ using an organohydrogel [26]. WANG ET AL. proposed an iongel-based, capacitive pressure sensor that measures pressure of up to $2\ MPa$, reaching a maximum sensitivity of $0.008\ kPa^{-1}$ [27]. The sensitivity of the hydrogel created by ZHENG ET AL. is reported at $0.625\ kPa^{-1}$ for low pressure measurements below 6 kPa and at $0.0176\ kPa^{-1}$ above $100\ kPa$ [26]. HUANG ET AL. created an aerogel based on copper nanowires that offered a sensitivity of $0.267\ kPa^{-1}$ for low pressures and $0.04\ kPa^{-1}$ for high pressures [28].

Noteworthy temperature measurements were conducted with resilient sensors created by GAO ET AL. The sensor exhibited a Seebeck-effect with an extraordinarily high coefficient $35.9\ \mu V/K$ of and a minimum temperature threshold of $0.4\ K$ [16]. Other sensors were suggested whose output was dependent on ambient temperature effectively turning them into temperature sensors. However, even though measurable changes in sensor output were detected between $20\ °C$ and $60\ °C$ no additional information was presented that could be used to estimate their sensitivity to temperature [29].

4.2. Algorithmic Resilience in Sensing Technology

10 of the pertinent reports attain resilience through algorithmic computing. That is to be achieved in part by ensuring the correctness of the computed sensor outputs even when encountering internal logical or numerical errors. These systems and methods cannot be classified based on their measurement quantities as they are more generally used for the digital processing of data independent of quantity. [30, 31]

SARTORI presents a method for error resilience that relies on outlier detection for finding and replacing faulty data points. These can be detected by introducing possible ranges for correct data points. After detecting erroneous data, the system initiates a rollback to the last unaffected data point and recomputes affected data points and their propagated effects. [32]

Another method for establishing resilience through identifying and correcting faulty data involves checksums. In these cases, additional states known as check states are computed, that hold a known mathematical relation with the system's measured and derived quantities. By comparing the checksums with the sensor output or intermediate values, errors can be detected and faulty computations can be restarted to prevent any error propagation. This method was evaluated by deliberately introducing bit flips and then recovering the correct state. [30, 31, 33]

Lin et al. validated a resilient monitoring and control system combining systems-centric methods with Kalman filters to estimate state variables and assess the sensor's and system's health. This way faulty sensors can be caught and deselected in favour of redundant, correctly working sensors. [34]

Kumar et al. published a report on achieving sensor resilience through data-driven methods. In their work, a sensor is first calibrated, then used to attain data for the training of the data-driven model and finally augmented with a purpose-built algorithm which is tasked with reducing potential errors. Their results show that machine learning and deep learning approaches can predict the absent information in missing data points and thus help with their recovery. Specifically, the system was evaluated by measuring heat transfer and wind speed indirectly. The resilience shows through an improved accuracy by a factor of up to 4.78 compared to regular soft-sensing. [35]

4.3. Resilient Microelectronics in Sensing Technology

21 reports describe systems that incorporate resilient microelectronics. Often the functionality can be considered to be the component's power efficiency or the reliability of the performed logical operations. Resilience is achieved by counteracting disturbances which are generally internal manufacturing variations, voltage fluctuations, temperature changes or aging related events. [36–38]

For several systems these disturbances would manifest as timing related errors, such as a signal's delayed rising edges or insufficient timing margins or bit errors. Similar to the algorithmic resilience explored above, occurring errors can, if detected, be counteracted by recalculation, if necessary, with a higher supply voltage or a lower frequency. [36, 37, 39–43]

The reports at hand explore many ways to counteract these disturbances before they lead to critical faults. Tested methods include time lending/borrowing to counteract timing errors [43] and error prediction to catch errors before they occur [39, 40].

Other reports describe sensors capable of measuring true power and impedance, especially in scenarios with a varying electrical load. The systems are designed to be resilient against voltage standing wave ratios up to 3:1. These VSWR can occur due to variations in the resistors manufacturing process, temperature variations or voltage droop. [44, 45]

4.4. Mapping the Results

The reports presented in section 4 are arranged qualitatively in Figure 2 to show the coverage of research in the field of resilience in sensing technology. The figure portrays a matrix with 16 fields where the reports are located based on a comparative assessment. On the horizontal axis, it is plotted whether a report discusses software-based algorithmic resilience or resilient hardware. The reports that cover hardware only are arranged in the rightmost section of the matrix. Those that cover resilience through software are found on the left side. The reports closer to the middle encompass elements of both domains.

The degree to which they cover an experimental evaluation in contrast to a more methodological approach is mapped to the vertical axis. The arrangement is based on whether the resilient sensing technology was implemented and evaluated in a real system or rather represents a proof-of-concept for resilient sensing technology.

As the map illustrates, hardware-based resilient sensing technologies feature most prominently in the reports. The blank areas highlight research gaps, particularly in software-based methodological approaches to resilience. Section 5 discusses which of these approaches merit further research.

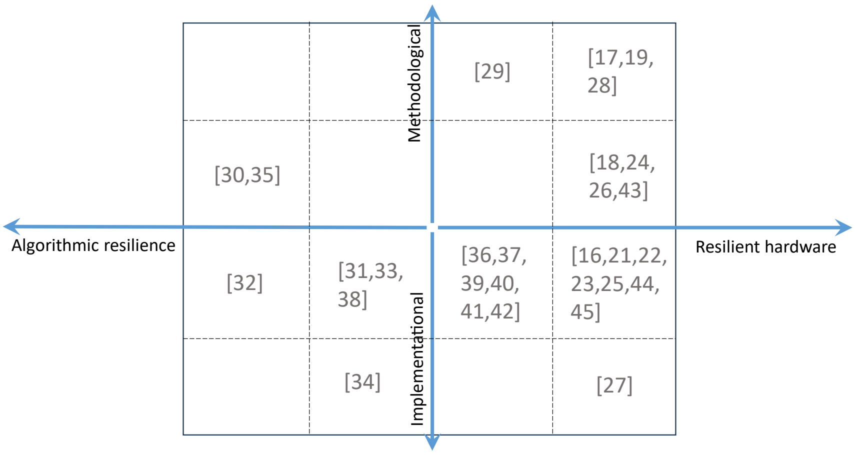

Figure 2: The presented reports organized by their hardware intensity and methodological focus

5. Discussion and Outlook

In this work a systematic review on current resilient sensing technology was conducted. The chosen methodology successfully identified an abundance of reports on resilient sensing technology. Based on the findings from the literature review, the research question was ultimately addressed: Implementation of resilience in sensing technology is predominantly achieved through (i) resilient materials for data acquisition and (ii) algorithmic resilience and resilient microelectronics for data processing.

It was shown that the most prevalent domain for the development of resilient sensing technology within the given criteria is the application of hydrogel-based materials. Such sensors are proven to be capable of reliably measuring mechanical strain and stress under adverse conditions with good sensitivity. The environment in which they can be used encompasses a wide range of ambient temperatures and acting pressures. However, fully integrated commercially viable products are yet to materialize.

Resilient measurement of less conventional quantities, beyond strain and stress, has not been adequately researched. The extent to which hydrogel-based sensors can be used to retrieve information about such other quantities of interest needs further research. One possible research domain encompasses the translation of these quantities into strain or stress. This could be done systematically by using effect catalogues similar to the work of HARDER ET AL. [46].

Using hydrogels for the design of resilient sensing technology would make a convincing case especially because of the hydrogel's ability to generate the sensor system's power in situ [47] in addition to measuring physical quantities. Self-powered, hydrogel-based sensors could be embedded in compact machine elements where space is scarce and external power routing to moving elements can be problematic.

The mapping of the results in section 4.4 reveals potential areas for further research. To cover resilient sensing technology to its full extent, resiliently processing the acquired data is mandatory but not yet well researched as can be seen in the upper left quadrant. The respective reports in the lower left quandrant cover resilience against certain disturbances only. Consequently, algorithmic resilience would benefit from a holistic methodology that allows for resilience even if uncertainty about potential disturbances is present.

Finally, the distinction between *resilient* and *robust* sensing technologies remains blurred. This work showed that the boundary is fluid and that the distinction is not trivial nor consistent between researchers. Subsequent work could build on the two-dimensional mapping by introducing a third dimension that quantifies the degree of resilience in contrast to robustness. This should reveal properties suitable for a consistent quantification of resilience in sensing technology.

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