# Test-driven Development to Overcome Challenges in the Design of Sensor-integrating Machine Elements

Julian Peters[1,*], Christoph Zimmerer[1], Thomas Gwosch[1], Felix Herbst[2], Claas Hartmann[2], Romol Chadda[2], David Riehl[3], Ferdinand Keil[3], Mario Kupnik[2], Klaus Hofmann[3], Sven Matthiesen[1]

[1] IPEK – Institute of Product Engineering, Karlsruhe Institute of Technology (KIT)
[2] Measurement and Sensor Technology Group, Technische Universität Darmstadt (TU-Darmstadt)
[3] Integrated Electronic Systems Lab, Technische Universität Darmstadt (TU-Darmstadt)

** Corresponding author:*
*Julian Peters*
*Kaiserstr. 10*
*76131 Karlsruhe*
☎ *0721/60845652*
🖂 *julian.peters@kit.edu*

## Abstract

Sensor-integrating machine elements (SiME) are essential enablers for digitization in the industry. There are major challenges in the development of SiME as an interdisciplinary mechatronic system, requiring methodical support.
In this work, we address these challenges and aim to provide methods and tools by analyzing the state-of-the-art and ten ongoing projects of sensor integration in machine elements. Clustering shows similarities for example in the identification of design space or weakening of the structure. Based on this, a test-driven development process with a focus on interdisciplinary negotiations and iterations is described to overcome the challenges in developing SiME.

## Keywords

*Sensor integration, machine element, method, support, testing*

 | DOI: https://doi.org/10.35199/dfx2022.12

## 1. Motivation

Global trends such as Industry 4.0, the Internet of Things, cyber-physical systems [1] or large-scale digitization are challenging the industry. For those trends, acquiring accurate data of the processes, machines and systems is essential. However, retrofitting or replacing machines on a large scale with suitable sensors is hardly possible. A solution to acquire accurate data are next-generation machine elements called sensor-integrating machine elements (SiME) [2] which are integrated into existing machines and plants due to their standardized interfaces and can gather high-quality data in-situ [3].

A key aspect of SiME is preserving the conventional machine element's primary function and interfaces and to be able to use them also in existing machines and plants [4]. The fundamental advantage of SiME is to improve the measurement and data quality of condition and process quantities by measuring in-situ, close to the process. Therefore, the data does not have to be estimated from subsequent systems but can be recorded directly at the process, reducing signal paths and therefore reducing the influence of possible disturbances [2], making external measurement systems obsolete.

The fundamentals of SiME as highly interdisciplinary products are being researched in the priority program of the German Research Foundation (DFG) (SPP 2305 [5]). The scope of the SPP is that sensor technology and electronics are integrated into a space-neutral, load-compatible, hermetically sealed, self-sufficient manner and preserve the machine element's primary function and interfaces while providing the measurement function.

In developing SiME as a mechatronic product, many disciplines are involved and strict requirements apply, which leads to major interdisciplinary challenges with shared design parameters such as identifying suitable design space. That can lead to conflicts [6] and tradeoffs have to be made, as can be seen in the state-of-the-art where mechanical weakening or change of mechanical interfaces (outer dimensions) are considered to achieve the measurement functionality (chapter 2). To propose support for developing SiME, those interdisciplinary challenges need to be analyzed and structured. For the support, testing is an important aspect because it is intertwined with the design from start to finish [7]. Yet, most design process models so far do not explicitly emphasize the integration of testing activities.

## 2. State of the Art

In the following, the state of research regarding existing machine elements with sensor integration is discussed. The focus is on the system, the problems solved, and specific challenges that still exist. Second, the existing methods to support sensor integration will be discussed.

### 2.1. Sensor Integration into Machine Elements

Martin et al. [3] shows possible advantages of component-integrated sensors (SiME) and a design adapted to that. It highlights the commercial potential of the approach as well as the challenge to keep the changes in the mechanical interfaces, such as assembly tools and processes to a minimum [3].

Schork et al. [8] present an elastomer coupling with strain gauges to measure momentum and radial displacement as well as a spring bar coupling with strain gauges to measure axis displacement. The electronics for data acquisition was on the outside, thus space neutrality is not given. Also, there is no wireless energy and data interface. The authors highlight the preservation of the original interfaces as an important challenge [8].

Groche and Brenneis [9] developed a screw with an integrated deformation body implementing three strain gauges to measure three-axial forces and moments. In addition, a temperature sensor was integrated to compensate for temperature influences on the strain gauges. Due to the cavity, the screw is weakened by approximately 20 %, which is a tradeoff between load carrying function and measurement quality. The implementation is not space neutral and extends the geometry on the head. The axial force was calculated by deriving a virtual sensor model. The shear forces and bending moments were estimated by the calculation models but were not tested and analyzed in this contribution. Also, only the sensor elements were integrated inside, which are connected via wires, the electronics for data acquisition and energy supply were external [9].

Brecher et al. [10] also mention the preservation of the geometry as an important challenge for integrating sensor screws in existing machines. The solution shown is an M12 screw with a centric cylindrical strain gauge to measure axial forces. The strain gauges are connected via wires to an external data acquisition system [10].

The CiS Research Institute for Microsensors [11] uses piezoresistive silicon strain gauges in the bolt head for uniaxial measurement of bolt pre-tensioning force. This makes it possible to measure the bolt pre-tensioning force both statically and dynamically. However, the electronics for evaluation and data transmission are attached externally to the bolt head. The energy supply and data transmission is carried out using RFID communication so that a distance of a few centimeters can be covered wirelessly [11].

The energy self-sufficiency challenge is addressed in the Smart Screw Connection technology demonstrator from Fraunhofer CCIT. The required energy can be obtained via solar cells or a thermogenerator with a specially developed voltage converter. A thin-film sensor system (DiaForce) was used as the sensor element which can measure the pre-tensioning force and the temperature [12]. Changes in the measured pressure on the sensor layer are an indicator for a loosening of the screw. The measured data was transmitted wirelessly via Low Power Wide Area Network (LPWAN). The disadvantage, however, is that the integration into the screw is not neutral to the installation space, and, thus, cannot replace a conventional screw [13].

Horn et al. [14] integrated sensors in fasteners for concrete. The focus is on finding design space for the integration of the sensor into the force flow without compromising the primary function (load carrying capacity). To solve these substantial interdisciplinary challenges, methods focusing on analysis and synthesis activities for overcoming observation barriers and validating solutions were used, called ASTra by the authors. Design space for the sensor was found without weakening the fastener by identifying and changing structures that are not relevant to the function. The sensors were connected via wires to external data acquisition electronics [14].

Peters et al. [15, 16] integrated acceleration sensors on gears for measuring the wear state of the gear. Electronics for acquiring and storing data as well as power supply was not integrated directly into the gear but on the gear shaft. Problems occurred with the measurement range of the sensors, which impedes the wear state interpretation. According to the authors it is challenging to estimate a suitable measurement range in advance because it is highly use-case dependant [15, 16].

In summary, most contributions do not evaluate the weakening of the machine element’s structure caused by the sensor integration. Also, the electronics for data acquisition and energy management are mostly not integrated in a space-neutral way, but external, which compromises the mechanical interfaces. Moreover, only a few contributions implement wireless interfaces for data transfer and energy supply or use energy harvesting, which makes wires necessary. This also compromises the mechanical interfaces and increases implementation effort.

### 2.2. Test-driven development

Many methodologies exist in the state-of-the-art that support product development. There is the VDI 2221 for developing technical products and systems [17] with various extensions and adaptations such as the procedure model published in Pahl/Beitz [18], for example, or the VDI 2206 for developing mechatronic systems [19]. Also, stage gate processes are commonly used in industry. Those methodologies provide generic approaches on the macro level, but cannot fully support developing SiME due to the specific interdisciplinary challenges [20].

In the product development processes of mechatronic products, the design activities are elementary. There the geometric and material characteristics of the concept are transformed into a manufacturable form or structure [21]. For designing, knowledge about the interrelationship between the function to be fulfilled and the structure to be realized must be gained by the designing engineers, which can be formulated in function-structure models [22]. In order to gain this knowledge, iterative steps including analysis and synthesis activities are typical [22]. This procedure can be seen as a sort of a micro method for problem-solving, which is included in various process methodologies such as the VDI 2206, for example [23]. This is as well a generic approach, but can be adapted to a wide range of problems and therefore is useful for developing SiME.

ASTra, developed by [14, 24], proposes an approach focused on analysis-synthesis cycles suitable for sensor integration in concrete fasteners. It also involves testing activities to validate the (subsystem-)solutions early. This methodology is focused on the system chemical fastener for concrete, which is not a machine element and therefore has different requirements and environments compared to machine elements. However, it offers the potential to be a reference for developing SiME as well, because the objective is similar.

In product development testing is an important aspect and is intertwined with design from start to finish, not limited to the final phases. However, most design process models do not explicitly emphasize the integration of testing activities throughout product development [7]. Testing can be both virtual and physical and is important to support verification and validation [25], which is elementary for SiME that are supposed to preserve the mechanical functionality.

Tahera et al. [7] extend the differentiation by introducing different types of testing: Testing for learning, demonstration, verification, validation, and certification. Especially testing for learning is of importance for gaining the aforementioned function behavior structure knowledge. The authors observe that the foci of the testing change throughout the stages of development. In the early stages there is a lot of technology viability testing with emphasis on CAE and virtual testing. In later stages, the focus switches to physical testing for performance and full mechanical durability and reliability. The authors emphasize the importance of CAE simulation and virtual testing and analysis as overlapping processes to design activities with constant iterations, to reduce uncertainties before starting costly and time-consuming physical tests. A key factor is the timing of the testing and the availability of the results throughout the development and design phases [26].

## 3. Research Objective

There are only a few SiME in the state-of-the-art, and applying the requirements of the SPP2305 (see chapter 1) none exist. The problem is, that for the specific, interdisciplinary challenges of developing SiME no methodologies have yet been developed [20]. Also, a systematic description of the specific challenges for developing SiME is missing.

Micro-level methodologies such as analysis-synthesis cycles or system-specific methodologies such as ASTra for sensoric fasteners offer the potential to be used as a reference for creating support for developing SiME. Testing is an important aspect to support developments, especially for products like SiME containing interdependent subsystems and the requirements to preserve mechanical functionalities. By triggering iterations testing can support the synthesis by early building up reliable knowledge of what works and why. Therefore, support for developing SiME should emphasize testing activities from the start and consider the right timing.

In order to propose support for developing SiME the interdisciplinary challenges that arise as a consequence of interdisciplinary collaboration need to be analyzed. This leads to the following research question:

*"What are the interdisciplinary challenges in developing SiME and how can they be supported?"*

The research focuses on cylindrical machine elements such as screws, as this is a widespread class among machine elements. They have similar geometries and properties due to their design and are also likely to set similar demands on supporting methodologies. Furthermore, state-of-the-art shows that design space restrictions pose the most challenging requirements, therefore structuring based on geometry seems advisable.

## 4. Methods

First, the challenges and methods of integrating sensors into machine elements are clustered. The foci are on the interdisciplinary challenges during development and the preservation of the machine element's function. To identify the relevant challenges and methods, the state-of-the-art in integrating sensors into machine elements is analyzed, using the search engines Scopus and Google scholar. The operators and keywords are narrowed down by iterative screening from the search terms. The results of the final search terms are filtered for the integration of sensors into actual standardized machine elements. Integration of sensors in structures, such as aircraft wings for example, are filtered out. The findings are read and screened for machine elements, challenges, methods used, and the criteria of the SPP 2305.

Second, expert discussions within the interdisciplinary working groups inside the SPP 2305 are used to extract challenges and potential methods for developing solutions. There are three working groups with the following thematic foci [20]:

- Interaction of sensor system and machine element;
- Operating strategy (Energy Management);
- Microsystems technology (Micro-electronic components).

The working groups serve as a forum for the exchange among each other regarding crucial research questions and provide valuable insight for establishing support for developing SiME. Discussions are documented and serve as input for identifying the challenges and proposing the solutions in this contribution. The focus is on iterations because managing them is an important issue in design and development [27] and they can be used to identify methodical needs [28]. The SPP 2305 contains ten different projects encompassing a variety of machine elements such as gears, shafts, shaft-hub joints, screws, roller-, plain- and gas foil bearings, feather keys, couplings, and radial shaft seal rings. Findings are marked with [SPP].

The challenges found in the literature and the discussions within the SPP 2305 are summarized and clustered thematically in a table. Afterwards, activities with a focus on testing are proposed to address these challenges and are organized in a framework picking out one major challenge.

## 5. Results and Discussion

### 5.1. Challenges and Methods

Various contributions to the state-of-the-art of sensor integration share similar challenges, clustered in Table 1. One of the main challenges is that the disciplines involved share the same design parameters. In our case, the design space volume is an example of that. From the mechanical point of view the design space should be as small as possible, because a cavity weakens the machine element, and compromises the primary function of the machine element. From the electronics/sensors perspective, the design space should be big enough for the sensors and electronics needed to meet the requirements of the secondary function for measurement quality (resolution, signal-to-noise-ratio, and frequency). Maximizing measurement quality mostly leads to a bigger cavity volume needed for sensors and electronics which compromises the strength of the structure. The struggle of setting these shared parameters to maximize a local criterion for one group that may deteriorate the solution for others is also observed by Minh et al. [6]. This leads to opposing objectives between the disciplines.

Another challenge is that use cases are not fully known, since machine elements are used in many different machines and plants. Therefore, requirements vary widely.

Also challenging due to conflicting objectives is the need to provide wireless data and energy transfer inside the mostly metallic machine elements. Antennas need to break the housing which acts as a shielding for the electromagnetic waves. This compromises the requirement to preserve the mechanic interfaces and hermetically seal the SiME.

Various contributions examined lack the definition of requirements, which makes it difficult to test and validate the solutions and assess the preservation of the mechanical function and the quality of the measurement function.

Table 1: Challenges identified in the state-of-the-art of sensor integration and the ongoing SPP 2305.

| **Challenges** | **Sources** |
|---|---|
| **Use cases**: Knowledge of use cases and requirements – machine elements are used widely, therefore requirements vary widely. | [15, 29] [SPP] |
| **Mechanical function preservation**: Strength, stresses, interfaces. | [8–10] [SPP] |
| **Measurement function**: Identification, validation, measurement quality, measurement range, amplification, sensitivity of sensors, noise of sensors, and test circuits. | [8, 9, 15, 16] [SPP] |
| **Design space**: Identification, testing, and validation of design space for sensors and electronics inside the machine element regarding conflicting targets of mechanical function and measurement function while ensuring their reliability. | [8–10] [SPP] |
| **Integration of the measurement function:** If sensors are to be embedded inside the structure, manufacturing is a key issue. | [9] [SPP] |
| **Interdependencies and disturbances** (electronics and sensors): Conflicts of sensors and electronics in case of measurement resolution, noise, and energy consumption. | [SPP] |
| **Validation of measurement quality**: Testing in realistic use-case with evaluation measurements. | [10, 15] [SPP] |
| **Virtual sensors**: Development and validation of calculation models to calculate process-relevant values from the sensor elements' measured quantities and compensate for disturbance variables. | [8, 9] [SPP] |
| **Operating strategy:** Condition-based transmissions, data conditioning such as pre-processing of measurement data before transmitting, data comprimation. | [SPP] |
| **Data transfer**: Wireless data transfer and energy supply in hermetically sealed, metallic machine elements. | [8] [SPP] |
| **Energy-Management**: Energy consumption of sensors, electronics, and energy supply. | [SPP] |

Some of these challenges that involve shared design parameters, especially identifying design space, can only be solved by negotiations and tradeoffs between the disciplines involved. Wynn and Ecker [27] analyzed iterations concerning negotiations, among others. It shares similarities with the challenges identified within this contribution, which are conflicting objectives and missing knowledge of what people may achieve.

In Table 2 the methods identified in the state-of-the-art and the ongoing SPP 2305 are summarized. They are thematically clustered to the challenges in Table 1. The methods mainly used in the SPP 2305 are only proposals at the current state and are not thoroughly validated.

Table 2: Methods and activities identified in the state-of-the-art and the ongoing SPP

| Methods and activities | Source |
| --- | --- |
| **Design space**:<br>**Bottom-up** (prioritize measurement function): Volume is defined by sensors and electronics that are needed to achieve the measurement function.<br>**Top-down** (prioritize mechanical function): Define a minimum load capability, that defines the design space volume for sensors and electronics. To avoid weakening, possibilities to step up strength classes can be investigated. In the case of screws, stepping up to 6.8 from 5.8 results in 20 % higher yield strength, which is then available as design space for sensors and electronics.<br>Combining bottom-up and top-down in an iterative approach can be appropriate depending on the use case, for instance when the measurement concept is researched in parallel or when both functions are equally important. | [9] [SPP] |
| **Measurement function - integration of sensors - manufacturing**: Product-Production Codesign - regarding manufacturing and its requirements for the sensor integration from the beginning. | [9] |
| **Measurement function – Identification of measurands**:<br>**Use-cases are known**: Analyze possible use-cases for loads and stresses<br>**Use-cases are not known**: Research maximum loads and stresses of the machine element in standards and guidelines (worst case), that exist for most of the machine elements.<br>Analyze the functional structure of the machine element to break down loads and stresses to find suitable measurement concepts. | [8] [SPP] |
| **Virtual sensor**:<br>**Data-based approach**: Measure numerous load conditions with known results of the quantity of interest. Calculate transformation matrix via regression.<br>**Physical-based approach**: Formulate the connection between primary measurand (electrical) and quantity of interest in formulas and models. The behavior of the desired information and the possible data a sensory function is delivering are relevant inputs for the models. | [4, 9, 10, 16] [SPP] |
| **Function validation (mechanical and measurement)**:<br>For **validating mechanical functions**, analytical calculations followed by virtual testing with CAE-based approaches are mostly appropriate. Physical tests are only necessary if the virtual tests are not trusted.<br>For **validating measurement function,** virtual tests that predict the physical quantities to be measured by the sensors are a good option to start, this helps to implement the right sensors. To validate the measurements however physical tests are inevitable to quantify the uncertainties that come with sensor application, and noise, among others. Incremental physical testing with varying integration levels (sub-system to system) is recommended. | [9, 24] [SPP] |
| **Early measurement function validation**: Physical tests to validate measurement function should start as early as possible in a simplified manner to avoid costly iterations later. In the case of screws, sensors can be applied to a cylindrical shaft with an external data acquisition system and tested in a pulling machine. That simplifies manufacturing, lowers integration effort, and keeps the focus on the most critical part.<br>To ease early testing further, start with big sizes of the machine elements. Miniaturization, especially in electronics can be achieved by application-specific integrated circuits and is mostly only a matter of costs. | [8, 9, 14–16, 24] [SPP] |
| Identify **operation strategy** suitable for use case: continuous streaming of data or data-preprocessing in machine element and only damage identification being sent (fire alarm) | [SPP] |

## 5.2. Test-driven development as a solution

In the following Figure 1, the framework for structuring the challenges and proposals for methods supporting the development of SiME is shown. The framework is challenge specific, the design space is picked as a showcase due to the shared parameters and conflicting requirements of the disciplines on this part. The negotiations and tradeoffs between the disciplines to solve the conflicts are regarded as the most challenging activities in the development process of SiME, which is why the disciplines are explicitly integrated. References to the methods in Table 2 are marked in bold.

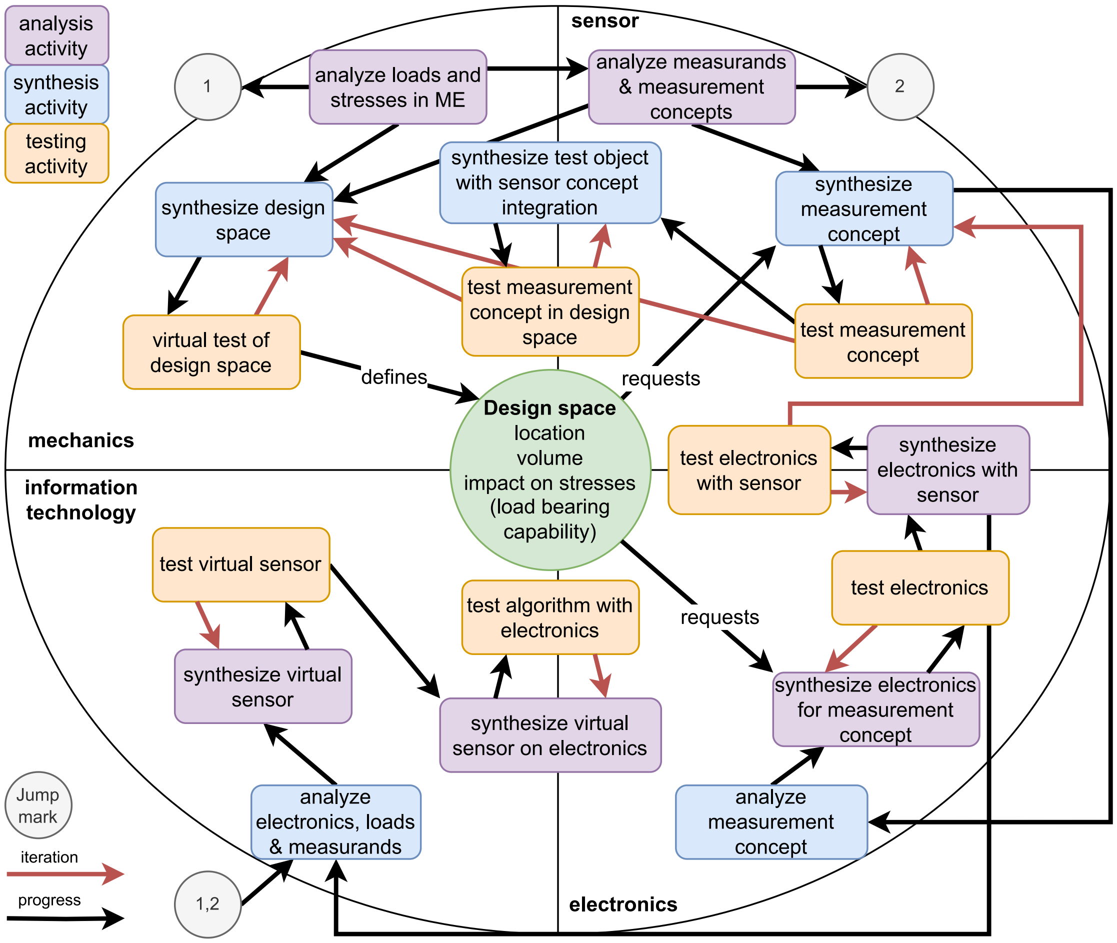


Figure 1: Framework for the interdisciplinary challenge of defining design space with testing-focused activities

At the beginning (Figure 1), analysis steps of the conventional machine element are emphasized, because the SiME with its new measurement function extends the functionality of those. **Maximum loads and stresses** are explored to identify potential design spaces and to **identify measurands and measurement concepts**. Minimum load capability is defined based on the loads and stresses. Further, design space is synthesized in a **top-down** approach by considering **strength classes** and by using **virtual testing** with CAE methods, which results in the volume and location of the design space. For this step knowledge of the favored measurement concept is required to localize the design space accordingly. Next, a measurement concept that fits in the design space can be synthesized and tested separately. If the test fails or if no measurement for the previously defined design space can be synthesized, one needs to *iterate* with a **combination of top-down and bottom-up** approach to negotiate a design space that makes a tradeoff between mechanical- and measurement function. If needed, **adjust the priorities** of mechanical- versus measurement function. **Validate** the measurement concept **early in a simplified test**. If failed, *iterate* and pick another measurement concept. If succeeded, **integrate to the next levels** by including the data acquisition electronics and by getting to the final geometry in several steps and **test again until system level**.

The first level of testing should be done as early as possible, which usually is inside a discipline. Interdisciplinary tests should follow shortly afterwards due to the shared design parameters which leads to interdependent (sub-) solutions, as can be seen with the influence of the electronics on the measurement concept. If the electronics needed to acquire data of a measurement concept that fits in the design space cannot be integrated, a cross-discipline iteration to the sensor or even to mechanics is inevitable (see Figure 1). Also, the data acquisition and conditioning algorithm influence the electronics which can lead to cross-discipline iterations up to mechanics as well.

In Figure 1 the influence of electronics on synthesizing design space is not shown to avoid overloading the figure. For the same reasons, the higher integration levels of three disciplines (for example mechaincs+sensor+electronics) are not depicted.

This procedure shows one possible way to handle the challenges of shared design parameters for design space by focusing on negotiations between the disciplines and testing. As mentioned above, testing-driven development helps by early validating solutions that help build up knowledge and avoiding cross-discipline iterations that involve two or more disciplines. The procedure can be transformed to apply as well to the other challenges.

## 6. Summary and Outlook

Sensor-integrated machine elements (SiME) can be game changers in industry and support current and future trends by providing extensive data in-situ with minimum installation effort due to their standardized interfaces. Objectives for developing SiME are formulated in the SPP 2305. They include preservation of the mechanical interfaces and geometry of the conventional machine elements while providing quality measurements and being self-sustainable and hermetically sealed.

Challenges in developing SiME are interdisciplinary, interdependent, and occur in different kinds of machine elements. A major challenge is that the disciplines involved share the same design parameters, which for example leads to conflicts in defining the design pace. Setting these shared parameters to maximize a local criterion for one group may deteriorate the solution for others.

The challenges were identified, clustered, and described. Test-driven development is proposed as a solution to solve the challenges of developing SiME by focusing on interdisciplinary negotiations and early testing activities, which is shown graphically as a framework.

In the future, further methods and tools for supporting the development of SiME are researched, tested within the ten different projects of the SPP 2305, and implemented in the described framework.

## Acknowledgments

This research was funded by the Deutsche Forschungsgemeinschaft (DFG, German Research Foundation) - project number 466650813.

## References

[1] Stücheli, Marius; Meboldt, Mirko: Mechatronic Machine Elements: On Their Relevance in Cyber-Physical Systems. In: Abramovici, Michael; Stark, Rainer (Hrsg.): *Smart Product Engineering*. Berlin, Heidelberg: Springer, 2013, S. 263–272

[2] Vorwerk-Handing, G., et al.: *Classification and examples of next generation machine elements*. In: *Forschung im Ingenieurwesen* 84 (2020), Nr. 1, S. 21–32

[3] Martin, Georg, et al.: *MME - Potentiale durch mechatronische Maschinenelemente*. In: *Konstruktion* 70 (2018), 01-02, S. 71–75

[4] Vogel, Sven; Kirchner, Eckhardt: *Simple Integration of Sensory Functions*. In: *Proceedings of the Design Society: International Conference on Engineering Design* 1 (2019), Nr. 1, S. 3711–3720

[5] Deutsche Forschungsgemeinschaft: *DFG Schwerpunktprogramm 2305: Sensorintegrierende Maschinenelemente*: *Wegbereiter der flächendeckenden Digitalisierung*. URL https://www.spp2305.de/ – Überprüfungsdatum 2022-08-01

[6] Mihm, Jürgen; Loch, Christoph; Huchzermeier, Arnd: *Problem-Solving Oscillations in Complex Engineering Projects*. In: *Management Science* 49 (2003), Nr. 6, S. 733–750. URL http://www.jstor.org/stable/4134021

[7] Tahera, Khadija, et al.: *Testing in the incremental design and development of complex products*. In: *Research in Engineering Design* 30 (2019), Nr. 2, S. 291–316

[8] Schork, Stefan; Gramlich, Sebastian; Kirchner, Eckhard: Entwicklung von Smart Machine Elements - Ansatz einer smarten Ausgleichskupplung. In: Krause, Dieter; Paetzold, Kristin; Wartzack, Sandro (Hrsg.): *Design for X* : *Beiträge zum 27. DfX-Symposium*. Hamburg: Tutech Innovation GmbH, 2016 (27).

[9] Groche, Peter; Brenneis, Matthias: *Manufacturing and use of novel sensoric fasteners for monitoring forming processes*. In: *Measurement* 53 (2014), S. 136–144

[10] Brecher, C., et al.: *Methodik zur Ermittlung der Schraubenzusatzkräfte von Schraubenverbindungen*. In: *Konstruktion* 68 (2016), Nr. 06, S. 78–82

[11] Frank, T., et al.: 2.2.4 Hybridintegration von Mikrodehnungssensoren. In: *20. GMA/ITG-Fachtagung Sensoren und Messsysteme 2019*: AMA Service GmbH, 2019, S. 153–158

[12] Biehl, S., et al.: *Wear resistenat thin film sensor system for industrial applications*. In: *International Journal of Instrumentation and Measurement* (2016), Nr. 1, S. 6–11

[13] Fraunhofer-Institut für Schicht- und Oberflächentechnik IST: *Intelligente Schraubverbindung – Drahtlose und energieautarke Monitoringlösung*. URL https://www.ist.fraunhofer.de/de/referenzprojekte/intelligente-schraubverbindung.html – Überprüfungsdatum 2022-07-25

[14] Horn, Sebastian; Gwosch, Thomas; Matthiesen, Sven: *Sensor-integrated chemical anchor for continuous monitoring of the fastening situation*. In: *Beton- und Stahlbetonbau* (2021), Nr. 116, S. 1–8

[15] Peters, Julian, et al.: *Design of sensor integrating gears: methodical development, integration and verification of an in-Situ MEMS sensor system*. In: *Procedia CIRP* 100 (2021), S. 672–677

[16] Peters, Julian, et al.: *Sensor-integrating gears: wear detection by in-situ MEMS acceleration sensors*. In: *Forschung im Ingenieurwesen* (2021)

[17] VDI-Richtlinie 2221 Blatt 2. November 2019. *Entwicklung technischer Produkte und Systeme*

[18] Gericke, Kilian, et al.: Der Produktentwicklungsprozess. In: Bender, Beate; Gericke, Kilian (Hrsg.): *Pahl/Beitz Konstruktionslehre*. 9. Aufl. Berlin, Heidelberg: Springer Berlin Heidelberg, 2021, S. 57–93

[19] VDI-Richtlinie 2206. 2021. *Entwicklungsmethodik für mechatronische Systeme*

[20] Hofmann, Klaus, et al.: Potenziale und Herausforderungen Energieautonomer Sensorsysteme für den Einsatz in sensorintegrierenden Maschinenelementen. In: Schrecker, Olivier (Hrsg.): *EASS* : *Energieautonome Sensorsysteme*: VDE Verlag GmbH, 2022 (102), S. 36–38

[21] Lindemann, Udo: *Methodische Entwicklung technischer Produkte*: *Methoden flexibel und situationsgerecht anwenden*. Berlin, Heidelberg : Springer-Verlag Berlin Heidelberg, 2005 (VDI-Buch)

[22] Matthiesen, Sven: Gestaltung – Prozess und Methoden. In: Bender, Beate; Gericke, Kilian (Hrsg.): *Pahl/Beitz Konstruktionslehre*. 9. Aufl. Berlin, Heidelberg: Springer Berlin Heidelberg, 2021, S. 397–465

[23] Gausemeier, Jürgen; Moehringer, Stefan: *New Guideline VDI 2206 - A Flexible Procedure Model for the Design of Mechatronic Systems*. In: *DS 31: Proceedings of ICED 03, the 14th International Conference on Engineering Design, Stockholm* (2003)

[24] Horn, Sebastian, et al.: *Ermittlung eines Designraums zur Mechatronisierung von Befestigungsmitteln am Beispiel von Verbundankern*. In: *Beton und Stahlbau* 115 (2020)

[25] Shabi, Jacob; Reich, Yoram: *Developing an analytical model for planning systems verification, validation and testing processes*. In: *Advanced Engineering Informatics* 26 (2012), Nr. 2, S. 429–438

[26] Hardenbrook, Donovan R., et al.: *Ready, Set, Dominate: Implement Toyota's Set-Based Learning for Developing Products and Nobody Can Catch You!* In: *Journal of Product Innovation Management* 26 (2009), Nr. 6, S. 687–689

[27] Wynn, David C.; Eckert, Claudia M.: *Perspectives on iteration in design and development*. In: *Research in Engineering Design* 28 (2017), Nr. 2, S. 153–184

[28] Bremer, Frank, et al.: *Analyzing iterations in mechanical design processes – a method for data acquisition in meso-level studies*. In: *Procedia CIRP* 100 (2021), S. 756–761

[29] Peters, Julian, et al.: *Requirements for Sensor Integrating Machine Elements: A Review of Wear and Vibration Characteristics of Gears*