Forschung im Ingenieurwesen (2025)89:164
https://doi.org/10.1007/s10010-025-00931-x

ORIGINALARBEITEN/ORIGINALS

Microelectronic modular system for sensor-integrating machine elements—model-based configuration and prototypical implementation of sensor-integrating bolts

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Received: 14 February 2025 / Accepted: 10 November 2025

Abstract

In the Priority Program 2305 of the German Research Foundation, so-called Sensor-integrating Machine Elements (SiME) are to be developed. These are essentially highly standardised components with integrated microelectronics. This article presents the development of a model-based construction kit to support the design of integrated sensor systems for these new machine elements. A methodical procedure for collecting the development data required for modelling the construction kit is presented. Use cases, system architecture and module diagrams were developed and modeled for the machine element bolt. These are then linked in SysML models to enable sensor systems to be configured in line with requirements. An exemplary prototype of a sensor-integrating bolt has been developed an validated in a test environment. The modeling of modular system architectures deepens the understanding of the underlying mechatronic system and allows for application-specific configuration of sensor systems by taking differentiation features into account while exploiting synergy potentials between SiME. This configuration represents an approach to making sensor-integrating machine elements accessible to a broad range of users with different requirements.

1 Introduction

Digitalisation is a driving force in today's society and in industry. The need for high quality data from within mechanical structures is a key driving force in current sensor integration research with the goal to enable means such as predictive maintenance or other monitoring activities, see among others [6, 19]. In the *Priority Program* 2305 (SPP 2305) of the *German Research Foundation* (DFG), the goal is to develop innovative machine elements (ME) with integrated sensory functions, enabling extended functionality without restricting the primary function of the machine element. These so-called Sensor-integrating Machine Elements (SiME) integrate mechatronic sub-functions to acquire data, convert the measurement signal, process and transfer the signal [10]. As pioneers of large-scale digitalisation, SiME will be able to specifically record and process high-quality data in process-related areas in order to draw conclusions about the behaviour and condition of machines and systems. In the future, SiME are anticipated to be used in a wide range of applications in order to record various measurement variables, to forecast defined cases of damage or machine failure and to monitor machine statuses and processes [3].

In the project MiMoSe (Microelectronic Modular System for Sensor-integrating Machine Elements) within the SPP 2305, the aim is to develop modular system architectures for SiME and integrate them in a model-based modular building kit (MBK). The modular structure allows for interchangeability and adaptation of the system according to specific needs and application cases as illustrated in Fig. 1. To achieve this, system models are developed and modelled in SysML, where development data is stored and made accessible for the configuration of sensor systems. A python-based configurator calculates customised sensor systems for different SiME applications. Viable system configurations

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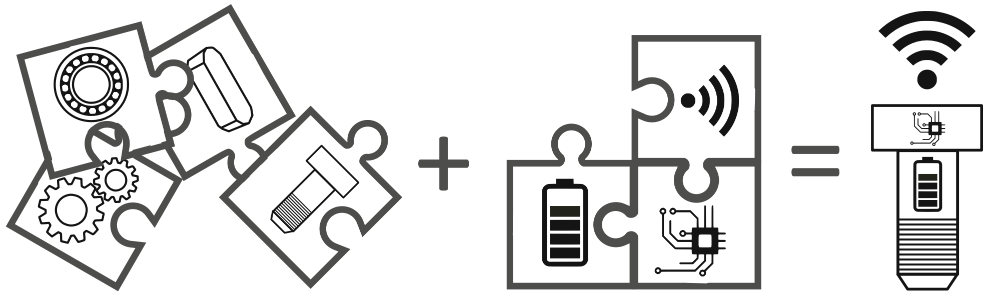


Fig. 1 Development of adaptive SiME through customised system modules [20]

can be further developed to a prototype which is done within this study on the example of a sensor-integrating bolt and finally tested in a test rig.

A large number of possible applications, process and measurement variables bring high future diversity and significant complexity into the development task. In order to successfully manage the complexity of systems, methods of modularisation and system development are suitable [31, 33]. Modular product structuring is particularly suitable for dealing with variance-induced complexity [33]. In combination with approaches of mechatronic system development, the product development process of SiME could be adequately supported considering complexity and interdisciplinarity. The aim of this study is to provide methodological support for the interdisciplinary, systematic development of SiME with the aid of a model-based microelectronic MBK. This is being researched in a combination of methodical product development, mechanical engineering and microelectronics using the example of fastening and movement bolts. Bolts are particularly suitable for sensor integration because they are a classic ME with numerous possible applications and because preliminary work on this topic has already been carried out within the consortium [7, 34]. To verify and validate the modular system, a sensor system for sensor-integrating bolts is configured from predefined electronic modules based on already available components, prototypically implemented and integrated into the bolts [24]. Finally, the realised SiME prototypes will be tested experimentally. The results obtained in this project form the basis for making sensor-integrated machine elements freely accessible by demonstrating their configuration for various applications and proving the applicability of the systems configured in this way.

This paper outlines the content developed in this project and the resulting implications. To this end, in the following Sect. 2, the necessary basic theoretical considerations from the various research areas are presented. On this basis, the problem definition is derived in Sect. 3 and the research hypotheses discussed are presented. Section 4 explains the solution approach that was pursued in the study. Section 5 deals with the validation of the model-based modular construction kit, the microelectronic system and finally the SiME by means of tests on a test bench and its evaluation. This article concludes in Sect. 6 with a conclusion and outlook.

2 Research background

The successful development of SiME requires the co-operation of various engineering disciplines with the corresponding knowledge backgrounds. Accordingly, literature from the respective research areas is presented. Firstly, machine elements and the further classification of SiME are discussed and developments in this area are mentioned. Furthermore, the state of knowledge on the development of microelectronic systems is outlined. Finally, the development of modular product architectures is discussed and their modelling and implementation for software-based configuration on the basis of modular construction kits is described.

2.1 Sensor-integrating machine elements

In the wake of digitalisation, machine elements (ME) have been enhanced via the introduction of sensory functions into the ME, thus turning these into sensing machine elements (SME) [34, [10]. This new class of machine elements can be further distinguished into sensor-carrying machine elements (ScME), sensor-integrating machine elements (SiME) and sensory utilisable machine elements (SuME). These types of SME can be differentiated by the relation between primary, usually mechanical, and sensory function. In ScME, the primary function of the ME and its sensory function are independent from one another. That means that the physical quantity measured by the sensor has a negligible impact on the primary function of the ME, for example when measuring the temperature in a bolt. On the other hand, in SiME, primary function and sensory function are connected, meaning the physical quantity measured by the sensor is part of the primary function, as it is the case when measuring axial force in a bolt. Finally, SuME are using changing electrical behaviour of the ME itself to measure physical quantities. One example for the latter is the use of the electrical impedance occurring in the lubrication film of a roller bearing to measure its speed and radial force [23].

Since the first introduction of this new class of ME, various examples of these have already been implemented, which can be found in a review paper written for this purpose [10]. Additionally, several dedicated methods have been developed to support the design of SME. Research foci vary from the robustness of the sensory functions [29, 30], the general development of sensory functions [8, 11], the use of SME in the context of digital twins [9] as well as overcoming competing objectives in the design of SME via the use of optimisation algorithms or specific test strategies [35, 36].

2.2 Modular product architectures and configuration systems

Products can be comprehended in the functional and in the physical domain. The assignment of functional elements to physical elements is understood as product architecture [25]. When physical elements are organised in chunks that implement functional elements in their entirety, a modular architecture can be defined in which the interactions are well defined and the primary function of a product can be realised. If the interaction between the chunks is poorly defined and functional elements affect more physical components, this is referred to as an integral product architecture [25]. Product modularity can furthermore be understood as a gradual property of different perspectives. Salvador defines component commonality, component combinability, function binding, interface standardisation and loose coupling [21]. Vogt and Krause expand the perspective of overdimensioning. Together with interface standardisation, oversizing allows modules to be used across a range of variants [28].

Complex technical systems can be modelled with help of Model-Based Systems Engineering (MBSE). Different engineering views with heterogeneous product models can be consolidated to consistent and interconnected product models. [1]. This can be used in the context of product generation engineering or to support the development of MBKs. [1]. Development information can be stored consistently and continuously, enabling better control of system complexity [4, 22]. Once a modular architecture is defined, it can be modelled as a MBK or configuration system. Scherer et al. introduce a modeling method for requirements of MBKs and validate it on hybrid drivetrain systems [22]. Dambietz et al. developed a methodical framework for a set up of modular product architectures in an MBSE environement and an interconnection to a configuration system [37]. This can ultimately be used to configure modular product architectures as a MBK and evaluate product architecture alternatives based on different target values which can be addressed by the Configuration Value Vector (CVV) using the Dijkstra algorithm [37]. This approach was validated on the example of laser welding machines. The consistent storage of interlinked data, the reuse of components and modules and the possibility to map broad configuration spaces are key advantages of modelling complex systems in MBSE [1].

2.3 Development of micro-mechatronic systems

Electronic systems are part of everyday life and play a crucial role in the modern digital world by being connected to the Internet [18]. The increasing complexity of processes requires assistance in the form of automation, where monitoring and control are applied using sensors and actuators accordingly. In addition, miniaturizsation is a key to denser integration and improved operation in terms of energy consumption, response time, environmental interaction, and level of integration. The use of alternative methods, e.g. optical gyroscopes instead of Micro-Electro-Mechanical Systems (MEMS), enables better performance, but both require similar fabrication technology as for semiconductors and special knowledge and skills [5]. Applications with multi-sensor and micro-scale systems for customised needs and precise operation, as exemplified by Kuo et al., can be used as soon as they are available on the market [16], but were avoided in this project in terms of their development. Additive manufacturing methods able to directly print capacitors as shown by Ma et al. [17] or inductors as shown by Valenziano et al. allow some degree of customisation, but rely on expertise and characterisation of devices [26]. In order to simplify the development of SiME by integrating sensor systems and communication modules, devices such as MEMS, integrated circuits or microcontrollers are used as the smallest module in this work. The advantage is that they are available in a variety of functions, have documented connection instructions and digital interfaces with standardised protocols. This makes them the most suitable for the modularity of SiME.

Since SiME are a combination of the mechanical ME, microelectronic components, and the necessary information technology behind it, the development task can only be accomplished with the co-operation of various disciplines. The VDI 2206 with the V-model as a macro-cycle for the development activities is suitable for the development of mechatronic systems and describes a generic procedure for designing mechatronic systems [27]. Starting from the requirements, solution concepts are created, e.g. at functional level. This is followed by the discipline-specific design in the respective disciplines involved. In the system integration phase, the properties of the system are assured step by step until a validated product is the result of the endeavours. In order to consider product variance and modularity in the sense of modular product families in the development process and to take into account the many iterations in the initial development of products and the development of product family generations, Küchenhof et al. present an adapted V-model [14]. The domain-specific design can further be methodically supported by the harmonised development of mechatronic modules [32].

For the design of a mechatronic system architecture and holistic system modelling and synthesis, systems engineering is regarded as a suitable integrative method [2]. This integration can be realised using a model-based approach, for example. The data elements of the requirements, functions and the physical structure can be modelled separately and independently of disciplines and then transferred to an overall model. In order to enable a systematic design process of mechatronic systems with a high integration density, so-called multidisciplinary integrated design is required. In order to organise the design activities of the various disciplines Zheng et al. propose a design methodology based on a multidisciplinary interface model to ensure consistency and traceability between the micro and macro levels [31]. In line with systems engineering, an extended V-model is used as the macro-level process and a hierarchical design model as the micro-level process in the proposed design methodology. It starts with the identification of the requirements for the overall system and ends with a user-validated system [31].

3 Problem statement

Since the design of SiME represents a mechatronic challenge, the use of a V-model approach with the support of model-based systems engineering approaches is seen as expedient for the methodical development of SiME. An application approach for the methodical model-based development of micro-mechatronic systems such as SiME could not be found in the state of the art. The resulting gap in the state of research makes fundamental investigations necessary.

Approaches that consistently support the development of mechatronic products on the basis of SysML models and at the same time focus on the development of modular architectures could not be identified. No approaches to the modularisation of microelectronic architectures and sensor systems such as SiME were found in the current state of research.

When integrating microelectronics into SiME, knowledge of the loads acting on the ME in the respective application and the resulting stresses is essential for the selection of suitable components and the identification of their application limits. One example of such an application limit is the measuring range end values of acceleration sensors that are used in rotating components. The compatibility of mechanical stresses with the performance limits of (micro-)electronic components is described by Großkurth and Martin for the example of the sensor-integrating timing belt [38]. Ziegltrum et al. also address this problem and solve it by developing special microelectronic components for the application they are dealing with [39]. A method for determining the requirements for sensory components as a necessary prerequisite for the targeted development of SiME and for the definition of modular structures of SiME is not known.

Taking into account the partly conflicting requirements for component size, energy consumption and data volumes compared to the quality of service of the sensor system to be ensured, such as accuracy, real-time capability or reliability, SiME have so far only been realised as custom-made products. No comparable approach to the development of SiME, or a supporting framework in the sense of a microelectronic MBK, which is implemented utilising a model-based approach, was identified in the reviewed literature.

3.1 Hypotheses

Using the bolt as an exemplary ME, this study aims to generate suitable sensor systems with the help of the developed microelectronic modular construction kit, as well as to realise prototypes of these systems and then examine them experimentally. In order to specifically address the research activities, partial aspects were formulated in the form of hypotheses. The following research hypotheses (H) were formulated and tested as part of the study:

H1: The requirements for the mechanical and electronic, in particular the sensory functions of the sensor-integrating bolts, depending on the application and environmental conditions can be used as module drivers for sensor systems.

H2: The compatibility of microelectronic components to form electronic modules based on energy and data classes as well as the fulfilment of functionally relevant requirements can be checked a priori.

H3: The three basic strategies—energy-, data- and space-optimised—are suitable for an effective configuration of sensor system alternatives for SiME.

H4: The required electronic modules for sensor-integrating bolts as well as their potentials and limits can be predicted and experimentally verified.

H5: The procedure for variant-orientated module formation and the development of a microelectronic module construction kit for bolts is generally transferable to other ME.

The research hypotheses are analysed on the basis of the solution approach and corresponding validation activities.

4 Solution approach

In order to take into account the various requirements within the scope of the SPP 2305, an adapted V-model is being developed, which will be used for the development process in the project. The various disciplines, levels of product architecture and system integration are taken into account. Verification and validation activities are also planned. Comprehensive modelling in the MBK serves as a central knowledge repository. Figure 2 shows the procedure for sensor-integrating bolts. Further macrocycles for the development of new SiME can be carried out on the basis of the emerging knowledge.

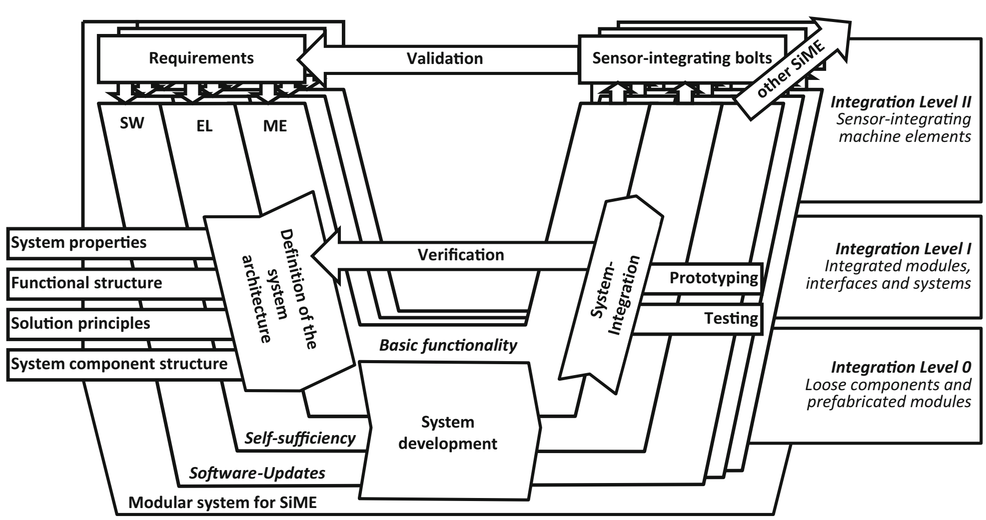
Firstly, the requirements for the development are determined. These can be assigned to the different areas of mechanics, electronics and software. The system architecture is then defined by specifying system properties, functional structures, general principles and a physical system structure, which is composed of the sub-architectures of the individual areas of mechanics, electronics and information technology. The architecture, and thus also the interfaces of modules and components, is defined prior to development as the basis for the new development of modular systems. System development is driven forward iteratively so that the main functionality is implemented first. Performance enhancements can be introduced in further development iterations. Software updates can also be subsequently implemented in the system in order to test new functions or algorithms.

System development is followed by system integration. Starting with loose components and prefabricated modules that can be tested individually (Integration Level 0), integrated modules, interfaces and systems are created (Integration Level I), which are finally integrated into machine elements in order to reach Integration Level II. The functional testing of system elements of the individual integration levels can be verified via individual or combined tests. Finally, the SiME is validated in the application space. The modular system spans the V-model by recording development data and modelling it. Each SiME can be mapped by iteration in the V-model. This is illustrated in the *diagram* by layers in depth. The single steps, that were conducted in the project are visualised in Fig. 3.

At the beginning, the application and the use case are defined. Based on this, the requirements for the SiME are determined. There are general requirements that every SiME must fulfil, such as reliable data acquisition and data transmission. In addition, the data must be processed and stored. As for all projects within the SPP 2305, the primary function of the ME must not be restricted and the system must also be supplied with energy. Using the example of the sensor-integrated bolt, the specific measured variables include force and acceleration values that originate from the specific application. In this project, an M12 bolt is to be used in which the sensor system will be integrated.

Product features are derived based on the requirements. These range from installation space and classification in terms of data and energy to other features such as control and measurement issues. Furthermore, possible solutions for implementing the features with suitable components and modules are explored. The compatibility of the microelectronic components and the effects of interaction, also with regard to the environment, need to analysed carefully. The modular structure of the microelectronic sensor systems can then be mapped hierarchically so that the sensor system is arranged at the top level and can be broken down into microelectronic modules and components. Once the concept has been created, a SiME prototype is realised. At the same time, the test environment can be developed and designed. System verification can take place at lower hierarchy levels so that, for example, sensor modules can be tested individually (IL 0). The sensor system can be verified before

Fig. 2 V-model for the development of different SiME that are integrated in a MBK



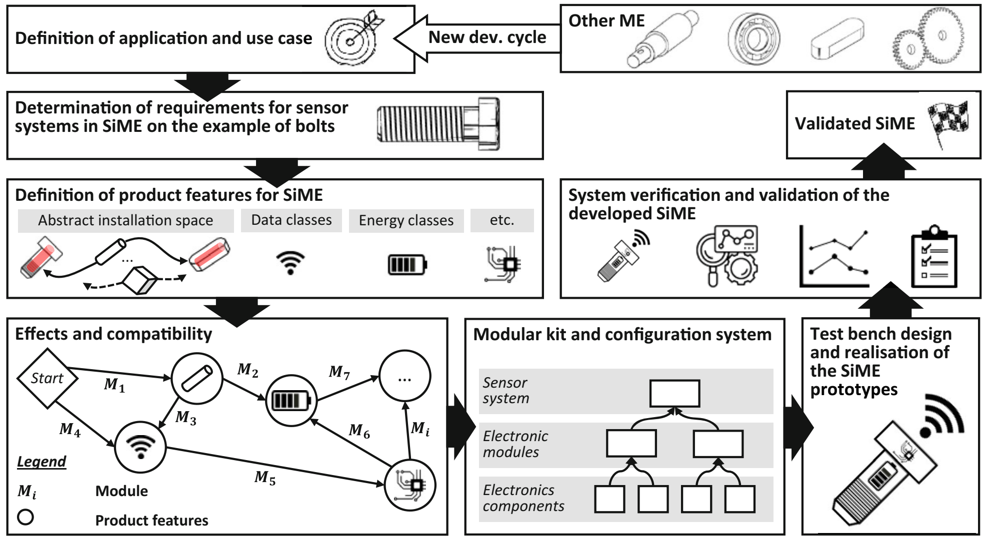


Fig. 3 Approach to the design of SiME

it is integrated into the ME (IL I) and ultimately becomes the SiME (IL II), which is finally validated in the use case, in this instance the test bench. After successful validation, a new development cycle can be performed following the V-model as a macro-cycle. Sensor systems can also be developed for other MEs. Ideally, the already implemented data framework in the form of the model-based MBK can be used here and expanded to include the new requirements, components and relationships.

The development of the model-based MBK (Sect. 4.1), the resulting microelectronic system for sensor-integrating bolts (Sect. 4.2) and the physical integration and testing (Sect. 4.3) are described in the following.

4.1 Modular system for SiME

The schematic structure of the modular system is shown in Fig. 4. The left-hand box contains the input data. A component database with microelectronic off-the-shelf components is created. The metadata such as geometric parameters, electronic specifications and operating conditions are extracted from the data sheets and stored in the database. In addition, development models of the system must be available that can be modelled in SysML. These are tools that support system development according to the V-model. These include use case diagrams, requirements lists and diagrams, variety trees, product structures and network plans. Finally, the simulation input is defined. This includes the configuration value vector, configuration algorithms and the CND.

To implement the model-based modular system, the system architectures are implemented in SysML in the Cameo Systems Modeller. Alternative architectures can be exported in a further step in order to generate system configurations. The data is read in and then runs through the configuration process (see Sect. 4.1.3). The resulting configurations can be evaluated based on performance criteria (installation space, energy behaviour, data quality). The system configuration selected for further implementation can be extracted.

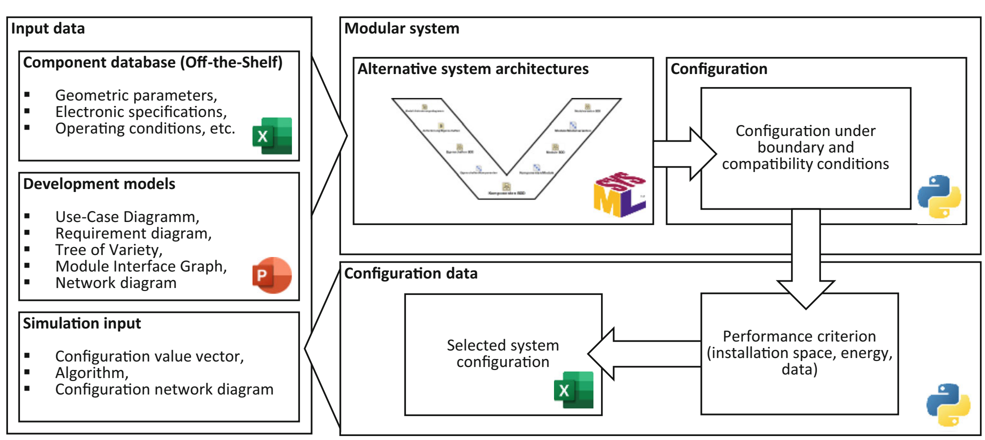


Fig. 4 Schematic overview of the modular system. (Based on [13])

Table 1 Component database of microelectronic devices (excerpt)

Specific component	Generic component (MIG)	Volume [mm^3]	Umin [V]	Umax [V]	Tmin [°C]	Tmax [°C]	Interface
A1366	MAS	22.50	4.5	5.5	–40	150	–
ACS712	MAS	47.62	4.5	5.5	–40	85	–
AD7747	CDC, TES	39.16	2.7	5.5	–40	125	I2C
adt7410	TES	54.25	2.7	5.5	–55	150	I2C
ADXL202E	BES	50	3	5.25	–40	85	–
adxl335	BES	23.2	1.8	3.6	–40	85	–
ADXL345	BES	15	2	3.6	–40	85	I2C, SPI
ADXL356-357	BES	67.2	2.25	3.6	–40	125	I2C, SPI
ADXRS290	GYS	31.32	2.7	5	–25	85	SPI
asm330lhhx	BES, GYS, TES, MCO	6.22	1.71	3.6	–40	105	I2C, MIPI, SPI
ATmega48A	MCO	16	2	5	–40	85	I2C, SPI, USART
ATmega640	MCO	208.75	1.8	5.5	–40	85	I2C, SPI, USART
Atmel_8067	MCO	196	1.6	3.6	–55	125	I2C, SPI, USART, EBI

4.1.1 Input data

The data input area includes the component database, development models and input variables such as the CVV and suitable algorithms.

Component database The component database is created in the form of a table and can be imported as a CSV file in SysML so that the data is available for modelling within the MBK. Table 1 shows an extract from the table. The first column lists the specific components with their device name following by its function, type, physical parameters for estimation of required size and power consumption, etc.. The generic components of the system are defined in the *Module Interface Graph* (MIG). Generic and specific components are linked in the second column. Specific components and their device name are listed. Specifications and parameters are also recorded. For example, the volume of each component, minimum and maximum voltage levels, temperatures, interfaces, etc. are listed. This information can later be used to analyse the compatibility of components with each other and filters can be used to sort out components that are unsuitable for a particular application. The identification and definition of relevant parameter sets for the design of SiME can be comprehended in Kruse et al. [12].

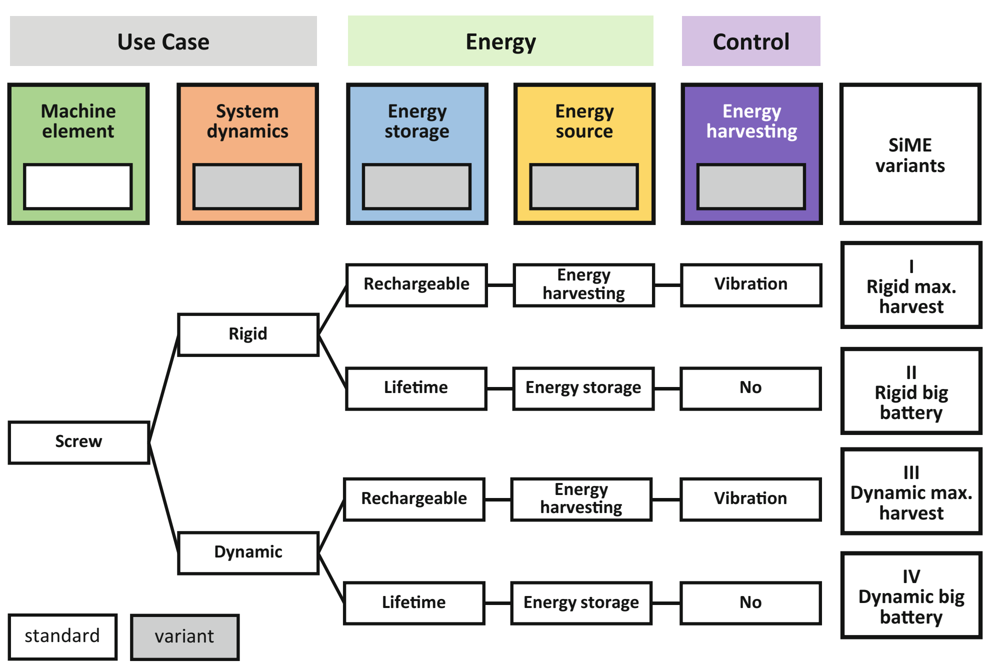


Fig. 5 Definition of SiME in a TEV

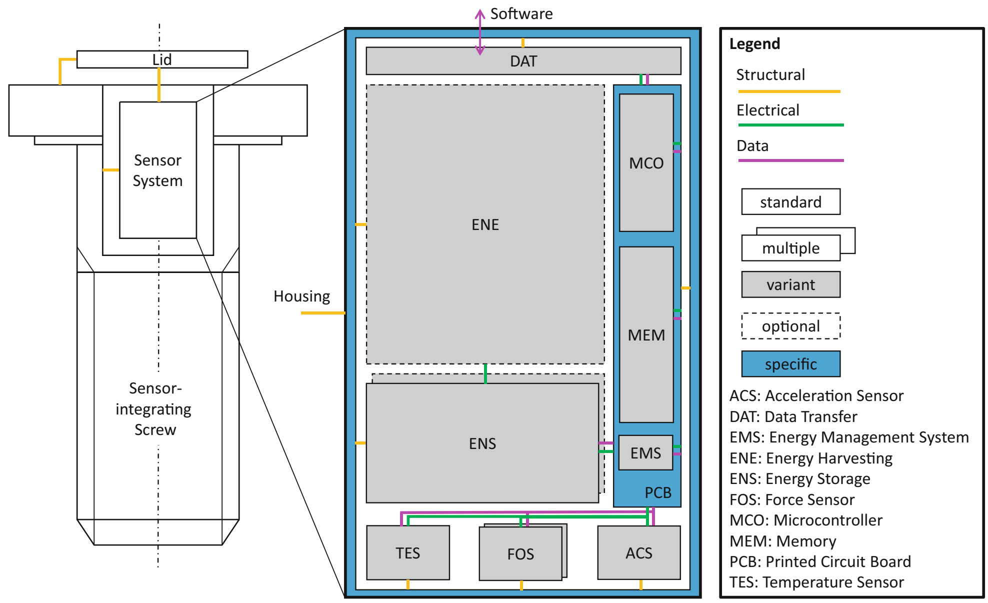


Fig. 6 MIG of sensor-integrating bolts. (Based on [13])

Development models The created development models lead from the requirements level to the definition of suitable modules. In accordance with the customised *Integrated PKT-approach*, product features are first recorded in a *Tree of Variety* (TEV), functions are defined and viable solutions are identified. Then, different modular product structures are developed [15]. The product structure can be visualised in the form of a MIG. Figure 5 shows the TEV of a minimal example of sensor-integrating bolts in rigid and dynamic application. A bolt is used in this application. In the configurator, it should later be possible to choose between different sizes and different ME. The first differentiating feature is the system dynamics, whereby a rigid and a dynamic application are defined. The energy storage device can be rechargeable or provide a lifetime energy supply, which is the second distinguishing factor. The energy source is therefore the storage device itself or, alternatively, an energy harvesting system. Energy harvesting is based on vibration, but could be expanded to include other options in the future.

The functions of the system can be plotted using a flow-orientated function structure. In accordance with the conventional design methodology, alternative solutions can be found for individual functions or already identified function modules, e.g. by means of morphology. Various maxims can be aimed for when designing compatible overall solutions. These can be, for example, *lifetime energy storage* or *high measurement performance*. The concept for *maximising energy harvesting* was developed further in the project. The concept can be represented in the form of a product family structure in the MIG, as shown in Fig. 6.

The sensor system is installed through a hole in the bolts head and structurally attached to the inside of the bolt. Most of the microelectronic components are located in a housing. A temperature sensor, force sensors and an acceleration sensor are provided for signal acquisition. The sensor data is transmitted to a microcontroller located on a circuit board. The data is processed there and stored on a memory unit, which is also attached to the circuit board. The sensor data can be transferred from the ME via a data unit located on the top near the bolt head opening. Firmware updates can also be carried out via the communication unit, e.g. new functions and algorithms can be uploaded to the system using wireless technology. Energy management takes place via the energy management system, which is also located on the circuit board and is connected to an energy storage unit. In the concepts with energy harvesting, a unit is used for energy storage. If there is no energy harvesting, the remaining installation space can be used for additional energy storage units.

The components are coloured differently, which indicates their variety. There are various alternative components in the database for all grey components. Therefore, each sensor system can look different in terms of the specific components used. The energy harvesting unit is marked with dashed lines, which means that it can be optionally installed in some variants. If no energy harvesting unit is used, more space is available for additional energy storage units, which is why they are defined as optional multiples. The PCB and housing are specific parts as they are designed individually for each system combination. The PCB is designed after a sensible combination of microelectronic components has been identified using the SiME configurator (see Sect. 5.1). The housing in which the sensor system is embedded is manufactured using 3D printing and must be specially designed for each size and each machine element, making it highly specific.

Simulation input With the knowledge about product features, product structure and their relationship, the CND can be created. This links product features with components and modules. An algorithm for the configuration must also be selected and implemented. The CVV is defined as an optimisation vector for the final selection of suitable system configurations.

4.1.2 System architecture

In the next step, the data is stored in the model-based MBK. This is done in SysML with the Cameo Systems Modeler. The component database is read in as a CSV file. The development models are implemented in the form of requirements diagrams, use case diagrams and block definition diagrams. The model-based MBK acts as a knowledge repository and provides information consistently across different hierarchy levels and development phases.

However, configuration in SysML is not possible. The necessary existing data is therefore exported and made available for configuration in the next step.

4.1.3 Generic configuration process

The generic configuration process for sensor systems for SiME is shown in Fig. 7. It consists of 7 steps and leads from a database of microelectronic components to an application-specific system configuration.

In the first step, input data from the system architecture which has been implemented in SysML beforehand is exported as a .csv file which is read by the configuration software. The database consists of the specific device data that has been obtained earlier (see Table 1).

Also, the CND provides the mapping from features to generic components in order to retrieve cluster. The generic component clusters consist of the specific device components and their meta-data (volume, energy, interface, etc.). Depending on the desired features, the respective clusters are selected. This is designated as the 1st filter. After deciding on the necessary features, constraints can be set in order to filter out non-suitable components (2nd filter). The remaining components are used for the combinations in the subsequent steps. Based on iterations, all possible and compatible solutions are calculated. Using the Dijkstra algorithm, optimal solutions can be given out. The algorithm calculates the distance for every valid path from a defined starting point to a defined end point and determines the shortest path between two points. Values must be defined in order to perform an evaluation. When configuring sensor systems for SiME, the evaluation dimensions of a path could be, for example, minimum volume or optimal data or energy management. Therefore, the CVV must be adapted to the respective target goals. The final system configuration is selected by manual choice. The optimal solution is selected from a range of choices, that the configuration software provides (3rd filter). This is also described in more detail in the flowchart in Fig. 18, which describes where the data comes from, i.e. the exchange of SysML and CSV files as well as the input in Python and their interaction.

4.2 Microelectronic systems development

The development begins by mapping the requirements to properties needed to define constraints and select components. Size, power and data throughput are limiting strategies in this study to simplify this transformation and benefit the research of module-based methodology of component selection as the main goal. As a result, the configuration process described above, applied to the component database, issued sets suggested for hardware development. The scheme of a sensor system shown in Fig. 8 consists of a microcontroller, sensor units, an antenna for data transfer, connector extensions and a strain gauge unit. Printed circuit boards (PCBs) will be the result for system assembly as a standardised and available manufacturing method. The final step is the programming of firmware written to the microcontrollers, defining the operation and enabling preprocessing features. Since there was no specific application, the components were selected to maximize the system's

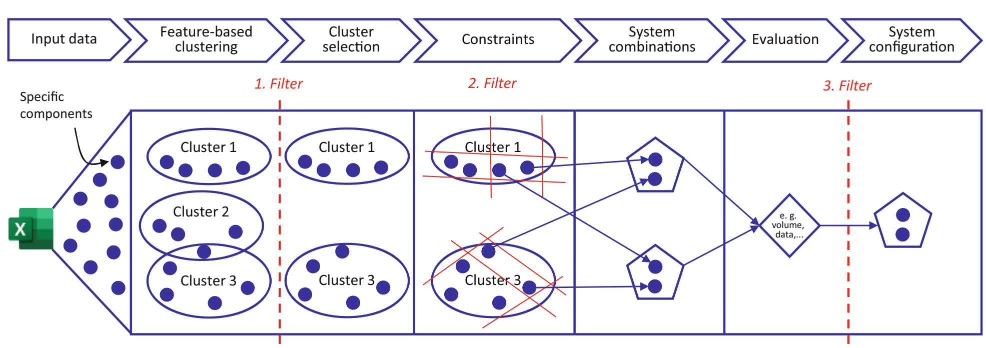


Fig. 7 Generic configuration process

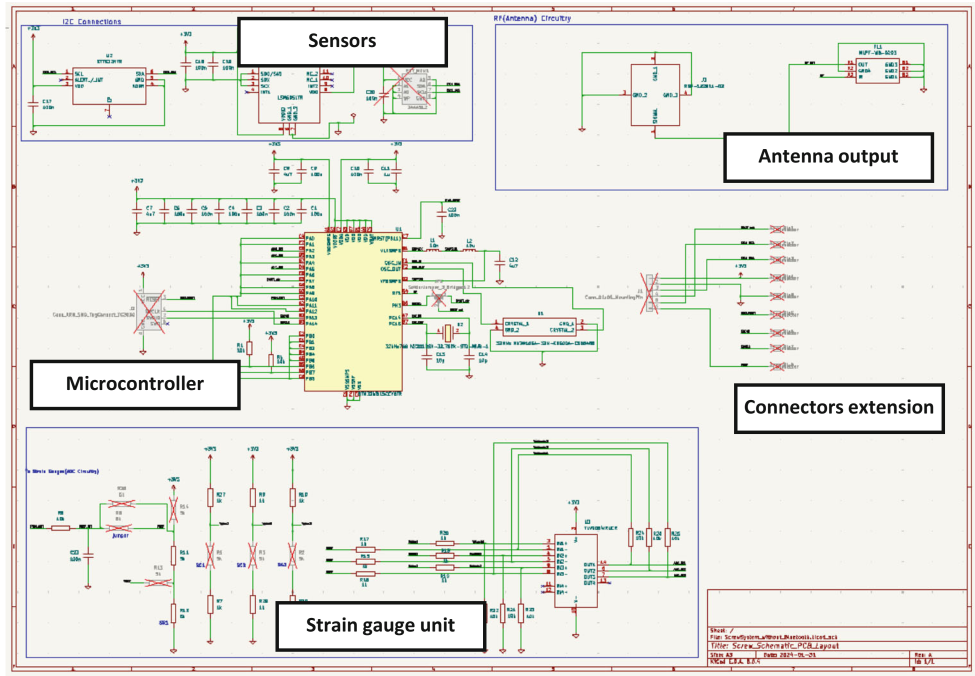


Fig. 8 Scheme of the bolt sensor system with two digital sensors, analog unit for strain gauge digitalisation, microcontroller and an output for an antenna

functionality by balancing their properties. The microcontroller offers a good compromise between size, number of pins, number of ADCs and their available resolution, connectivity protocols, low power consumption, and—keeping in mind the goals of the next phase—on-chip availability of Bluetooth Low Energy with over-the-air updatability. The strain gauge was primarily chosen for its size, which allows three pieces to fit into the screw. The digital sensors were chosen for their compatibility with the microcontroller in terms of libraries and connectivity, as they are from the same manufacturer. The temperature and IMU sensors offer flexible options for selecting between sampling rate and consumption, and the IMU additionally has adjustable sensitivity ranges. After collecting the necessary information from the data sheets, a system scheme was created that connected the digital and analog circuits of the various functions. Parameters such as communication addresses for the sensors Fig. 8 (top left) or in the case of analog circuits Fig. 8 (bottom) the functionality itself are defined in this step. Everything is then completed by connecting to the microcontroller. Programming the microcontroller establishes logical connections and controls the operation and modes of the system.

The physical representation begins with the definition of the board layout, taking into account the constraints of the available space, followed by the placement of the components and routing, which is called PCB design. Placing the components in the board boundary indicates whether the configured sets have reasonable sizes. Both sides of the board are used for components due to the high density of additional components such as resistors or capacitors. In addition, the size of the package pins limits manufacturing. Therefore, the board has 4 layers for routing, uses microvias and is 1 mm thick. Figure 9 shows the result of the final design. For initial functional testing and programming, the main system Fig. 9 (left) is extended with connectors (right) for external equipment and installation of software.

The breaking line in the center of Fig. 9 is implemented to enable the connector extension to be disconnected after programming has been completed allowing to integrate the system into the bolt. Figure 10 shows the concept of the integrated system in an M12 bolt.

4.3 Mechanical integration and test (rig)

In order to validate the configured sensor-integrating bolt, it is implemented in a prototype. The necessary assessment of the mechanical weakening of the bolt due to the insertion of sensor systems and the development of support structures for the insertion of strain gauges into the bolt are the subject of the following two subsections.

4.3.1 Installation space for sensor systems in the machine element

For the physical integration of microelectronics into the bolt, a corresponding installation space must be created. The creation of installation space in the bolt however may reduce its strength. Hence, these adapted bolts need to be tested for their load-carrying capacity. In the context of this study, the loading-carrying capacity is determined by the necessary axial force acting on the bolt for plastic deforma-

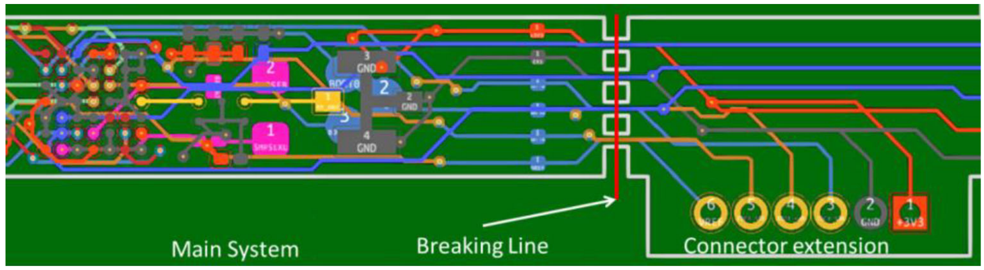


Fig. 9 PCB design of the bolt sensor system ready for fabrication

tion. For this purpose, bolts of the strength class 8.8 with a diameter of 12 mm and a shaft length of 42.5 mm are prepared with an installation space in the form of a simple drill hole with varying diameter and a constant depth in the centre of the bolt. The diameters are varied between 5 and 9 mm in 1 mm increments. These bolts are then tested by applying axial force to them until mechanical failure occurs and the bolts break. Each of these tests is repeated five times to ensure statistical validity. The evaluation of these tests shows that the failure of the bolts always occurs in the shaft area. The exact location is distributed over the length of the shaft so that no pattern can be recognised, whereas the forces at which failure occurs shows limited deviation. From this it can be concluded that neither the notch effect at the head of the bolt nor the notch effects at the bottom of the drill hole are decisive for the failure of the bolts. In addition, the force at which the plastic deformation of the bolts begins indicates that the strength of the bolts is not weakened below the load carrying capacities defined of the bolts strength class by removing the core material of the bolt. Therefore, an analytical formula is used to approximate the maximum axial load of the bolt for the configuration of the bolt, considering the remaining bolt cross-section and the maximum tolerable nominal stress of the bolt material based on the strength class of the bolt. The specific formula is displayed in the appendix in Fig. 19. Instead of using that formula, the use of the original strength is suitable as well, as testing has shown their limitations are not violated by the drill hole. Based on the findings of the experiments, this represents a conservative approach for the design of sensor-integrating bolts.

4.3.2 Physical connection of the strain gauges to the bolt

For accurate stress measurement in bolts, strain gauges are ideally positioned on the outer surface, where they can be easily applied. However, this location may alter the bolt's external geometry, which is undesirable for many engineering applications that require the bolt's original dimensions to remain unchanged. To address this, an innovative approach involves embedding strain gauges directly within the bolt structure, maintaining its exterior geometry while enabling precise internal strain measurement.

Conventionally, strain gauges require application under pressure to adhere effectively to surfaces, but in the bolt's internal cavity, direct application pressure cannot be achieved. Instead, the strain gauges are pre-mounted onto a support structure before insertion. This support structure is a thin-walled hollow cylinder with a wall thickness of 80 µm manufactured using temperature-resistant material via 3D printing. The specific material used is High Temp V2 by Formlabs, which is deployed in a selective laser sintering process, using the Form 3 3D printer by Formlabs. This fabrication process allows for exact dimensional accuracy, ensuring that the carrier structure fits seamlessly within the bolt's drilled cavity. On this support cylinder, three strain gauges are adhered to the outer surface at 120° intervals, allowing comprehensive measurement coverage. Once prepared, adhesive, Loctite 3090, chosen for its ability to bond onto metal and the used polymers, is applied within the bolt cavity, allowing it to distribute evenly between the inner bolt surface and the carrier structure upon insertion. To implement this integration, a hollow cavity is created within the bolt to house the strain gauges. The cavity's precise diameter is designed to match the dimensions of the strain gauge's mounted carrier structure, ensuring a secure fit once the assembly is inserted. The adhesive layer inside

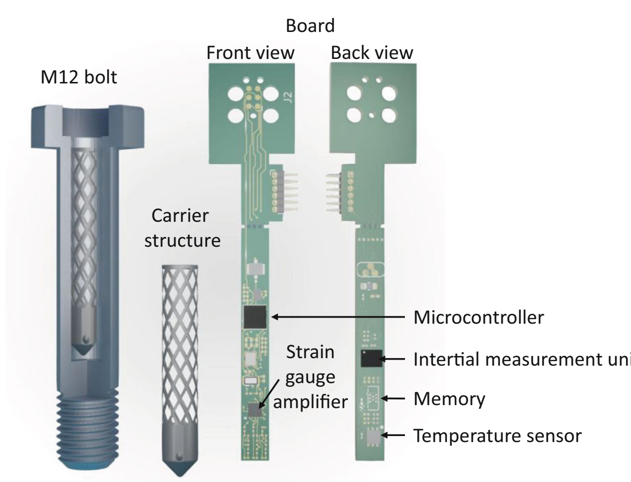


Fig. 10 Concept of the prototype of the sensor system of a sensor-integrating bolt

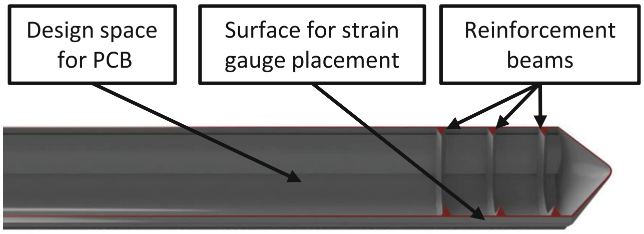


Fig. 11 Sectional view of the carrier structure

the cavity is thicker than in conventional strain gauges' applications, but the increased bonding length compensates for this, ensuring strong adhesion and durability.

Design space is reserved inside the carrier structure for the integration of essential electronics from Sect. 4.2 such as a circuit board and an energy source, enabling advanced data processing and power supply for the embedded strain gauges (Fig. 11).

5 Verification and validation

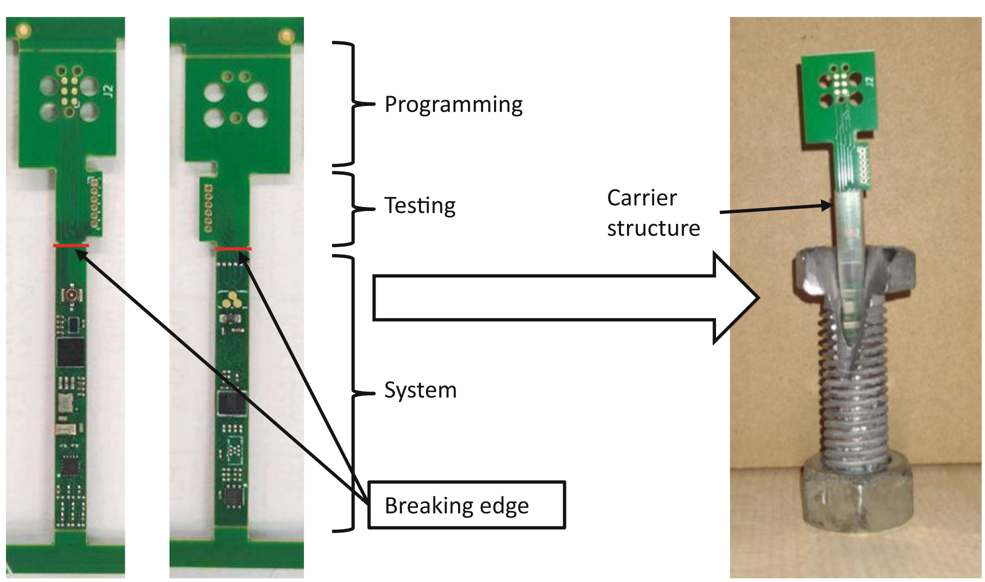
The validation activities are divided into the three sections. In Sect. 5.1, the configuration of sensor systems for sensor-integrating bolts based on the MBK modelled in SysML is validated. Section 5.2 shows the manufacture and testing of the developed microelectronic system. In Sect. 5.3 the final SiME is presented and tested in the application environment. Finally, in Sect. 5.4 the hypotheses stated in Sect. 3.1 are discussed.

5.1 Validation of the model-based MBK and the sensor system configurator

To verify the configuration process and validate the model-based MBK, including the configuration system, different sensor systems are generated for two different use cases and two usage scenarios. On the one hand in the static and dynamic application and on the other hand with self-sufficient energy supply compared to a lifetime memory as defined in the TEV in Fig. 5. The input data is implemented in SysML for this purpose. This includes i.e. the database of the microelectronic components and the system structure, which can be entered in the form of the CND.

The database and the relationships between data (e.g. properties—components) are exported from SysML to be available for the configuration process. Following the generic configuration process (see Fig. 7), the Python software is executed and the component database is read. The entries can be made step by step in the GUI. The entire configuration process in the GUI can be comprehended in Fig. 19 in the appendix. First, the ME is selected. Calculation rules can be stored for each ME. In the next window, the parameters for the ME for sensor integration, in this case for the bolts, are entered. The available space and the maximum load are calculated directly in the program. In the next step, the user can select the required system properties. Check boxes and drop-down menus are available for selection. Boundary conditions can be set using the system filter in the next window. Minimum and maximum temperatures, maximum acceleration values and a selection of intersection points are currently defined. Other filters can be added in the future. The optimisation parameters are selected before configuration begins. From the large number of possible system combinations, those are prioritised according to the dimension selected in the CVV, e.g. the

Fig. 12 Prototype of the sensor system of a sensor-integrating bolt



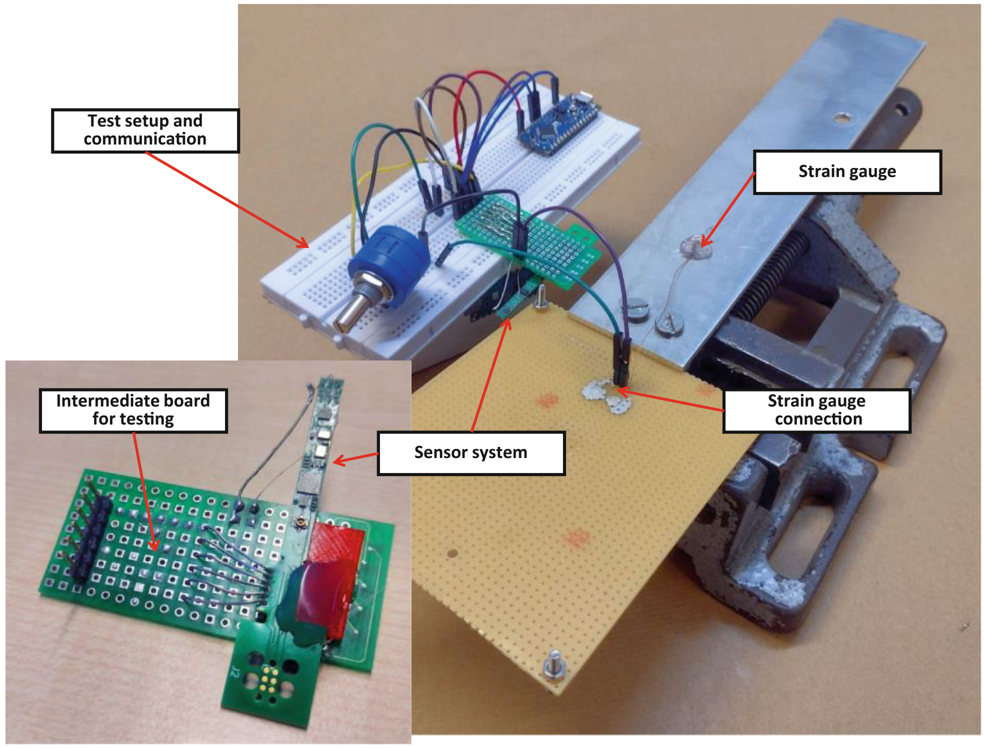


Fig. 13 Setup for programming and testing the system functions

best five. The best system configurations for two variants in terms of volume optimisation are shown in Fig. 20 in the appendix. Following the Dijkstra algorithm, each generic component from the MIG is assigned a volume-optimised and compatible specific component and is evaluated in terms of its total volume. Concept 1 has two batteries that act as lifetime storage. In concept 2 energy is generated via a vibration-based energy harvesting system. To enable a multidimensional evaluation, the configuration algorithm must be expanded to include additional dimensions such as optimum energy consumption or fast data processing.

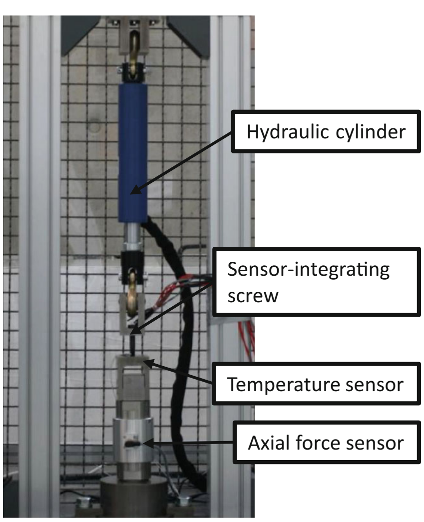


Fig. 14 Structure of the test bench

5.2 Validation of the microelectronic system design

The fabricated system shown in Fig. 12 (left) has two additional sections for testing and programming. Right at the beginning, H3 and H4 are partially verified as shown in Fig. 12 (right). The space-optimised strategy is applicable for the selection of components by the configurator, since the created system, which is only 4 mm wide, fits perfectly into the carrier structure.

For further testing, the setup shown in Fig. 13 was created and the microcontroller was programmed. An intermediate board is prepared to simplify the connection to an single-board microcontroller and the strain gauges. For this, an Arduino Nano Every microcontroller was used which acts as a serial communication bridge allowing to transfer the data to a computer. On the I2C communication bus the sensor system plays the main role and is defined as the master and the single-board microcontroller as the slave simulates the communication module that will be exchanged with a wireless connection. A more robust connection between the board and the strain gauges is realised by using jumper wires. This avoids soldering each time a reconnection is required, as the signal input pins on the board and the wire of the strain gauges itself are too small and therefore very fragile. Furthermore, this setup allows easy access for preconditioning the operating modes with an externally connected reference voltage and connection to external measurement equipment.

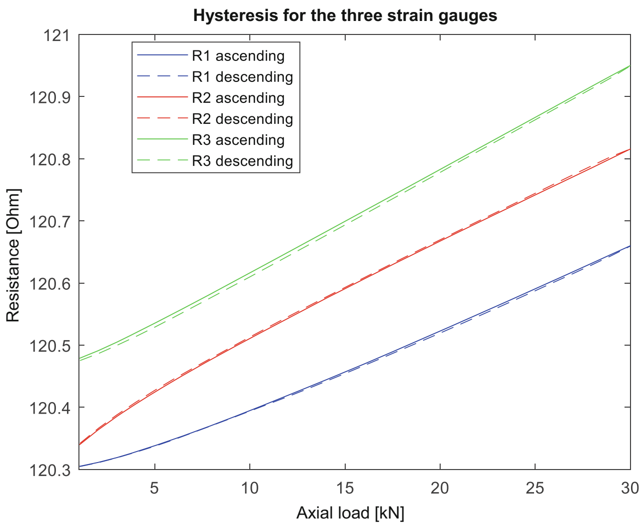


Fig. 15 Measurement behaviour of the strain gauges R1, R2, R3

The post-processing of the data is done in Matlab. A script establishes the serial communication to the single-board microcontroller, which is connected via USB, reads the data, processes it and then visualises it. The applied sensors are the STTS22HTR and the LSM6DSLTR, both from STMicroelectronics, as well as the BTM-1C from Althen Sensors and Controls. The STTS22HTR is a digital temperature sensor that has an accuracy of 0.5 °C and a range of –10 °C to +60 °C. The LSM6DSLTR is a digital IMU containing an accelerometer capable of measuring ranges of ± 2, ± 4, ± 8, and ± 16 g with respective resolutions of 0.061, 0.122, 0.244, and 0.488 mg/bit, as well as a gyroscope capable of measuring ranges of ± 125, ± 250, ± 500, ± 1000, and ±2000 dps with respective resolutions of 4.375, 8.75, 17.5, 35, and 70 mdps/bit. All digital sensors are factory calibrated, tested, and trimmed. The BTM-1C is a 120-ohm strain gauge that measures only 1 by 0.7 millimeters. However, its encapsulation measures 5.6 mm by 1.4 mm. To operate it, an analog-to-digital converter is needed to read the measurement. The microcontroller's ADC has only a 12-bit resolution and its reference voltages are fixed in the selected package. Since the 1 Ω resistance change of the Strain Gauge, as measured by PMD, results in a 700 uV difference, which is insufficient for the ADC, the resolution can be adjusted by amplifying the signal before analog-to-digital conversion.

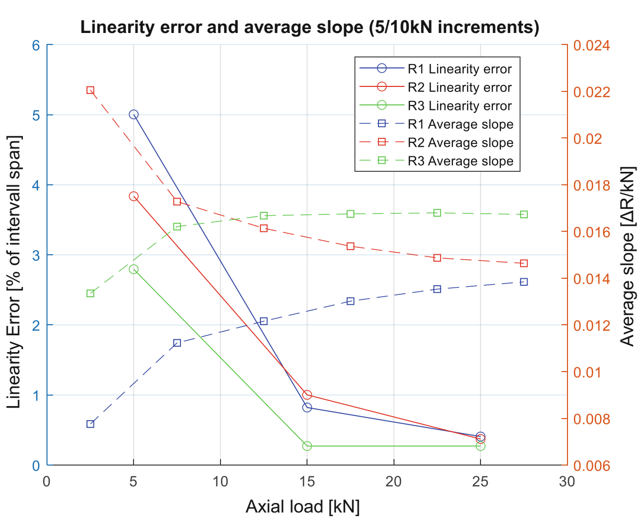


Fig. 16 Linearity error in 10 kN increments and average slope in 5 kN increments for three strain gauges respectively

As intended, the MBK demonstrates the possibility to be applied for sensor system integration into a SiME. The prototype fulfills the space requirement, fitting the electronic into a 4 mm hole and maintaining space for adjustments. The system provides access to all the senosr data, showing the data processing and transfer are working properly. While the fundamental reading of the strain gauge is operational, an additional iteration is necessary for the calibration and adjustment of the system within a test setup to ensure precise measurement. The potential for further enhancement of data optimization can be realized through the alignment of processing with specific applications. According to the datasheets, the maximum power consumption of the digital sensors and microcontroller alone is about 38 mW, while the entire system consumes 28 mW in its current, non-optimized state. This meets the energy requirement and allows for continuous operation of about 24 h with an average coin cell battery with a 200 mAh capacity.

The system has additional functions, such as wireless communication and data storage, to support further operation. In addition to application tasks, it provides greater control over data processing and can improve energy efficiency by managing the transmission of collected data or the operation modes of system components. Further enhancement is carried out through skilled programming and proper processing on the microcontroller.

5.3 Test environment and test results of the integrated strain gauges

In order to test the function of the axial force measurement of the strain gauges deployed in the bolt, a test rig is developed, shown in Fig. 14. Given the fact, that the system is not being developed for a specific use case, the investigation does not addres specific requirements which are to be met but rather investigates the potentials of the technology. This test rig applies axial force on the bolt by means of a hydraulic cylinder. The amount of axial force applied is measured using a force sensor in series, ZK2B50k-S2 by Althen. The measured values of the strain gauges, installed in the sensor-integrating bolt and the measured values of the force sensor are recorded using the data acquisition system

Quantum-X from HBM. In order to avoid temperature-dependent behaviour of the strain gauges, a temperature sensor is additionally placed in the measuring chamber. The developed test rig is used to test the function of the axial force measurement of the sensor-integrating bolt. This involves testing the hysteresis properties and linearity properties of the connection of the strain gauges to the bolt via the support structures. To measure the linearity and hysteresis properties, an axial force of 0 to 30 kN is applied to the sensor-integrating bolt to measure the linearity and hysteresis properties. Within this range, measuring points are analysed in 1 kN increments. In each of the ten cycles, the load is increased and decreased in these exact 1 kN increments between 0 and 30 kN. Figure 15 shows the results of these experiments. For the graph the results for the resistance measurement were averaged for each invidual measurement point for the load-increasing or load-decreasing half-cycle. The standard deviation of the individual averages is included in neither the graphic nor the evaluation of the hysteresis. This is due to the fact that the expected accuracy is evaluated for the assessment of hysteresis. Therefore, the evaluation is based on mean values and the standard deviation of the mean values is disregarded. This procedure is valid, as the standard deviation over the entire experiment is significantly smaller than the deviation between the subcurves of the hysteresis curve.

As can be seen from the graphs in Figs. 15 and 16, the behaviour of the measurement curves in the force range up to 10 kN cannot be assumed to be linear. However, the measurement curve in the force range from 10–30 kN is more linear, as can be seen from a decrease in the linearity error in the intervalls between 10 and 30 kN as well as the convergence of the slope in Fig. 16. As the higher force range can be assumed to be more important for the application of bolts, this is an acceptable system behaviour. In Fig. 15 the solid line represents the section of the measurement curve with increasing force, the dashed line the section of the curve with decreasing force. However, the hysteresis behaviour, displayed in Fig. 17, shows that the hysteresis is actually below 0.5 kN for the entire range of axial force and even under 300 N for higher axial forces. That means that the hysteresis is lower than one percent of the maximal axial force.

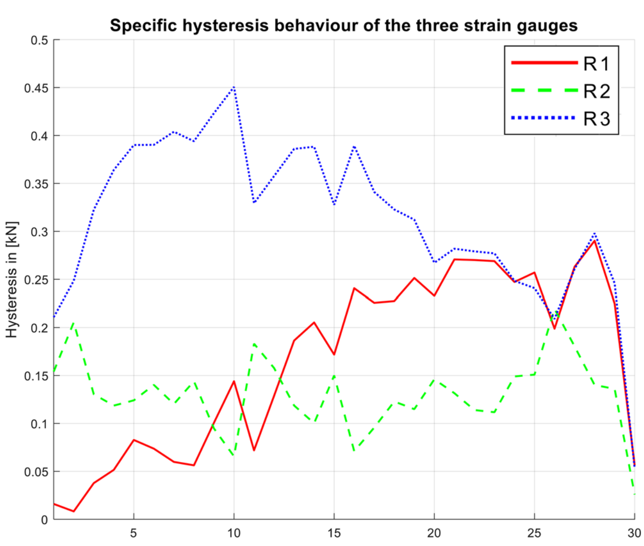


Fig. 17 Hysteresis behaviour for the three strain gauges

5.4 Discussion of the measurement results

The results of the measurements obtained show good characteristics with regard to the hysteresis and linearity of the measuring system developed. Nevertheless, the measurement results obtained are not generally meaningful due to the limited investigations. Only bolts of a single bolt size and a single bolt material were analysed. Similarly, only one bolt design with shaft was analysed. In addition, the tests were only carried out under controlled conditions, meaning that the evaluation of the measurement results cannot be transferred to real-life use. Further tests are therefore necessary for a more in-depth evaluation of the measuring system. For example, the dimensions of the bolt and its strength class must be varied. The latter in particular is of great importance for the investigation of the measuring system, as this increases the deformations occurring in the elastic load range of the bolt, which must be recorded by the strain gauges. Temperature measurement technology must also be integrated into the bolt in order to compensate for the temperature-induced expansions that occur in the real application. This extended measurement system must also be evaluated. However, use in bolts of other designs is only possible to a limited extent. This is because the strain gauges must be positioned between the last thread and the bolt head for this measuring method to be used. The geometry of the bolt head can therefore be changed, but a shaft must be present in the bolt.

5.5 Concerning the hypotheses

As a result of the study, the formulated hypotheses (H1–H5) could be tested and partially confirmed or refuted. It could be shown that the requirements for the mechanical and electronic functionality (especially the sensory system) could be used as module drivers, taking into account boundary conditions from application and environmental conditions (H1). It was possible to translate requirements into module drivers and characteristics and assign them to mechanical and microelectronic components so that meaningful modules could be formed. This was realised in the form of network diagrams which were implemented in SysML in order to analyse and document the module structures of sensor-integrating bolts, gears, couplings and feather keys [13].

The compatibility of microelectronic components and their functional fulfilment could be partially assessed a priori (H2). By assigning product properties to product functions and linking them to the corresponding function-fulfilling components in the feature allocation model, the functionality of the components and modules is taken into account when selecting a product property during the configuration process. The compatibility of the individual components could be checked prior to development on the basis of interfaces and voltage levels, among other things. However, not all compatibility conditions were taken into account, meaning that a subsequent check must be carried out for some conditions (e.g. number of slots on the microcontroller for microelectronic devices). These conditions can still be integrated into the modular system. As more knowledge is gained about the relevant features of SiME, further compatibility conditions could be identified.

Data, energy and installation space are the three critical variables in the development of SiME and should therefore be taken into account for an effective configuration (H3). A space-optimised strategy is valuable for the miniaturisation of microelectronic systems for small SiME. It was shown that this strategy could be successfully implemented. The energy aspects can also be evaluated on the basis of the system configurations by means of a performance assessment and is suitable for providing meaningful support for various applications. A data-optimised strategy is considered useful, but is the most difficult to implement because it depends on the application, the selected components and, above all, the measurement and data processing strategy.

The modules configured for a SiME can be tested individually before the final installation and their behaviour predicted in the configuration can thus be verified (H4). On the one hand, this shows that the system behaviour predicted in the configurator can be trusted. It also means that the SiME can be split into modules and interfaces, which are then specified independently.

It was shown that the configuration of sensor systems can be deliberately supported though Design for Variety and modularisation of the sensor systems for SiME. It was also shown that the procedure can be generally transferred to other SiME (H5) and that knowledge about the relevant product properties and modularisation of different SiME can be created (cf. [13]). The development data was successfully implemented in SysML so that sensor systems can also be configured for other SiME.

6 Conclusion and outlook

The development of SiME as part of the SPP 2305 poses new challenges for product development. In addition to maintaining the primary function of conventional ME, data management and energy self-sufficiency are special requirements that need to be taken into account. In order to counter the complexity in product and development, sensor systems were methodically developed and broken down into requirement-orientated modules. The development models have been implemented in SysML and serve as a knowledge-base for further developments. The model-based MBK now allows for application-specific configuration of sensor systems for SiME with optimising towards volume and energy sufficiency. Optimal configurations can be chosen and then be further developed and prototypically realised. This was demonstrated on the example of a sensor-integrating bolt within this study.

During the development of the sensor-integrating bolt prototype, it was shown that sufficient installation space can be freed in a bolt for the integration of sensor technology without restricting its primary function. Subsequently, a carrier structure was developed that allows for the placement of strain gauges inside the sensor-integrating bolt whilst taking up minimal design space. Finally, it was shown that measurement data of high quality can be taken using the aforementioned design solution. Hence, the design process using the MBK was validated as well as the specific design, developed for the prototype. However, the limited linearity of the sensor system poses a significant challenge to its application which needs to be addressed in future research.

The electronic system has shown that it can rely on the data from the configuration of the module sets based on parameter research and aggregation in the database and selected by mapping predefined requirements on it. In addition, the system provides reliable measurement output and its potential is not even fully exploited, including features for optimisation of energy consumption and wireless functions. The next steps will therefore focus on these optimisations for the realisation of a fully self-sufficient system.

For ongoing studies it is planned to expand the requirements towards complete energy autonomy of SiME with methods of energy harvesting and wireless data transfer concepts. The sensor systems should also allow for software updates and consider the future integration into larger SiME networks. The model-based MBK should be extended in a way that it can derive necessary test protocols for the verification of the systems functionality on the different integration levels. Also, other SiME should be considered so that the SysML are extended and the configuration software can be validated for further use cases.

7 Appendix

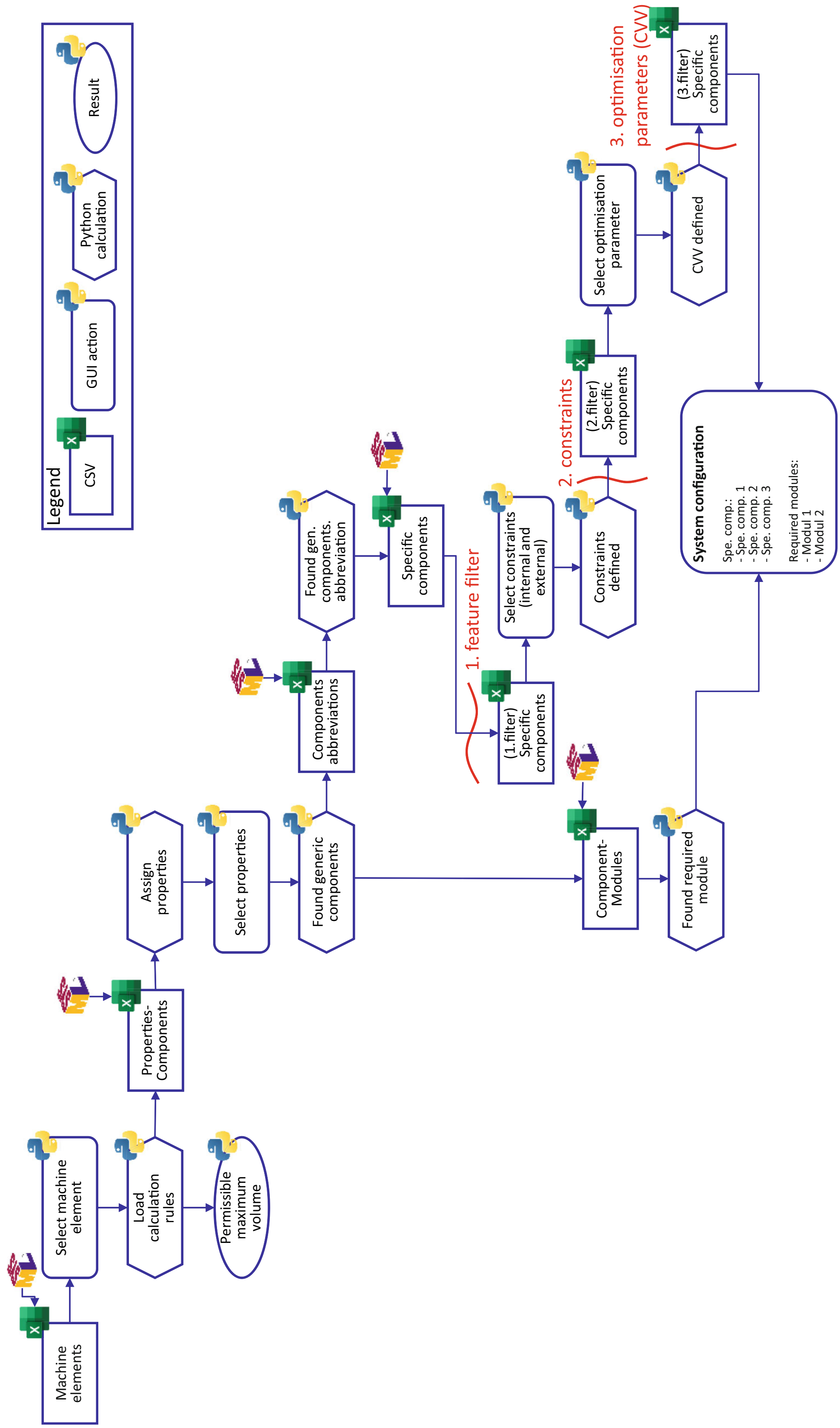


Fig. 18 Flowchart of the SiME Configurator

Fig. 19 GUI of the SiME Configurator

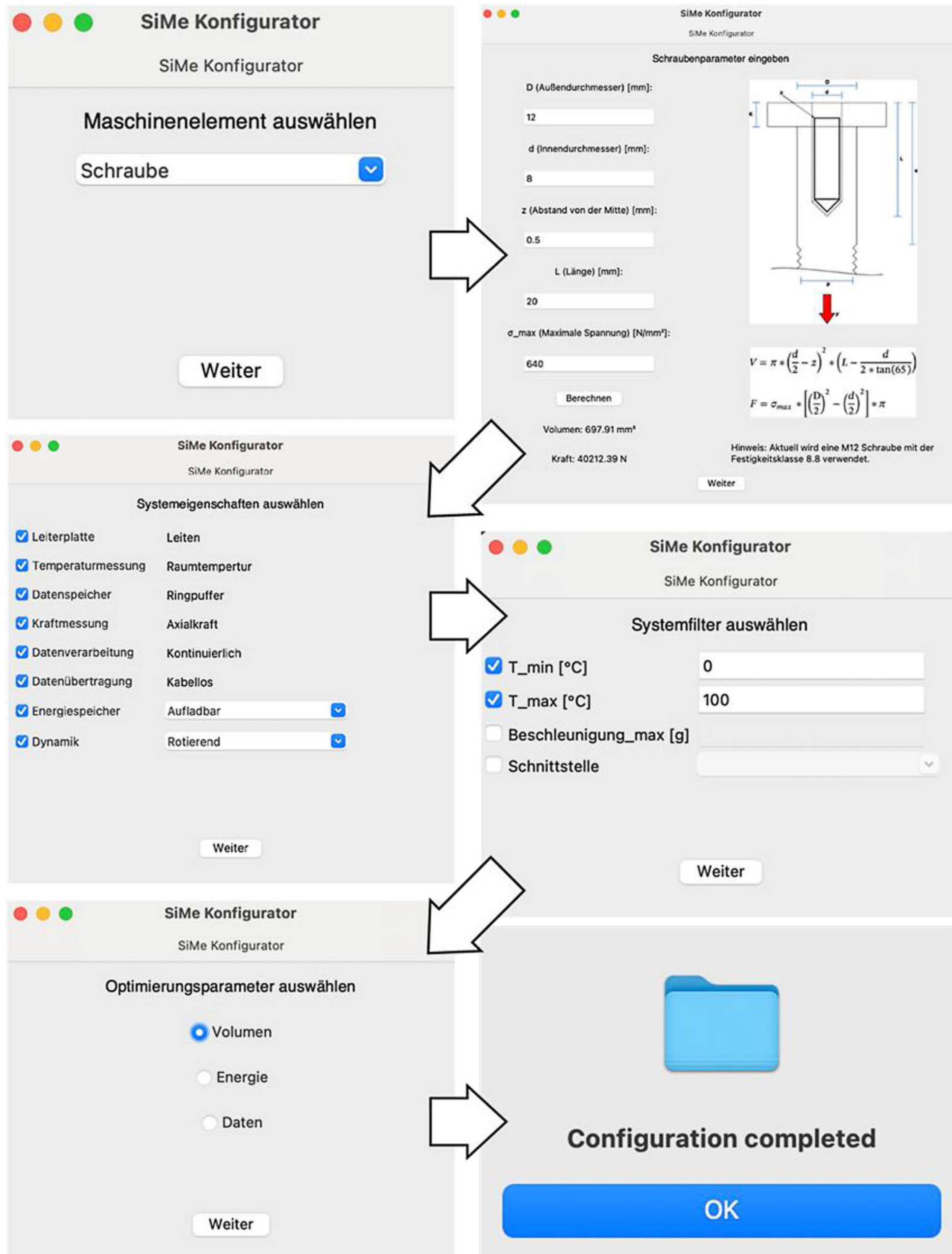


Fig. 20 Sensor system configurations optimised for installation space

Generic components	Configuration 1	Generic components	Configuration 1
Volume	104,525 / 134,925	**Volume**	104,525 / 134,925
Printed circuit board (data module)	PLA2	**Printed circuit board (data module)**	PLA2
Details	MIG: PLA Umin: 1.7, Umax: 3.6 Interface: I2C, SPI, I2S, USART Tmin: -30, Tmax: 120	**Details**	MIG: PLA Umin: 1.7, Umax: 3.6 Interface: I2C, SPI, I2S, USART Tmin: -30, Tmax: 120
Data storage (data module)	24CW16X	**Data storage (data module)**	24CW16X
Details	MIG: SPE Umin: 1.6, Umax: 5.5 Interface: I2C Tmin: -40, Tmax: 125	**Details**	MIG: SPE Umin: 1.6, Umax: 5.5 Interface: I2C Tmin: -40, Tmax: 125
Mikrocontroller (Datenmodul)	STM32F205RE	**Microcontroller (data module)**	STM32F205RE
Details	MIG: MCO Umin: 1.8, Umax: 3.6 Interface: I2C, SPI, I2S, CAN(2.0), USART, UART Tmin: -40, Tmax: 105	**Details**	MIG: MCO Umin: 1.8, Umax: 3.6 Interface: I2C, SPI, I2S, CAN(2.0), USART, UART Tmin: -40, Tmax: 105
Datenübertragung (Datenmodul)	DAT2	**Data transmission (data module)**	DAT2
Details	MIG: DAT Umin: 1.7, Umax: 3.6 Interface: I2C, SPI, I2S, USART Tmin: -30, Tmax: 120	**Details**	MIG: DAT Umin: 1.7, Umax: 3.6 Interface: I2C, SPI, I2S, USART Tmin: -30, Tmax: 120
Energy management system (energy module)	PMC2	**Energy management system (energy module)**	PMC2
Details	MIG: PMC Umin: 1.7, Umax: 3.6 Interface: I2C, SPI, I2S, USART Tmin: -30, Tmax: 120	**Details**	MIG: PMC Umin: 1.7, Umax: 3.6 Interface: I2C, SPI, I2S, USART Tmin: -30, Tmax: 120
Energy storage (energy module)	BAT2	**Energy harvester (energy module)**	ENE2
Details	MIG: ENS Umin: 1.7, Umax: 3.6 Interface: I2C, SPI, I2S, USART Tmin: -30, Tmax: 120	**Details**	MIG: ENE Umin: 1.7, Umax: 3.6 Interface: I2C, SPI, I2S, USART Tmin: -30, Tmax: 120
Energy storage 2 (energy module)	BAT2	**Energy storage (energy module)**	BAT2
Details	MIG: ENS Umin: 1.7, Umax: 3.6 Interface: I2C, SPI, I2S, USART Tmin: -30, Tmax: 120	**Details**	MIG: ENS Umin: 1.7, Umax: 3.6 Interface: I2C, SPI, I2S, USART Tmin: -30, Tmax: 120
Acceleration sensor (BWS/BFS measuring module)	asm330lhhx	**Acceleration sensor (BWS/BFS measuring module)**	asm330lhhx
Details	MIG: BES,GYS,TES, MCO Umin: 1.71, Umax: 3.6 Interface: I2C, MIPI, SPI Tmin: -40, Tmax: 105	**Details**	MIG: BES,GYS,TES, MCO Umin: 1.71, Umax: 3.6 Interface: I2C, MIPI, SPI Tmin: -40, Tmax: 105
Temperature sensor (BWS/BFS measuring module)	STTS751	**Temperature sensor (BWS/BFS measuring module)**	STTS751
Details	MIG: TES Umin: 2.25, Umax: 3.6 Interface: I2C, SMBus Tmin: -40, Tmax: 125	**Details**	MIG: TES Umin: 2.25, Umax: 3.6 Interface: I2C, SMBus Tmin: -40, Tmax: 125
Force sensor (measuring module BWS/BFS)	KRS2	**Force sensor (measuring module BWS/BFS)**	KRS2
Details	MIG: KRS Umin: 1.7, Umax: 3.6 Interface: I2C, SPI, I2S, USART Tmin: -30, Tmax: 120	**Details**	MIG: KRS Umin: 1.7, Umax: 3.6 Interface: I2C, SPI, I2S, USART Tmin: -30, Tmax: 120

Funding This research was funded by the Deutsche Forschungsgemeinschaft (DFG, German Research Foundation) Project-ID 441 853410—SPP2305, as part of the projects: Project-ID 466493340, Project-ID 466653706, Project-ID 466661922, Project-ID 466657550. Responsibility for the content of the report lies with the authors.

Funding Open Access funding enabled and organized by Projekt DEAL.

Conflict of interest J. Küchenhof, R. Breimann, I. Gomberg, E. Kirchner, H.K. Trieu and D. Krause declare that they have no competing interests.

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