Forschung im Ingenieurwesen (2024) 88:40
https://doi.org/10.1007/s10010-024-00761-3

ORIGINALARBEITEN/ORIGINALS

Development of a model-based modular building kit for sensor-integrating machine elements—Theory and application

Jan Küchenhof[1] · Richard Breimann[2] · Eckhard Kirchner[2] · Ilja Gomberg[3] · Hoc Khiem Trieu[3] · Kamal Alamsha[1] · Erich Knoll[4] · Karsten Stahl[4] · Johannes Menning[5] · Thomas Wallmersperger[5] · Arthur Ewert[6] · Berthold Schlecht[6] · Artem Prokopchuk[7] · E. -F. Markus Henke[7] · Stephanie Seltmann[8] · Alexander Hasse[8] · Chen Chen[9] · Welf-Guntram Drossel[9] · Dieter Krause[1]

Received: 12 November 2023 / Accepted: 11 September 2024 / Published online: 11 November 2024

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 standardized components with integrated microelectronics. The present 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 modeling the modular building kit for SiME is presented and applied to four different cases within the project. Use cases, product structure and module diagrams were recorded and modeled for the machine elements screw, gear, coupling and feather key. These are then linked in SysML models to enable sensor systems for SiME to be configured in line with requirements. The modeling of the system architectures deepens the understanding of the underlying mechatronic system architecture and supports the identification of differentiation features as well as synergy potentials.

✉ Jan Küchenhof
jan.kuechenhof@tuhh.de

[1] Institute for Product Development and Mechanical Engineering Design (PKT), Hamburg University of Technology (TUHH), Denickestraße 17, 21073 Hamburg, Germany

[2] Institute for product development and machine elements (pmd), Technical University of Darmstadt, TU Darmstadt, 64287 Darmstadt, Germany

[3] Institute for Microsystems Technology (MST), Hamburg University of Technology (TUHH), Hamburg, Germany

[4] School of Engineering and Design, Forschungsstelle für Zahnräder und Getriebesysteme (FZG), Technical University of Munich (TUM), 85748 Garching, Germany

[5] Institute of Solid Mechanics, Technical University Dresden, TU Dresden, 01187 Dresden, Germany

[6] Institute of Machine Elements and Machine Design, Technical University Dresden, TU Dresden, 01187 Dresden, Germany

[7] Institute of Semiconductors and Microsystems, Technical University Dresden, TU Dresden, 01187 Dresden, Germany

[8] Machine Elements and Product Development, University of Technology Chemnitz, TU Chemnitz, 09111 Chemnitz, Germany

[9] Adaptronics and Lightweight Design, University of Technology Chemnitz, TU Chemnitz, 09111 Chemnitz, Germany

Entwicklung eines modellbasierten Modulbaukastens für Sensorintegrierende Maschinenelemente – Theorie und Anwendung

Zusammenfassung

Im Schwerpunktprogramm (SPP) 2305 der Deutschen Forschungsgemeinschaft sollen so genannte Sensor-integrierende Maschinenelemente entwickelt werden. Dabei handelt es sich im Wesentlichen um hochstandardisierte Bauteile mit integrierter Mikroelektronik. Der vorliegende Beitrag stellt die Entwicklung eines modellbasierten Modulbaukastens zur Unterstützung des Entwurfs integrierter Sensorsysteme für diese neuen Maschinenelemente vor. Es wird ein methodisches Vorgehen zur Erhebung der für die Modellierung des Baukastens erforderlichen Entwicklungsdaten vorgestellt und auf vier verschiedene Fälle innerhalb des SPP angewendet. Für die Maschinenelemente Schraube, Zahnrad, Kupplung und Passfeder wurden Anwendungsfälle, Produktstruktur- und Moduldiagramme erfasst und modelliert. Diese wurden in SysML-Modellen verknüpft, um Sensorsysteme anforderungsgerecht konfigurieren zu können. Die Modellierung der Systemarchitekturen vertieft das Verständnis für die zugrundeliegende mechatronische Systemarchitektur und unterstützt die Identifikation von Differenzierungsmerkmalen sowie Synergiepotenzialen.

1 Motivation: high variety, complex systems and modularization

Machine elements (ME) such as screws, bearings or shaft couplings are basic design elements in mechanical constructions and are often available as purchased parts [4, 21]. They fulfill the same function in different machines, are highly standardized, and often normed across various ranges [4, 21]. By integrating electronic sub-functions into conventional ME, within the *Priority Program* 2305 of the *German Research Foundation* (DFG) these are to be developed into *Sensor-integrating Machine Elements* (SiME) [21]. As pioneers of large-scale digitization, SiME will be able to specifically record and process high-quality data in process-related areas in order to draw conclusions about the behavior and condition of machines and systems. 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 modularization and system development are suitable [24, 43]. Modular product structuring is particularly suitable for dealing with variance-induced complexity [24]. In combination with approaches of mechatronic system development, the product development process of SiME could be adequately supported considering complexity and interdisciplinarity. So far, to the best of the authors' knowledge however, there are no approaches that take both aspects into account at the same time and adequately consider the restrictions of SiME. The known developments tend to be individual solutions at the research level [21]. A practical, sustainable approach aimed at a modular design of SiME is lacking [21]. In this contribution, a method for the development of SiME is presented, which results in a *Modular Building Kit* (MBK) for sensor systems for SiME. The basics of modularization and model-based modeling of technical systems and products are presented in *Sect. 2*. In *Sect. 3*, these are linked in order to build the basic structure of the MBK. In *Sect. 4*, the modular toolbox is filled with the data. To fill the MBK, relevant development data of the SiME *Sensor-integrating Screws, Gear, Feather key,* and *Coupling* were captured. The use cases are evaluated and compared with each other to identify similarities and differences between the applications considered here. The use cases and module structures were then modeled and mapped in SysML in order to document the development data and prepare for the downstream automated configuration of the suitable sensor systems. The contribution ends with a summary and outlook in *Sect. 5*.

2 Research background

In the following, SiME are introduced as complex mechatronic systems and methods for the development of such systems are presented. Fundamentals of systems engineering and modeling of modular product architectures are described in order to model complex systems and integrate them into a model-based MBK.

2.1 Sensor-integrating machine elements

According to Kirchner et al. SiME are ME with integrated sensory functions [21]. They are highly integrated mechatronic systems and need to be designed for use in a wide range of advanced and complex systems and applications [21]. SiME are characterized by the fact that the measured variables are directly related to the primary function of the ME [41], for example via the integrated strain-variable resistance as in strain gauges [34]. By integrating sensory functions into the ME, the ME becomes the integrator of the sensor, hence the term sensor-integrating is used [Vor 2020]. Examples of SiME include a force-measuring fastening screw in which an integrated piezoelectric element detects dynamic changes in the length of the screw and thus changes in the operating force [18]. Another example is a sensor-integrating toothed belt with integrated acceleration measurement that uses resonant frequencies to provide information about the applied belt pretensioning force [19]. The main difference between SiME and individual industrial solutions with applied measurement technology is the complete integration of the sensor technology and, as far as possible, of the energy and data transfer into the ME. For example, the application of a strain gauge to the timing belt affects its outer geometry [23], whereas the shape of the sensor-integrating timing belt [19] is identical to that of the conventional ME. The classification of SiME can be based on the sensor output or the functional structure of the sensor and the way of integration in the ME [39]. A further differentiation into sensory usable and sensory utilizable ME is also possible [21, 41]. Major challenges in the development of SiME are the weakening of the ME due to the cavities created for the integration of the sensor system [5], data transmission in metallic environments and the power supply, which ideally are fulfil the requirements of autonomy in the application environment [6, 21]. SiME can be understood as mechatronic systems with different hierarchy levels embedded in different environments on which they interact [25]. Modularization can leverage the use of parts of the system within the same hierarchy level or across different hierarchy levels. This requires the identification of case-specific requirements and a suitable parameterization [25]. For modularization of SiME, a design method for the consideration of disturbance factors for the using the example of a sensor-integrating timing belt, is given in [7]. Further preliminary work for the SiME under consideration (Screw, Gear, Coupling and Feather Key) is provided in the respective use case in *Sect. 4*.

2.2 Development of mechatronic systems

The increasing relevance of digitization and the focus on interdisciplinary collaboration imply a special challenge for the product development process. Inconsistencies and a lack of communication result not only in unused synergies but also in errors in the final products [20]. The combination of the classical disciplines of Mechanical Engineering, Electrical Engineering and Information Technology require a holistic view of the systems to be developed. In order to enable a systematic design process of mechatronic systems with a high integration density, the so-called multidisciplinary integrated design is required. The design methodology for mechatronic systems according to the VDI 2206 addresses this problem and methodically supports the product development process by stepwise decomposition and recomposition of the system and its subsystems with help of the V-model [42]. Iterations can reduce the development risk, e.g. safety-critical systems can be processed iteratively before continuing with the development of higher-level system [2]. An extension of the V-model considers the architecture design of cyber-physical systems and products [26]. The system design is broken down into a property, a functional and a component domain which are then modeled. The iterative design of mechatronic modules with regard to the development disciplines involved is a particular challenge that can be addressed with the use of adequate development methods [2, 30, 44].

2.3 Systems engineering for modeling complex systems

For the design of a mechatronic system architecture and the holistic system modeling and synthesis, systems engineering is regarded as a suitable integrative method [1]. This integration can be achieved by means of a data management system which can be realized by a model-based approach [2]. The data elements of the requirements, functions and the physical structure can be modeled separately and independently of the discipline and then transferred into an overall model [30]. To organize the design activities of different disciplines and to achieve multidisciplinary integrated design, Zheng et al. propose a design methodology based on a multidisciplinary interface model to ensure consistency and traceability between micro and macro levels [43]. Consistent with systems engineering, an extended V-model is used as the macro-level process and a hierarchical design model is used as the micro-level process in the proposed design methodology. The methodological procedure starts with the identification of the requirements for the overall system and ends with a user-validated system [43]. Early analyses enable early verification of the mechatronic partial solutions. Systems engineering can contribute to that and serve as a basis for the development of intelligent technical systems [14]. Also based on the V-model, Vazquez-Santacruz et al. present an MBSE methodology that serves as a guideline for mechatronic design by means of SysML modeling capabilities [40]. They present a three-dimensional cube model with interacting V-models [40]. SysML also supports hardware and process systems, which means that model-based product development and essentially model-based systems engineering (MBSE) can be realized [38]. Along the development process, the specification, the analysis, the conceptual design as well as the verification and validation of complex systems can be supported. The semantic basis for the modeling of the requirements, the behavior, the structure, and the parametrics of systems created by the implementation of graphical elements in the form of diagrams and tables in the development process [20]. Graphical representation of e.g. use cases can lead to a better understanding of the functionality of the system to be developed. Use case diagrams allow the modeling of several application scenarios by means of appropriate behavioral abstractions [20]. Due to a high quantity of functionalities, block definition diagrams are most frequently used in SysML [20]. Blocks can be used for the description of the components and structures occurring in a system or subsystem and can be assigned various properties, such as value properties, e.g. dimensions of an existing installation space [31]. In addition to the definition of value properties, these can be restricted by constraints. For the connection of the created models, dependency matrices can be used [31]. These tools and functions can be used to implement the data for the MBK and define the ranges of the identified parameters. Kruse et al. present an approach for the identification of such parameter sets for the selection of microelectronic components for SiME on the example of sensor-integrating screws [25]. The parameter sets describe the solution space for component selection when configuring sensor systems in the modular system or in the configurator. For the MBK and the configurator itself, the method from Dambietz et al. is followed and adapted [10]. To represent a modular product architecture in SysML, properties are mapped to the product components which themselves are associated to modules creating so-called Configuration Network Diagrams (CND) [35]. In a CND, product properties are linked to components, which are then combined into modules. The product properties describe the external view of the product in terms of its functionality. When developing modular product families, the external view can be described in a tree of external variety, in which the product properties are elaborated with differentiating features. Each path in the tree of variety describes a product variant that can be selected by the customer or user [24]. In the early phase of product development, the product characteristics are usually not yet so clear. They can therefore be derived from the requirements and refined iteratively. The technical solution of a concept can be described in the form of a product structure, as is done in the module interface diagram (MIG) according to the integrated PKT approach for the development of modular product families [24]. After development, the differences in external and internal factors between different product variants can be visualized in product variety charts, such as the component commonality chart [11], to identify possible standard parts in products in early design phases.

The product architecture can be extended in terms of Product-Service-Systems by the additional mapping of dependency matrices for services [9]. Likewise, modular architectures can be described and their development can be supported by system models [3].

2.4 Research needs from the state of the art

The various areas of knowledge identified result in a gap in the current state of research. The first SiMEs have already been developed, but there is no consistent development methodology so far. The variety of solutions for specific applications and use cases results in inconsistencies in development activities and deliverables [21]. This results in specific individual solutions. Development steps are not documented in a standardized way without a larger framework. Model-based procedures, such as those found in systems engineering, are suitable for knowledge management, methodological support and maintaining data consistency. However, these are mostly applied to existing products and systems. A particular challenge with SiME is the new development part of the well-known standardized ME. The examples of mechatronic developments with MBSE found in the literature also relate to machines and systems, but not to the microelectronic level at which SiME can be found. Systems engineering methods that take up the boundary conditions of SiME and facilitate their development could not be identified.

3 Methodical development of a model-based modular kit for sensor-integrating machine elements

The development method is fundamentally based on the steps of mechatronic system development according to VDI 2206 [42] along the V-model as a macrocycle. In addition, a methodical support of the development of cyber-physical modular product architectures according to [26] is introduced. The steps are supported by MBSE, which ensures data consistency and traceable documentation, among other things. A schematic overview of how the MBK works is shown in Fig. 1. The left-hand block shows the input data. This includes system data from a database, in this case a component database with associated article numbers and other metadata such as costs, etc.. Further input data consists of development models such as use case and requirement diagrams or MIG according to [24] and a constant simulation input through a defined value vector and requirement profiles. The input data serves as input for the configuration data. Different product architectures can be implemented in SysML and configured into possible product variants using an algorithm. This can be implemented in the programming language Python, for example. A suitable product variant is then selected by evaluating it on the basis of defined performance criteria.

Figure 2 shows the overall structure of the implementation of the model-based MBK in SysML with its different

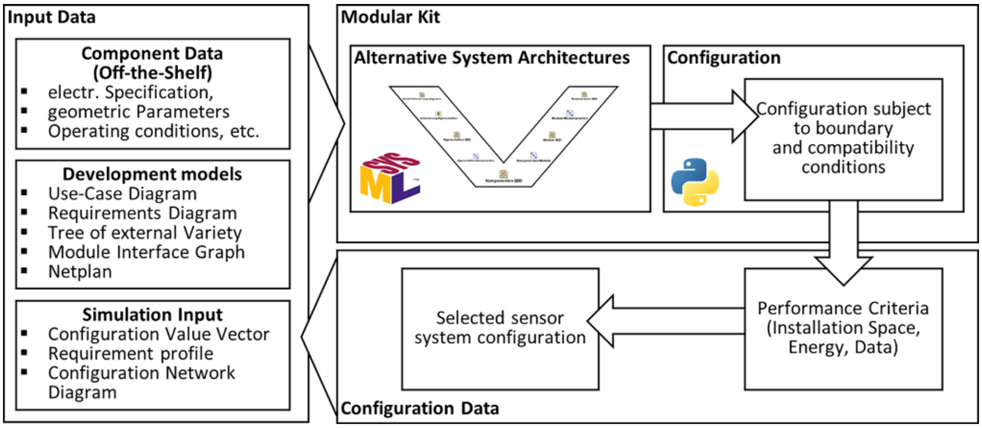


Fig. 1 Schematic overview of the structure and linking of input data and configuration data based on [10]

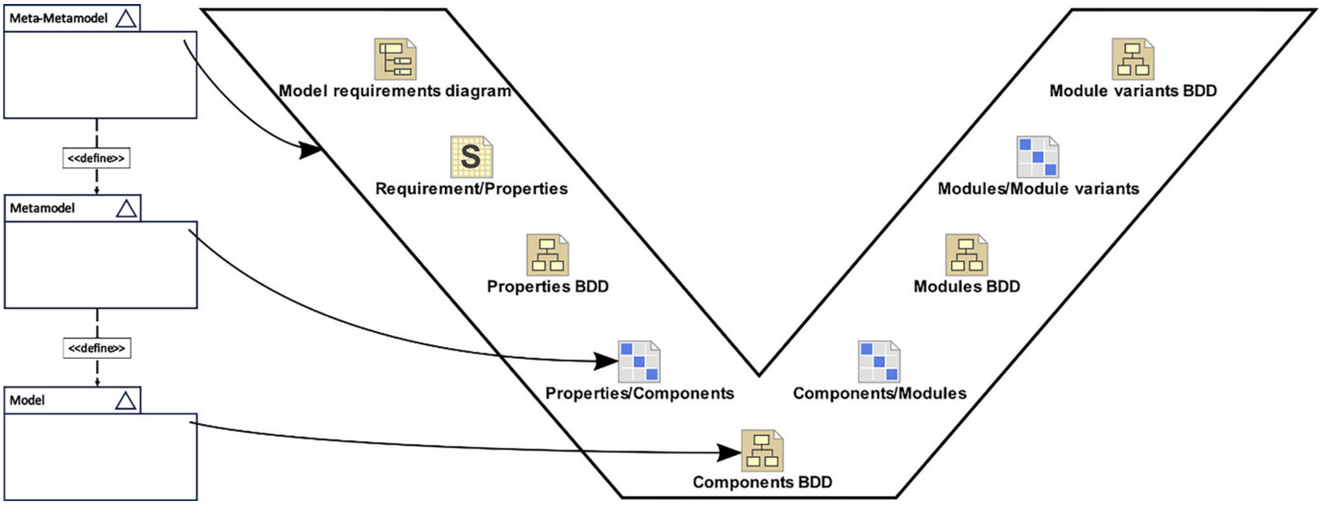


Fig. 2 Hierarchical modeling levels of the model-based *Modular Building Kit*

hierarchy levels shown on the left and the corresponding levels within the V-model in SysML on the right.

The bottom level shows the various product development models that are implemented, namely a requirements model, a property model, a component model, a use case model that links requirements and components, a model of the module structure and a module variant model. The metamodels in the form of dependency matrices are located one level higher. An example of a requirements diagram and its implementation as well as the structure of dependency matrices for requirements, properties and components can be seen in Fig. 3.

Each matrix describes the relationship between elements located in two different diagrams, which are: requirements/properties, properties/components, components/modules and modules/module variants. The V-model as a macro cycle corresponds to the meta-meta model. Via the high hierarchy meta-metamodel, the lower hierarchy level models (meta models and models) can be accessed via package diagrams (Fig. 4).

The step-by-step procedure for filling the MBK with the corresponding development data is shown in Fig. 5.

In *Step 1*, the system analysis takes place. Based on the defined use case or application, use case diagrams are created and requirements are derived and stored in requirement diagrams. The use cases represent and formalize the different application scenarios. For this purpose, the main functionalities are recorded in the form of use cases, their specializations and extensions. In addition, actors and constraints can be implemented to concretize the use case. Based on the resulting use case diagram, specific and general requirements can be derived documented in a requirement diagram in SysML. In our case, the requirements are mapped to the use case. The requirements are the basis for the product properties defined in *Step 2*, in which the associated external variety is specified. In *Step 3*, the physical system components that represent the internal variety are recorded in the form of *Module Interface Graphs* (MIG) [24]. The module structure is depicted in network diagrams [24] in *Step 4*. To extend the MBK, CNDs for *Sensor-integrating Screw, Gear, Feather key,* and *Coupling* are linked

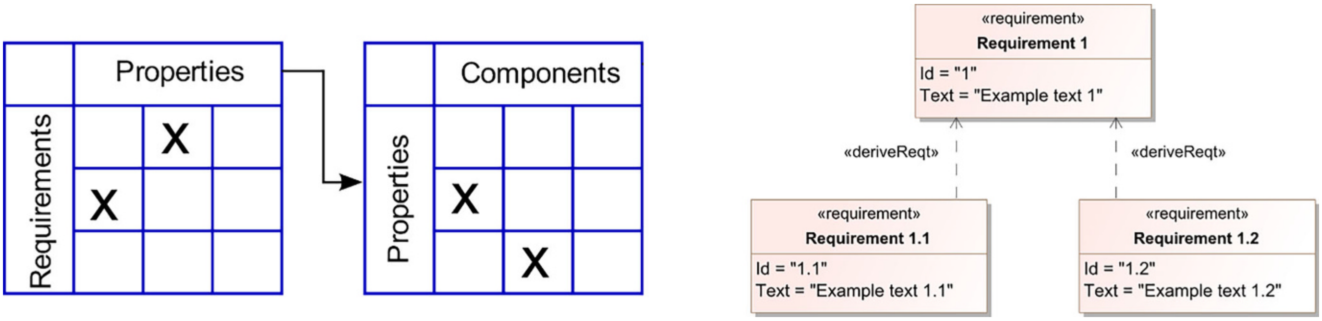


Fig. 3 Metamodeling using dependency matrices and example of a requirements model

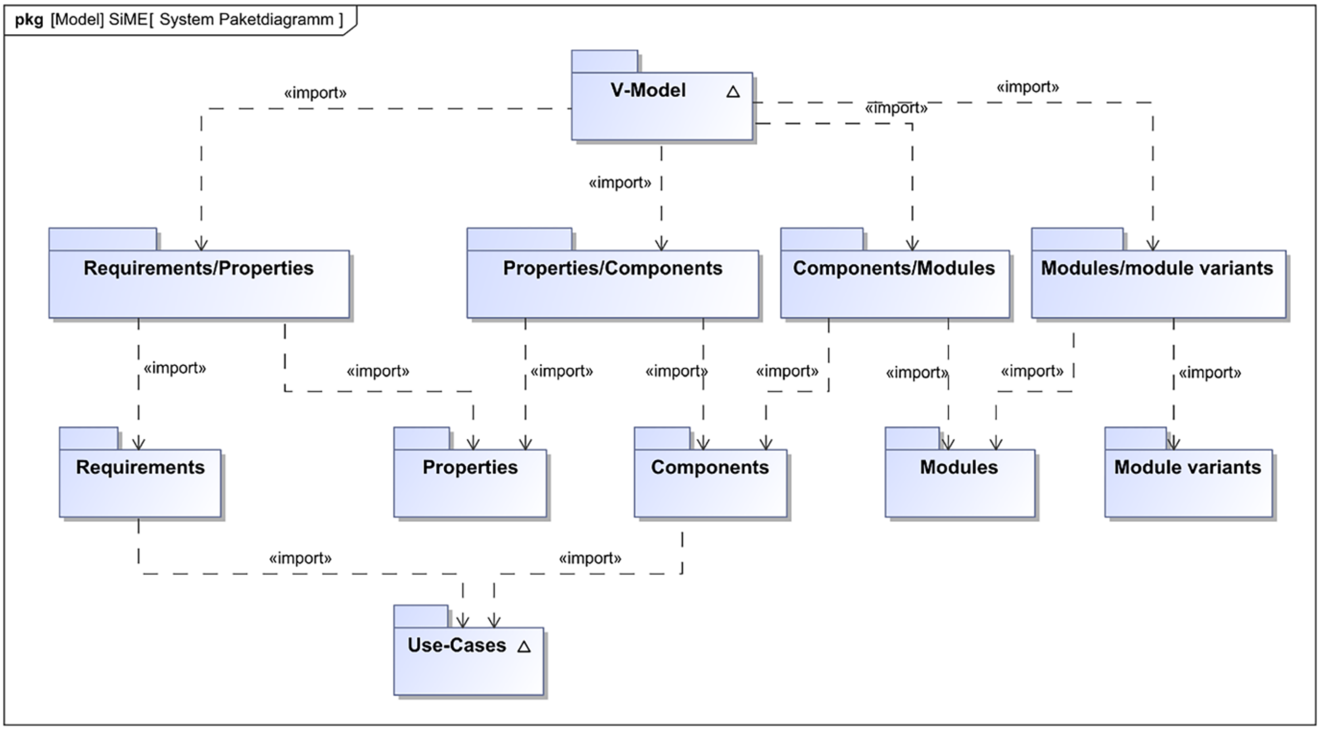


Fig. 4 Hierarchical access structure in the form of package diagrams

in *Step 5*. Finally, in *Step 6*, the different system architectures are compared with each other to identify differences and synergy potentials.

4 Use cases of the model-Based modular building kit

The integration of sensor systems in conventional ME is demonstrated for the four different development cases of screw, gear, jaw coupling and feather key. For each development case, the steps according to Fig. 5 presented in *Sect. 3* were performed and respective development models were created. In the following, the use case diagram, the MIG and the network diagram are always shown and explained. Finally, the data is implemented in the CND in the MBK. When describing the use cases and implementing the CND, each SiME is given its own color coding for better comprehensibility.

4.1 Sensor-integrating screws

Figure 15 in the *Appendix* shows the use case diagram implemented in SysML for the *Sensor-integrating Screws* (SiSc). The upper use case chain represents the application scenario, in this case a test rig that also defines the outer system boundary. Integrated into this, the use case of the SiSc is captured with its own system boundary and functionalities such as measurement task, data management and energy management. The technical components (*Actuators, Redundant sensors, Clutch* and the *Flange*) are located outside the system boundary of the use case itself. The *test*

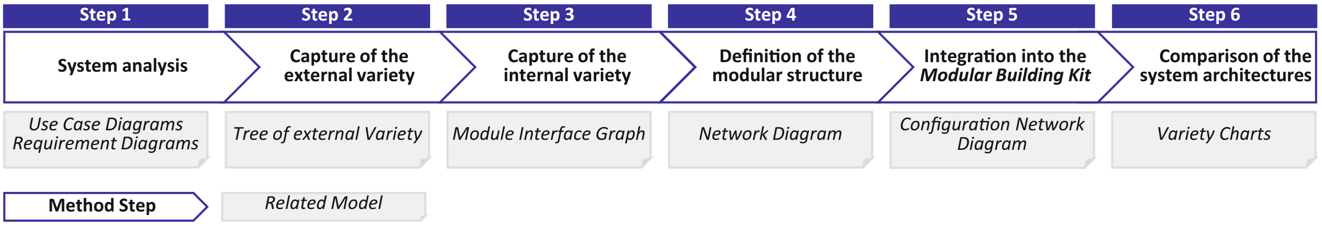


Fig. 5 Procedure for the development of the model-based *Modular Building Kit*

bench operator is shown on the left and the *data evaluator* on the right. The use case requires that the test operator first operates the test rig, calibrates the sensor system and installs the SiSc. The SiSc is represented within its own system boundary and contains all main functions, whereby two use cases are distinguished: a fixed and a moving application. In the rigid case, these are *Determine force, Determine acceleration, Determine optical signal, Determine temperature, Store energy, Store data* and *Transfer data*. The function *Determine temperature* is optional and can be performed if required. In addition, three specific functions are taken into account for the moving application with *Determine angular acceleration, Determine torque* and *Determine speed*. Within the test stand, test data is initially recorded and determined, which is hence referred to as input data. This is followed by the generation of the test variables with the aid of the actuator system and then the determination and transmission of the test and comparison data, which were recorded with the aid of the SiSc or by the redundant sensor system. The acquired output data is then compared by the data evaluator, so that the sensor systems can be verified. If measurement deviations occur, the sensor system of the test rig is recalibrated and the process described here is repeated iteratively. For a more detailed itemization of the requirements and the derivation of parameters, see [15, 25].

Figure 6 shows the MIG for the SiSc concept trying to achieve a maximum of self-sufficient energy harvesting. Orange lines represent structural connections, green lines electrical wires and pink lines data interfaces.

The basic structure consists of the screw itself, a lid and the sensor system, which is structurally connected to the screw by a housing. The sensor system consists of an energy harvesting system, which contains the largest volume fraction, an energy storage, a temperature sensor, a force sensor, an optional acceleration sensor, a speed sensor and a torque sensor, a variant data transmission unit and a printed cir-

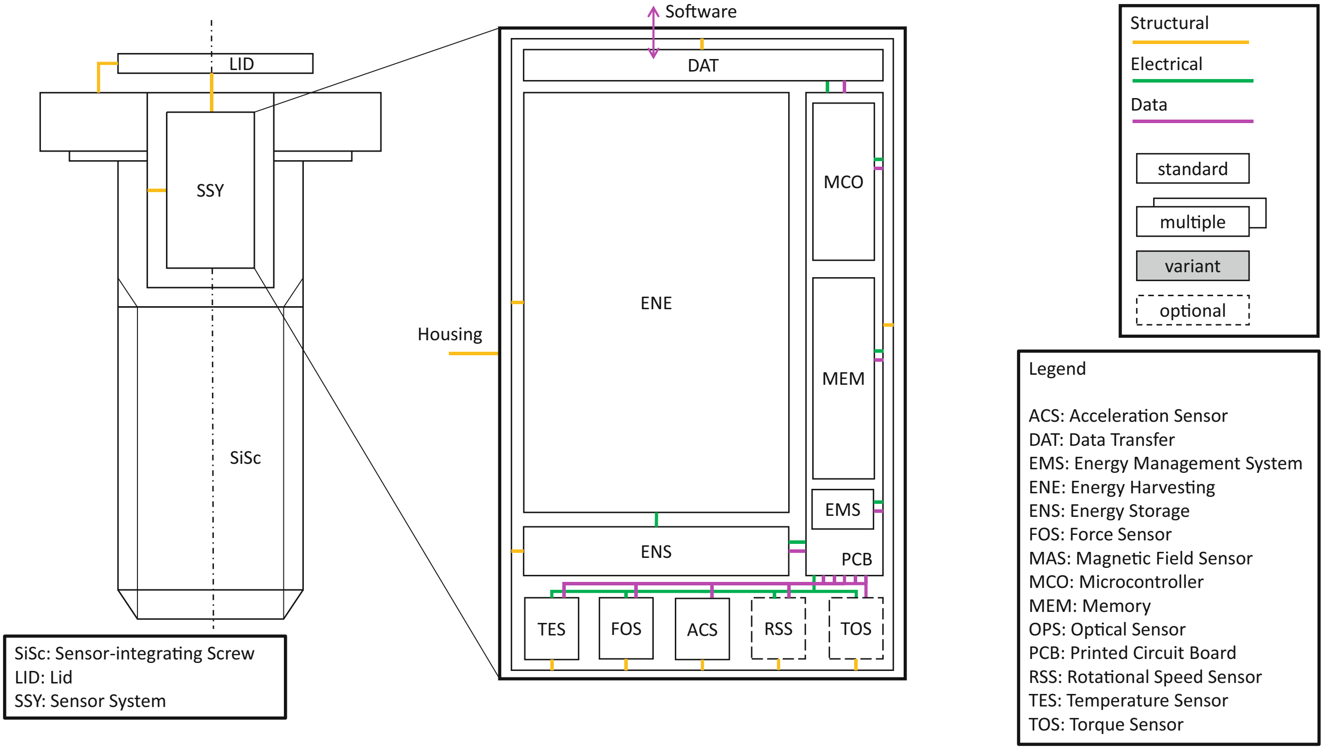


Fig. 6 *Module Interface Graph* of the *Sensor-integrating Screws*

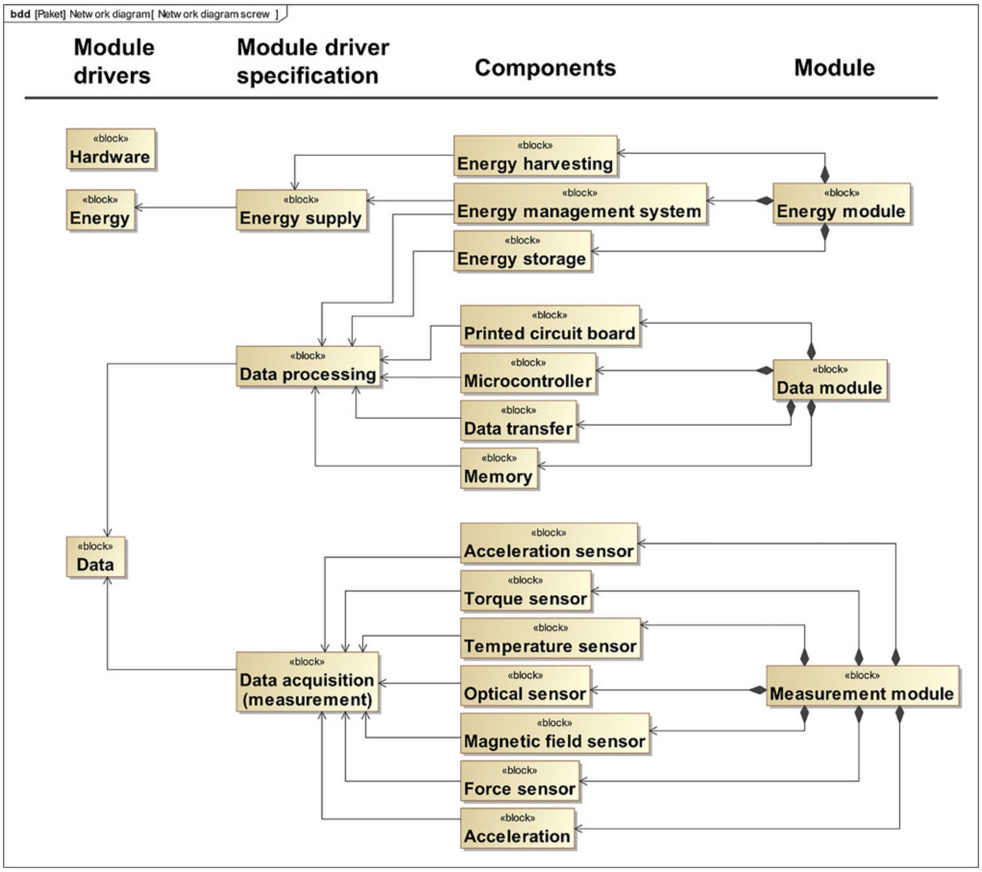


Fig. 7 Network diagram of the *Sensor-integrating Screws*

cuit board (PCB), on which a energy management system, a memory and a microcontroller are mounted [15]. All components of the sensor system which are not already attached to the PCB are structurally connected to the housing of the screw. All sensors are located below the battery and PCB, and are connected to the battery by electrical wires. The detected data is transmitted to the PCB and then transmitted outside the system via the data transmission unit and implemented software. The energy harvesting component transmits the harvested energy via an electrical connection to the battery, which in turn distributes the energy to the data transmission unit and the circuit board. In addition, data from the battery, such as the state of charge, is transmitted to the microcontroller. All components, which are located on the PCB, have electrical and data transmission. Also, the local data, like e.g. the charge state of the battery and the information to the memory status, are transmitted outside the system via the data transmission unit and the implemented software [15]. The components were then combined into modules using a network diagram, which can be seen in Fig. 7.

Energy and *Data* were selected as module drivers. The module driver *Energy* was specified as *Energy supply* and the module driver *Data* was specified as *Data processing* and *Data acquisition (measurement).* The module driver specification *Energy supply* is linked to the energy harvesting and energy management system. *Data processing* is mapped to microcontroller, data transmission and memory. The module decision results in an *Energy module* that contains components for energy supply and storage and a *Data module* which contains the PCB, microcontroller, data transmission and memory. The module driver specification *Data acquisition (measurement)* is assigned to all sensors which results in the *Measurement module*.

4.2 Sensor-integrating gear

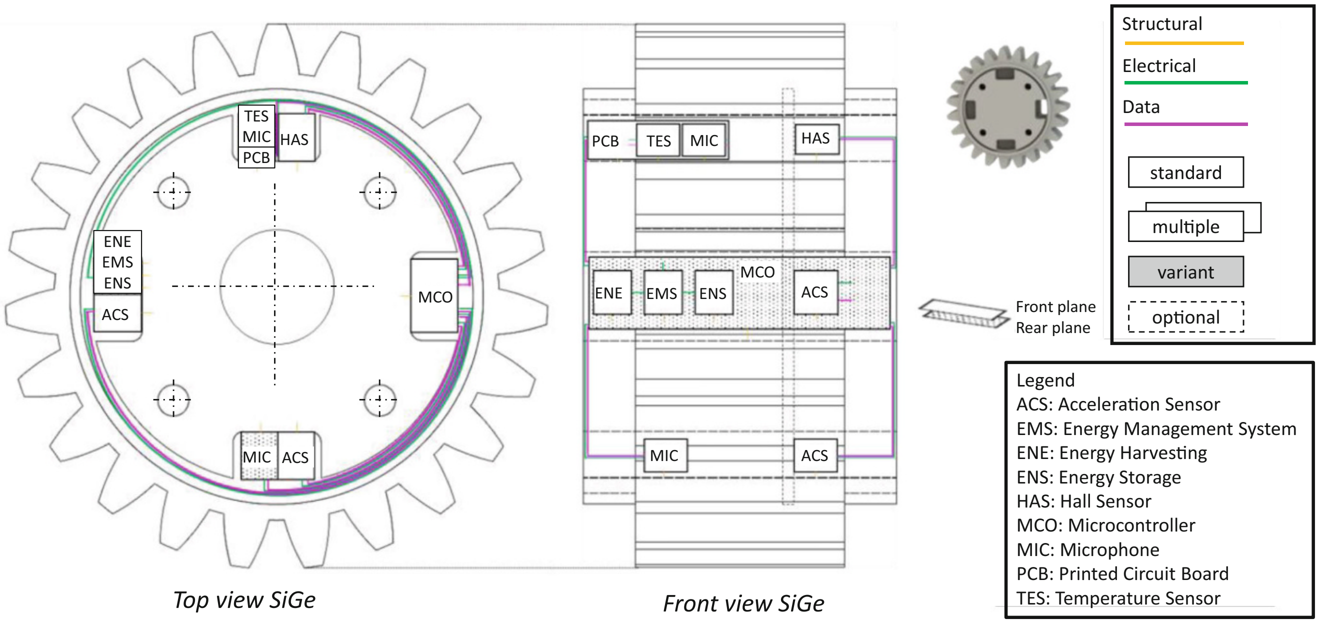
Based on an existing test rig and gear geometry, the *Sensor-integrating Gear* (SiGe) has been designed. The test gear set is very suited with the high tooth root safety factor for the adoption into a sensor-integration version. More details on the gear set, the test rig, and the integration progress on the gear wheels can be taken from previous works [5, 22]. Figure 16 in the *Appendix* shows the use case diagram of the SiGe. The operator on the left has two main tasks: calibration of the sensors before testing in order to archive reliable testing data and to operate the test rig. In addition, the operator stays in interaction with the SiGe. The SiGe has certain functions as the function of operating as a gear by transmitting forces, to detect typical gear failures such as tooth root fracture, flank fracture, pitting, micropitting, and adhesive wear [13]. With the extracted signals of the SiGe, an evaluation of the noise, vibration, and harshness behavior is possible. Other functions are data communication outside of the gear wheel and gearbox housing, harvesting energy, storing energy, and detecting the situation of energy supply in order to enable an optimal operating strategy in order to the state of all containing elements. There, the SiGe uses microphones, accelerometers, temperature sensors, and a Hall sensor to fulfill different tasks. The Hall sensor should sense the rotational speed and the signals of the other sensors are used to detect and identify the different gear fault. A microcontroller processes the signals inside the gear wheel and delivers data to the data transmission module. In addition to operating the SiGe, operating the test bench involves certain tasks for the operator. These include starting the test stand and setting the operating parameters, starting the measurement of the external sensors on the test stand, and comparing the data with the SiGe in order to evaluate the signals depending on the sensors and sensor positions.

Figure 8 shows the MIG of the SiGe. The case-hardened gear has four holes in the axial direction. This layout is selected because of the limitations caused by the conical interference fit connecting the gear to the shaft [5]. Three holes have a wall inside in order to place components like one-axis sensors properly. The fourth hole has no wall because of the space requirements for the microcontroller. Additionally, four holes are applied to place external sensing technology at the gear in order to evaluate the vibrational behavior. This technology has been presented by Goetz et al. [16, 17]. The accelerometers have been placed unmodified at the external technology in order to be able to sense the acceleration with one-axis sensors. The components are packed together in such a way, that they take up as little space as possible in the holes. All sensors are connected to the microcontroller for power and data transmission.

In Fig. 9, the network diagram of the SiGe is presented. So far, the energy supply has been planned with energy harvesting delivering energy to an energy storage like a battery or a capacitor. The power electronics are used to control the energy and enable DC-DC conversion. The data acquisition starts with the sensors delivering the signals to the microcontroller, where signals are processed and the decision is made when which sensor signal has been evaluated according to the operation situation of the gear and the possibilities of the energy supply.

4.3 Sensor-integrating coupling

In Fig. 17 in the *Appendix* the use case diagram of a *Sensor-integrating jaw Coupling* (SiCo) in a test bench is shown. The operators run the main systems, consisting of the test bench, the SiCo, and the computer. The computer brings together all data streams, records, and evaluates them. The structure of the coupling typically consists of three main elements (i) two hubs and (ii) an elastomeric gear rim. The hubs have two to five cylindrical curved claws that interlock with the elastomeric gear rim. Depending on the size of the rim, it contains four to ten rounded teeth. The gear rim is



Top view SiGe

Front view SiGe

Fig. 8 *Module Interface Graph* of the *Sensor-integrating Gear*

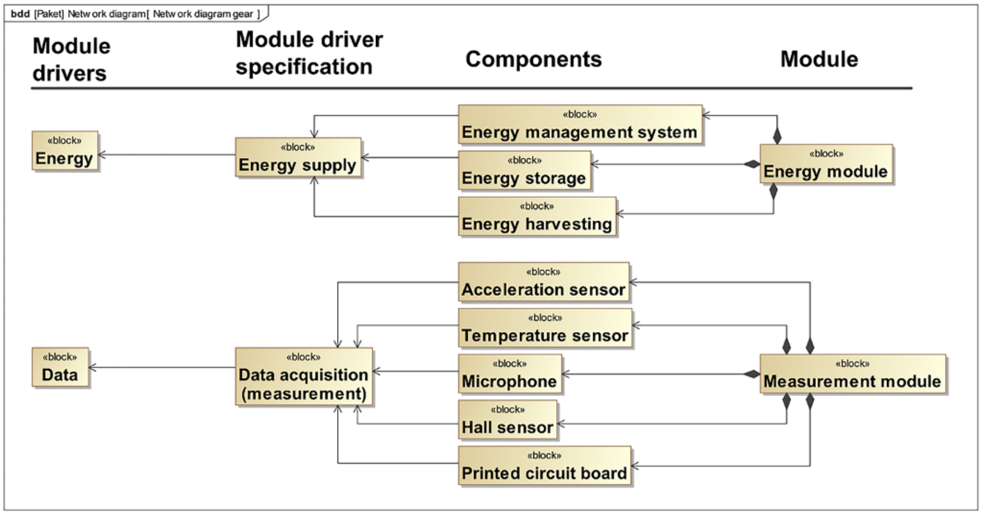


Fig. 9 Network diagram of the *Sensor-integrating Gear*

made of an elastomer with viscoelastic properties. The two hubs are connected to two shafts.

The aim of the SiCo is to determine (i) torque, (ii) rotational speed, (iii) temperature and (iv) shaft misalignments. For this purpose, in each tooth of the gear rim, a borehole is drilled and a dielectric elastomer sensor (DES) together with two strain amplifiers and a temperature sensor are implemented, cf. Fig. 10. The DES consists out of multiple smaller DES which are stacked upon each other to increase their total capacitance, cf. [32, 33]. The DES behaves electrically like a plate capacitor, i.e. when an electrical potential difference is applied to a DES, a capacitance can be measured by the capacitance sensor. During use of the coupling, the teeth of the gear rim are deformed, leading to a deformation of the DES, thus changing its capacitance. The electronics is placed centrally in the gear rim. The main components for the data acquisition and evaluation are the microcontroller with the subsystems battery management system, data storage and the temperature sensor. In addition, an energy storage unit, a data transmission unit and an accelerometer are integrated.

Due to the viscoelastic properties of the elastomer of the gear rim, it is not sufficient to determine only the current capacitance. The deformation history must also be taken into account. In addition, the temperature must be measured because of the temperature-dependent material behavior [28]. During operation, the gear rim heats up and thus becomes softer, which affects the measured capacitance-torque ratio as the DES is more compressed for the same torsion angle. Knowing current and previous capacitance as well as temperature values, the current torque can now be determined. The deformation is the same for all teeth unless there is a misalignment of the shafts, which can then be used to check whether a critical misalignment has occurred [12].

The two strain amplifiers, whose function is explained in [12, 29], are connected mechanically to the DES. The DES and temperature sensor are electrically connected to an energy source. The capacitance and its change can be measured by evaluating the charging time of the capacitor or via current integration and other methods [27].

In order to experimentally verify the integration of the sensors into the coupling, a special test bench is set up, cf. Fig. 17 in the *Appendix*. On the test bench, the coupling can be subjected to various loads. The torque and capacitance can be measured via laboratory equipment such as a torque measuring flange and an LCR meter to validate the data gathered by the sensor. After the proof of function has been provided, the sensor can be calibrated.

The physical properties of the jaw coupling have been selected as module drivers, in addition to *Energy* and *Data* as it was done in *Sect.s 4.1 and 4.2*, cf. Fig. 11. The former is mainly motivated by (i) the spatial separation of the individual teeth, in which the DES, the temperature sensor and the two strain amplifiers are integrated and (ii) the electronics, which are located in the free cavity of the gear rim. The driver *Energy* is very similar to the one presented in *Sect. 4.1* with the need of an energy storage and an energy management unit. Since sending data is very energy-intensive, the measured capacitance and temperature are saved in a data storage unit. Preferably, the regression of the measurement data for determining the torque is performed on the microcontroller. This makes it possible to send data only (i) when a deviation of the torque from the standard is detected, or (ii) to check at certain intervals whether everything is working as intended, cf. also Fig. 17 in the *Appendix*.

4.4 Sensor-integrating feather key

The feather key connection is a widely used shaft-hub connection. The feather key creates a form fit between the shaft and hub so that torques can be transmitted directly and is

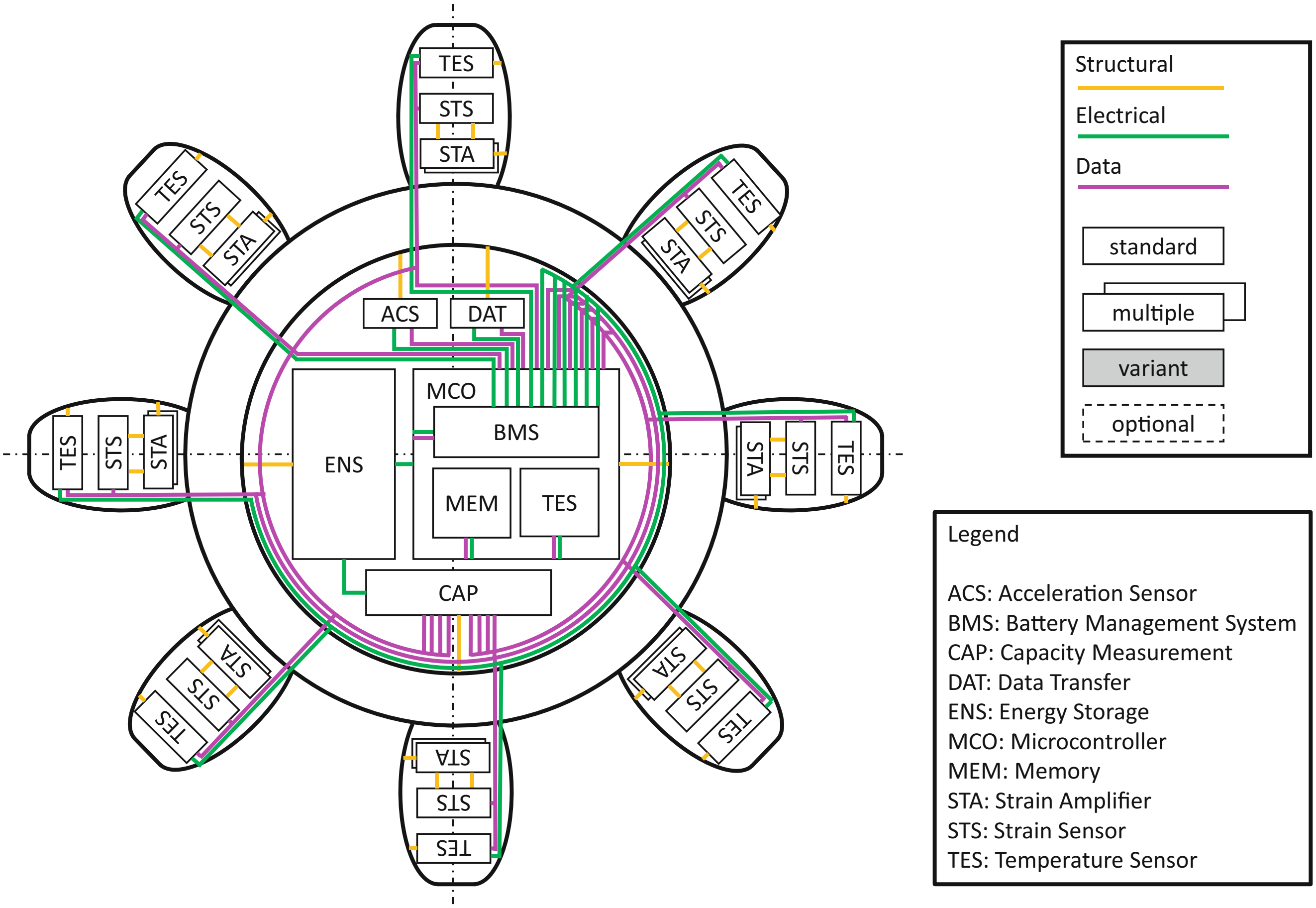
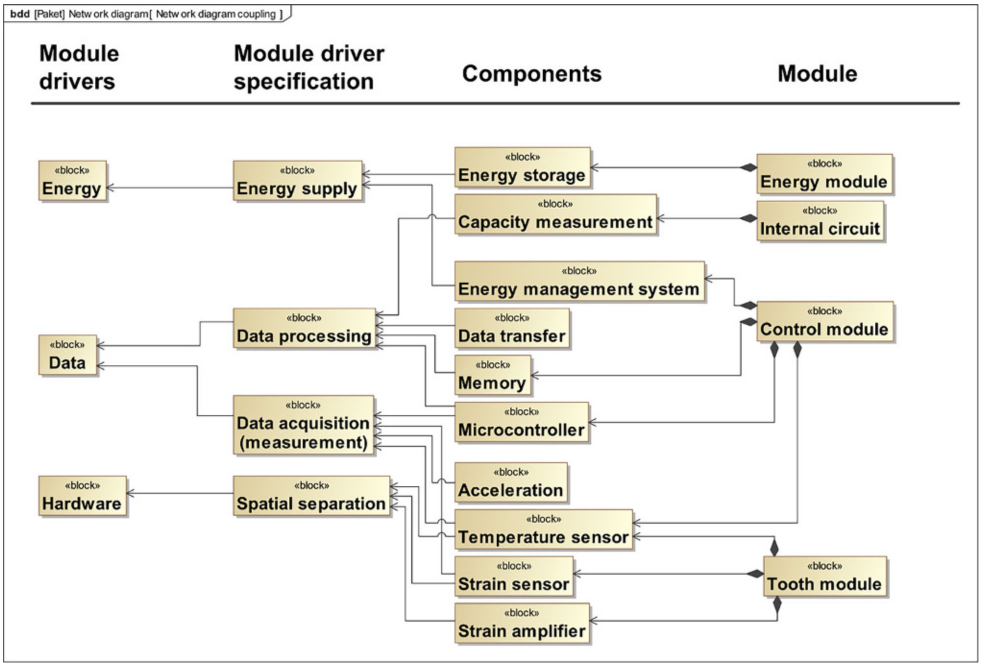


Fig. 10 *Module Interface Graph* of the *Sensor-integrating Coupling*

Fig. 11 Network diagram of the *Sensor-integrating Coupling*



therefore particularly suitable for in-situ measurements. In this way, the torques applied to the shaft-hub connection are recorded by measuring the deformation of the feather key generated by the transmitted circumferential force.

The *Sensor-integrating Feather Key* (SiFe) is tested in a suitable test bench. The corresponding use case diagram is shown in Fig. 18 in the *Appendix*. The test bench forms the outer system boundary. There are two separate actors at the test bench. The first actor operates the test bench, calibrates the sensor and installs the SiFe. The second actor evaluates the determined data after the test has been carried out. The actuators of the test bench are also outside the system boundaries. They generate a dynamic or static loading for the test of the SiFe. Within the test bench, the torque is then applied to the shaft-hub connection and the test bench data is determined. The shaft-hub connection with the actor’s shaft, hub and SiFe with their sub-components forms a subsystem in the test bench system. It transfers the load into the SiFe (hub actor) and out again (shaft actor). The SiFe is typically subjected to a non-uniform surface pressure, which depends on the torque and the hub geometry. The SiFe transmits the torque and itself forms another subsystem. This subsystem generates and stores electrical energy for the sensors, determines the strain at certain points on the feather key and transmits the data to the test bench system. Here, the data is evaluated, the applied torque is determined via a suitable calculation and the data is compared with the test bench data.

The non-uniform surface pressure on the feather key usually leads to a complex deformation. In order to be able to determine a resulting circumferential force from this deformation, it is usually necessary to measure the deformation of the feather key with a large number of strain gauges. Complex calculations are then necessary to determine the resulting circumferential force. However, it is possible to adjust the geometry of the feather key in such a way that the feather key always deforms approximately to a linear combination of a few deformation modes at different non-uniform surface pressures [37]. This reduces the number of strain gauges required to the number of deformation modes and simplifies the calculation of the resulting force. Such a geometry of the feather key can be found, for example, with the help of topology optimization [36]. The optimization does not change the entire geometry of the feather key. The variable region can be seen in the MIG shown in Fig. 12. As the feather key is currently optimized for two desired deformation modes, two strain gauges are needed to measure the entire deformation. These are marked as fixed components. It is also possible to specify three desired deformation modes during topology optimization. Therefore, a third strain gauge is marked as optional in between the other two. The feather key has invariable stiff areas on the upper and lower side. The energy harvester is integrated in the stiff area on the upper side. This is where the energy required for the sensor system is generated from the pressure load. With the SiFe, the installation space is very limited. For this reason, the evaluation unit in this version is mounted on the hub as a separate module. A description of this module can be found in [8]. However, a later integration into the feather key groove, is planned and necessary.

The schematic representation of the modular structure of the SiFe can be found in the network diagram shown in Fig. 13. The two separate modules are referred to here as the *Energy module* and the *Feather key module*. The module

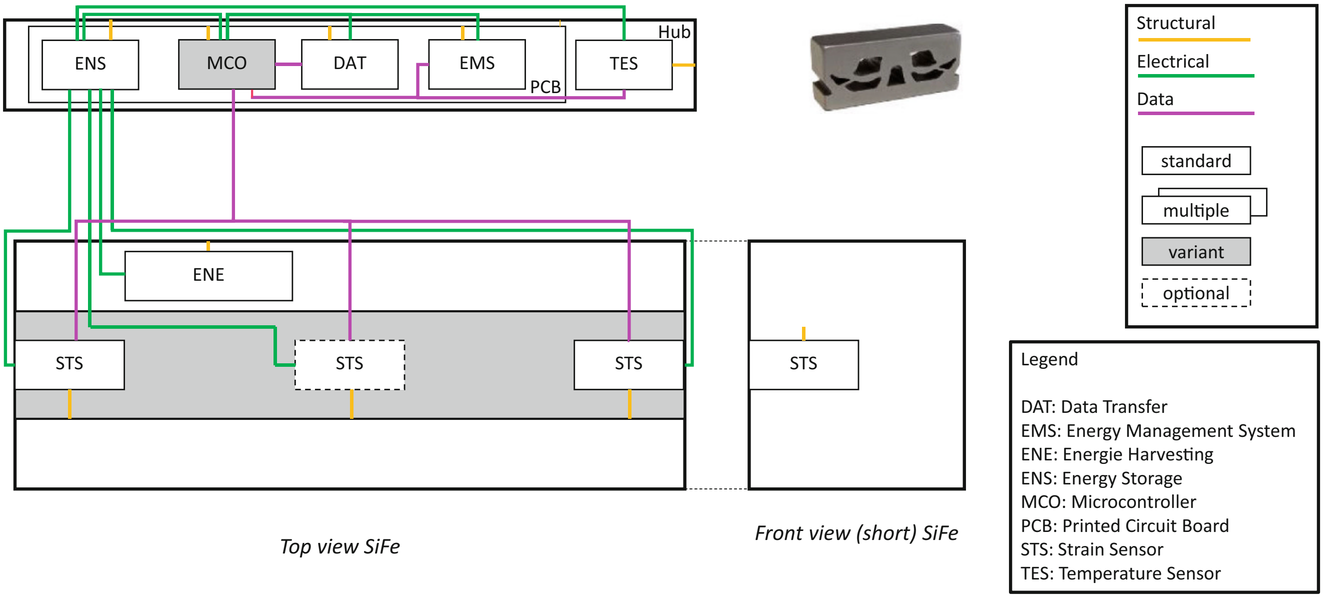


Fig. 12 *Module Interface Graph* of the *Sensor-integrating Feather Key*

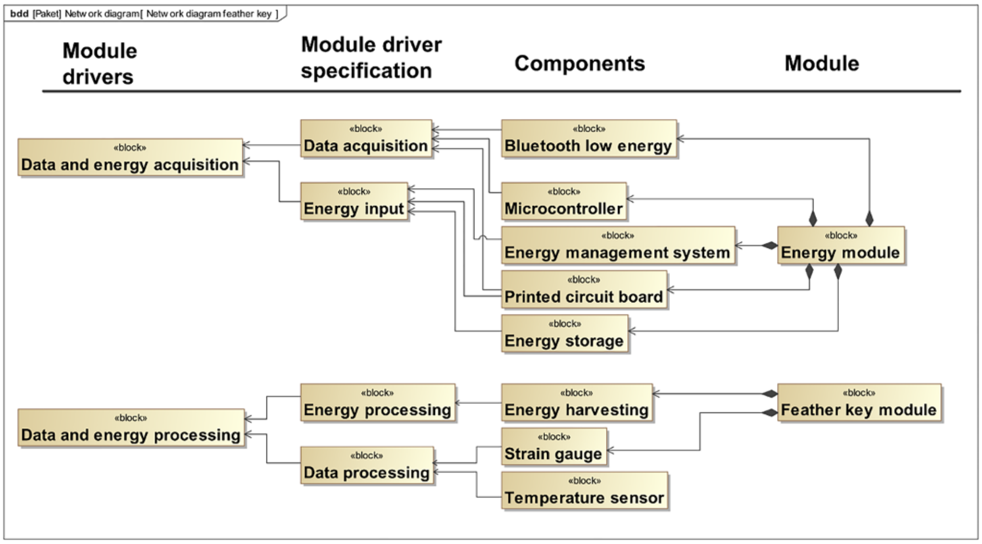


Fig. 13 Network diagram of the *Sensor-integrating Feather Key*

driver for the *Energy module* is the *Data and energy acquisition* and for the feather key module the *Data and energy processing*.

4.5 Merging the cases in the configuration network diagram

In *Step 5* of the procedure (c.f. Figure 5), the applications are linked in the CND and thus prepared for the subsequent configuration. Figure 14 shows an excerpt of the CND for the four use cases with the three design levels *Properties, Components* and *Modules* on the example of the energy supply, input and storage type. In order to display the configuration in one picture, a different color is used for each SiME. In the MBK, this information is provided via the module-module variant chart. If the product properties are selected, i.e. energy source, energy input and storage type in this excerpt, a link is defined for each use case for the corresponding module and the specific module variant. For the SiSc, the properties energy source with the characteristic vibration for wireless energy input and a rechargeable energy storage type lead to the energy module with the components energy harvesting, battery management system and energy storage. The same characteristics are selected for the SiGe. In the case of the energy source, thermal energy input is additionally used. The module therefore consists of the same components as the SiSc, but with an additional energy harvesting system. In the recorded version, the SiCo does not use an external energy supply. In this case, the energy module only consists of a rechargeable energy storage unit.

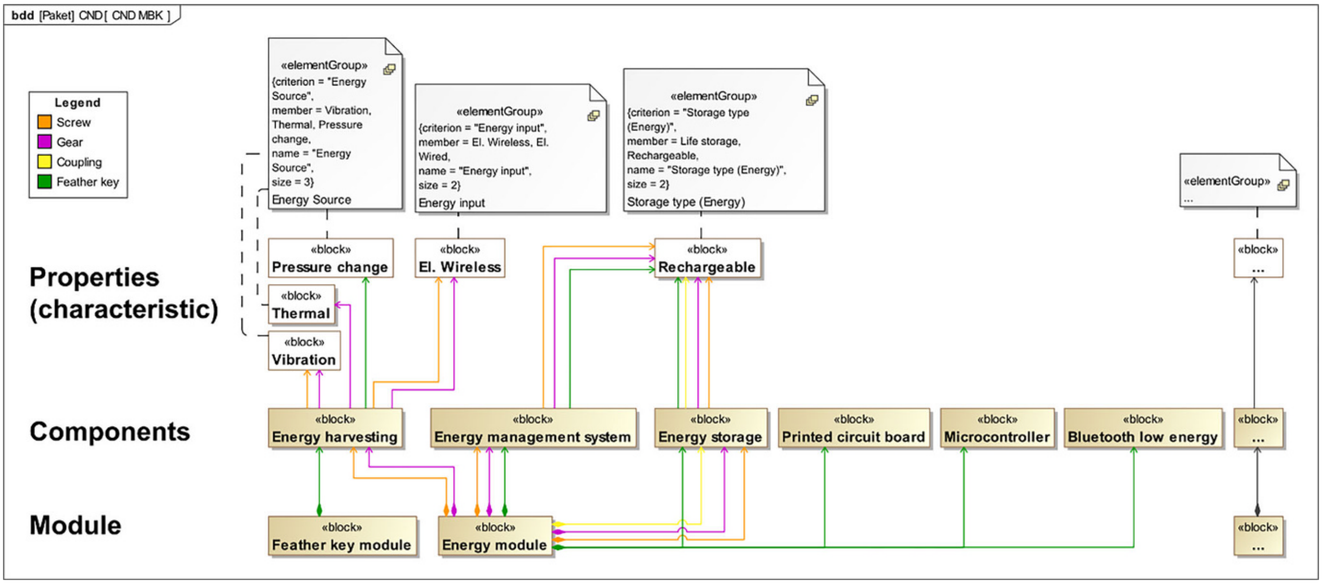


Fig. 14 Excerpt of the *Configuration Network Diagram* of the *Modular Building Kit*

The assignment of properties and modules is different for the SiFe. The properties *Energy Source* and *Energy Input* map to the *Feather key module*, which consists of an energy harvester and the strain gauge. The property *Storage type* leads to the *Energy module*, which consists of the components energy management system, microcontroller, PCB and energy storage.

In the MBK, specific component variants are stored behind each defined generic component, but these are not shown here. The component variants also contain metadata, e.g. volume, voltage or temperature ranges of the components, interfaces, etc.. For automatic configuration, the dependency matrices are exported with the metadata and configured using the suitable algorithms, e.g. Dijkstra, with regard to defined target variables.

5 Conclusion and outlook

In this contribution product development models for the four *Sensor-integrating Machine Elements* (SiME) Sensor-integrating Screw, Gear, Coupling and Feather Key were presented and their integration into the *Modular Building Kit (MBK)* has been shown. The environmental conditions and system functionality of the various applications were structured and standardized in the form of use case diagrams in which significant differences could be identified. To record the product structure, *Module Interface Graphs* were created for the four SiMEs. The module structure of the sensor systems was recorded in the form of network diagrams and implemented in SysML in order to make them available for configuration in the modular system. Many similar components are required to fulfill the functions of energy and data management, e.g. circuit board, microcontroller and energy storage. However, the specific requirements and boundary conditions of the different projects also show that these components are technically distinct and not directly interchangeable. The formalized design process satisfies the need for a common structure of data between the different projects, maintaining the same level of granularity and information density in the product development models. A modular approach also means that the product architecture is created early in the design process, so that modules and interfaces are defined at the beginning and their domain-specific elaboration follows. Components can be adapted later for different applications or different SiMEs without compromising the overall architecture and modules can also be exchanged within the same SiME through appropriate, previously defined interfaces. A major challenge of variant management at SiME is that the variety possible in the future is almost infinite, while in most individual projects only one product variant is actually manufactured.

The design teams gained valuable knowledge by learning not only about their own project through revealing the underlying system architecture but also by studying the architectures of other projects. The models implemented in SysML are the basis for linking the architectures in the MBK and the subsequent automatized configuration of sensor systems for SiME. For this purpose, data of the microelectronic components and a suitable format for data processing are required, so that relevant information of the application-specific design is available. Performance indicators such as installation space, energy efficiency and data transmission will be addressed in the configuration process. In future, different system configurations will be constructed with regard to the target variables for the SiSc, but also for other SiME. Furthermore, the existing MBK is to be expanded by more application scenarios and more ME so that the design of application-specific sensor systems for SiME can be adequately supported in a holistic manner.

6 Appendix

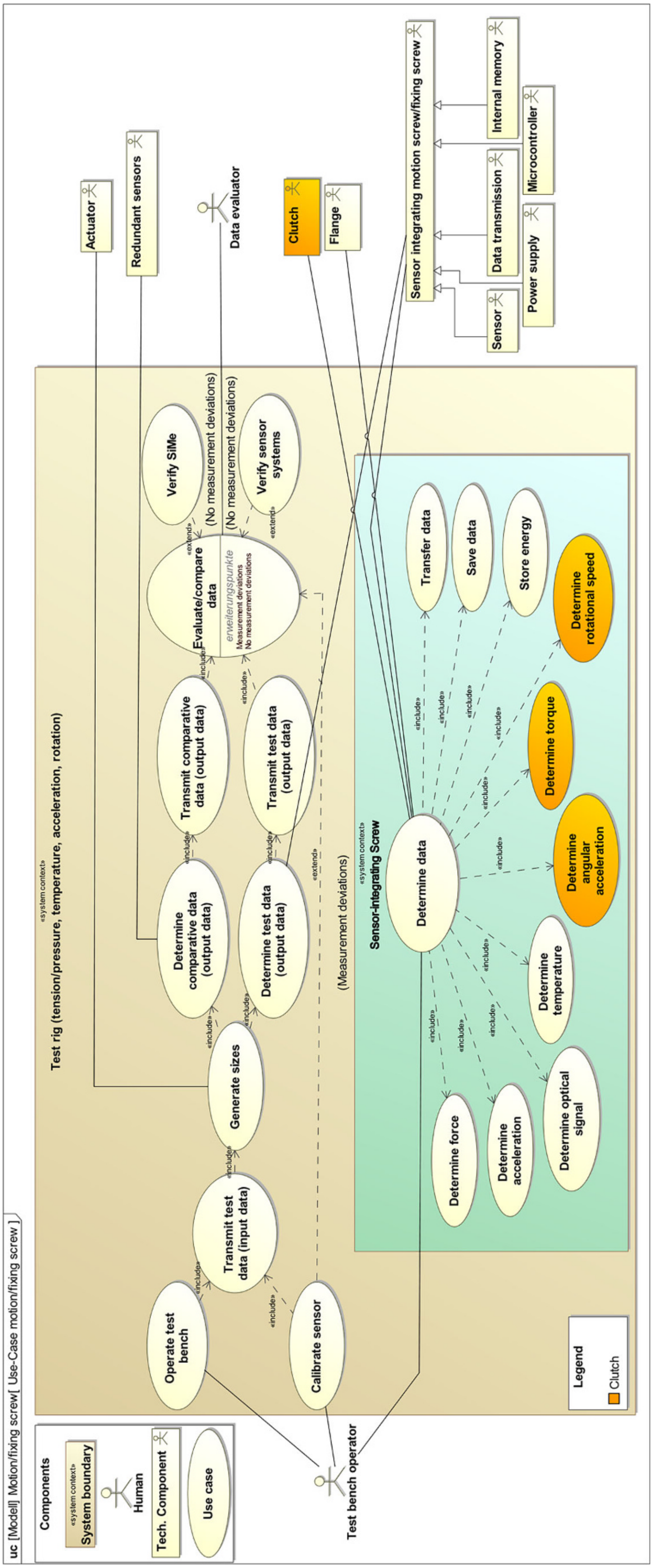


Fig. 15 Use case diagram of the *Sensor-integrating Screws*

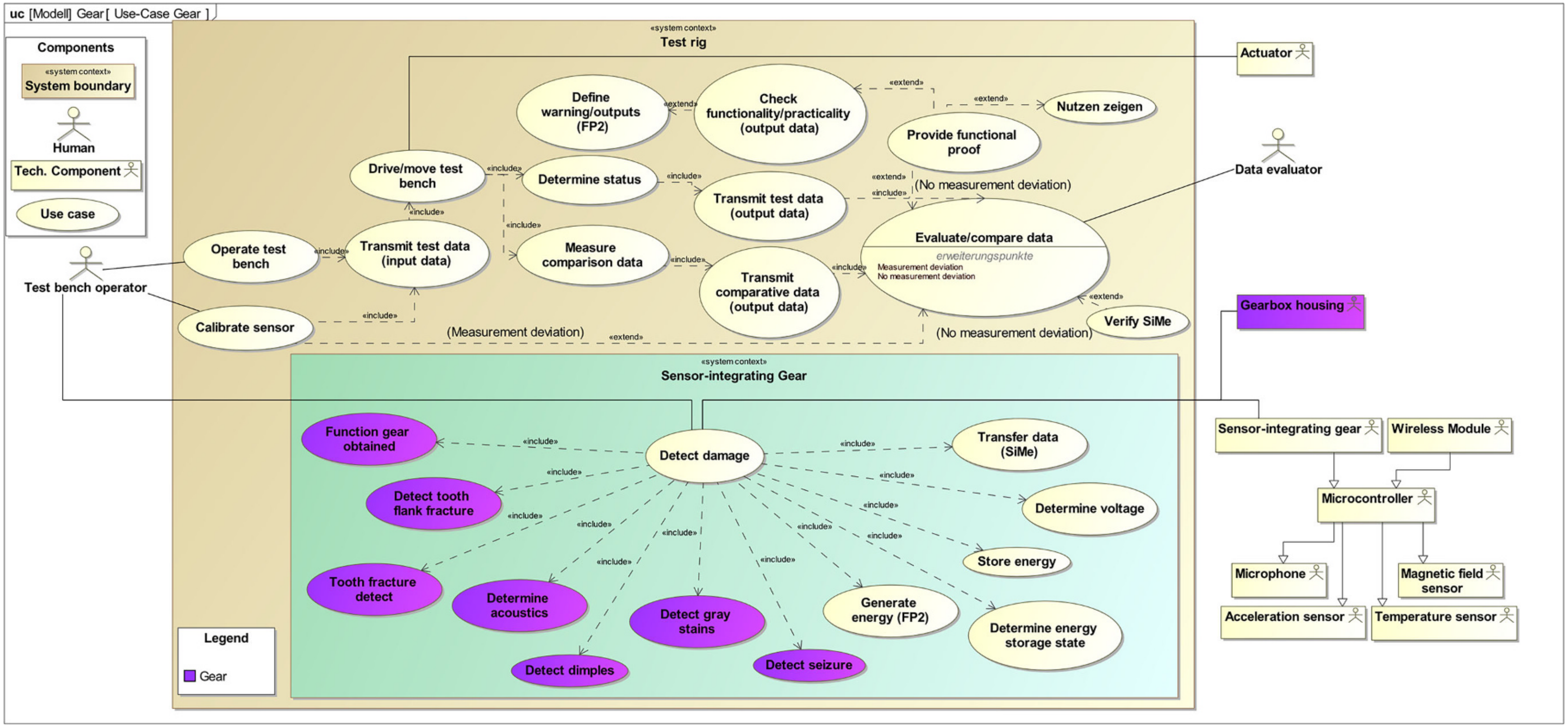


Fig. 16 Use Case Diagram of the *Sensor-integrating Gear*

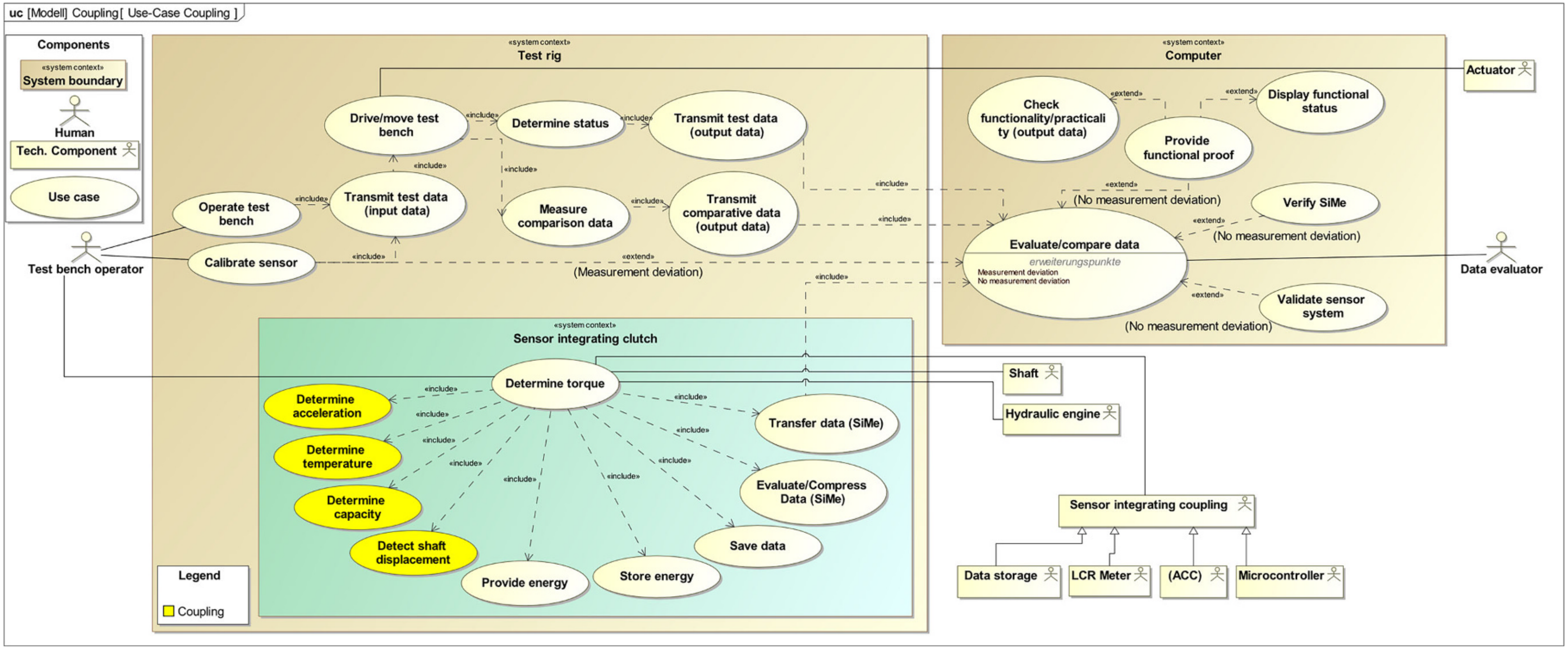


Fig. 17 Use case diagram of the *Sensor-integrating Coupling*

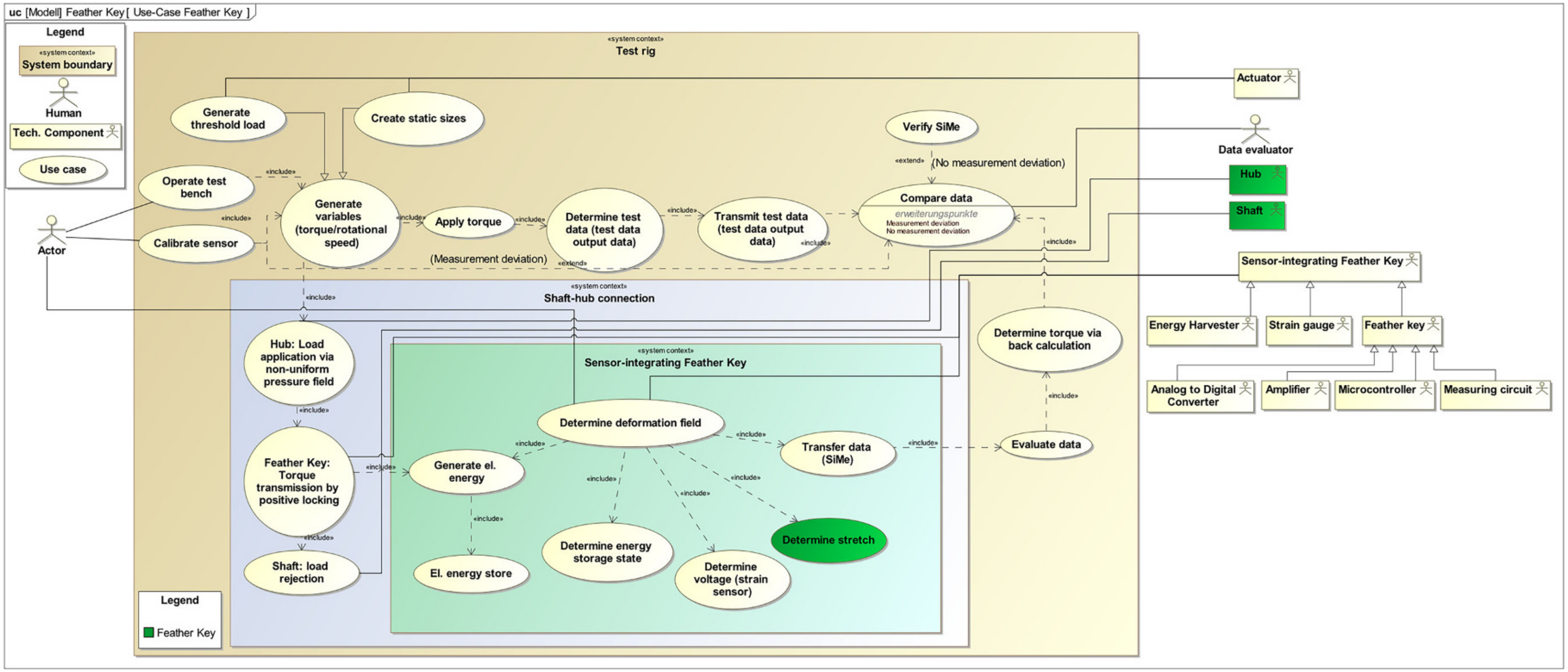


Fig. 18 Use case diagram of the *Sensor-integrating Feather key*

Acknowledgements This research was funded by the Deutsche Forschungsgemeinschaft (DFG, German Research Foundation) Project-ID 441853410—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, E. Kirchner, I. Gomberg, H.K. Trieu, K. Alamsha, E. Knoll, K. Stahl, J. Menning, T. Wallmersperger, A. Ewert, B. Schlecht, A. Prokopchuk, E.-F. M. Henke, S. Seltmann, A. Hasse, C. Chen, W.-G. Drossel and D. Krause declare that they have no competing interests.

References

1. Anderl R, Eigner M, Sendler U, Stark R (2012) Smart Engineering. Interdisziplinäre Produktentstehung (acatech DISKUSSION). Springer, Heidelberg u. a.
2. Barbieri G, Fantuzzi C, Borsari R (2014) A model-based design methodology for the development of mechatronic systems. Mechatronics 24(7):833–843
3. Berschik MC, Schumacher T, Laukotka FN, Krause D, Inkermann D (2023) MBSE within the engineering design community—an exploratory study. Proc Des Soc 3:2595–2604. https://doi.org/10.1017/pds.2023.260
4. Binz H, Bartholdt M (2014) Universitäre Lehre in der Produktentwicklung – Leitfaden der Wissenschaftlichen Gesellschaft für Produktentwicklung (WiGeP). Konstruktion 66:74–79
5. Bonaiti L, Knoll E, Otto M, Gorla C, Stahl K (2022) The Effect of Sensor Integration on the Load Carrying Capacity of Gears. Machines 10(10):1–4
6. Breimann R, Kirchner E, Küchenhof J (2022) Sensorintegrierende Maschinenelemente – Klassifizierung, Beispiele und Herausforderungen, Dresdner Maschinenelemente Kolloquium. DMK, vol 2022. Dresden
7. Breimann R, Fett M, Küchenhof J, Gomberg I, Kirchner E, Krause D, Trieu HK (2023) A method for optimizing product architectures for the management of disturbance factors. Procedia Cirp 119:1041–1046. https://doi.org/10.1016/j.procir.2023.02.179
8. Chen C, Bäcker D, Drossel W-G (2023) Simulation model for a low-power piezoelectric energy harvesting application, in10th ECCOMAS Themat. Conf. Smart Struct. Mater., Patras, Greece: Dept. of Mechanical Engineering& Aeronautics University of Patras, pp 1691–1702 https://doi.org/10.7712/150123.9940.444402
9. Dambietz FM, Rennpferdt C, Hanna M, Krause D (2021) Using MBSE for the enhancement of consistency and continuity in modular product-service-system architectures. Systems 9(3):63
10. Dambietz FM (2022) Performance simulation of modular product architectures by model-based configuration. PhD-Thesis, Hamburg University of Technology. Springer Vieweg https://doi.org/10.1007/978-3-662-64233-7
11. Eilmus S, Ripperda S, Krause D (2013) Towards the development of commonal product programs. In: DS 75-4: Proceedings of the 19th International Conference on Engineering Design (ICED13). Design for Harmonies, vol 4. Product, Service and Systems Design, Seoul, Korea, pp 19–22
12. Ewert A, Menning JDM, Prokopchuk A, Rosenlöcher T, Henke MEF, Wallmersperger T, Schlecht B (2023) Smart machine elements—sensor-integrated elastomer couplings, in 10th ECCOMAS Thematic Conference on Smart Structures and Materials, pp 1681–1690 https://doi.org/10.7712/150123.9939.444198
13. Fromberger M, Sendlbeck S, Rothemund M, Götz J, Otto M, Stahl K (2019) Comparing Data Sources for Condition Monitoring Suitability. Forsch Ingenieurwes 83(3):521–527
14. Gausemeier J, Tschirner C, Dumitrescu R (2013) Der Weg zu intelligenten technischen Systemen. Ind Manag 29(1):49
15. Gomberg I, Breimann R, Küchenhof J, Kirchner E, Krause D, Trieu HK (2023) Evaluation of a modular microsystem structure for sensor-integrating machine elements. MikroSystemTechnik Kongress
16. Götz J, Weinberger U, Siglmüller F, Otto M, Stahl K (2019) Experimental and theoretical assessment of mesh excitation in mechanical drive trains. VDI, Gesellschaft Produkt- und Prozessgestaltung
17. Götz J, Weinberger U, Siglmüller F, Otto M, Stahl K (2021) Experimental and theoretical assessment methods of mesh excitation in mechanical drive trains. 27th International Congress on Sound and Vibration. ICSV, vol 27
18. Groche P, Brenneis M (2014) Manufacturing and use of novel sensoric fasteners for monitoring forming processes. Measurement 53:136–144
19. Großkurth D, Martin G (2019) Intelligenter Zahnriemen, GMA/ITG-Fachtagung Sensoren und Messsysteme. 14:738–743
20. Holt J, Perry S (2018) SysML for Systems Engineering: A Model-Based Approach. eng, vol 3. The Institution of Engineering and Technology, London
21. Kirchner E, Wallmersperger T, Gwosch T, Menning JDM, Peters J, Breimann R, Kraus B, Welzbacher P, Küchenhof J, Krause D, Knoll E, Otto M, Muhammedi B, Seltmann S, Hasse A, Schäfer G, Lohrengel A, Thielen S, Stiemcke Y, Koch O, Ewert A, Rosenlöcher T, Schlecht B, Prokopchuk A, Henke E-FM, Herbst F, Matthiesen S, Riehl D, Keil F, Hofmann K, Pape F, Konopka D, Poll G, Steppeler T, Ottermann R, Dencker F, Wurz MC, Puchtler S, Baszenski T, Winnertz M, Jacobs G, Lehmann B, Stahl K (2024) A Review on Sensor-integrating Machine Elements. Adv Sens Res. https://doi.org/10.1002/adsr.202300113
22. Knoll E, Rupprecht B, Groppo E, Otto M, Vogel-Heuser B, Bred-erlow R, Stahl K (2023) Modular extension of FZG—gear test rig for in-situ measurement possibilities. 29th International Congress on Sound and Vibration. IIAV CZECH s.r.o, Prag
23. Köster L (1982) Bestimmung des Zugkraftverlaufs in schnellumlaufenden Zahnriemen mit Hilfe von Dehnungsmeßstreifen, tm – Technisches Messen 49. JG): 55–58
24. Krause D, Gebhardt N (2023) Methodical Development of Modular Product Families: Developing High Product Diversity in a Manageable Way. Springer Nature
25. Kruse F, Küchenhof J, Gomberg I, Breimann R, Krause D, Kirchner E, Trieu HK (2024) Identification of Parameter Sets for the Selection of Microelectronic Components for Sensor-integrating Machine Elements. IEEE Sensors J. https://doi.org/10.1109/JSEN.2024.3365271
26. Küchenhof J, Berschik MC, Heyden E, Krause D (2022) Methodical support for the new development of cyber-physical product families. Proc Des Soc 2:495–504

27. Landgraf M (2020) Leistungselektronik für den Einsatz dielektrischer Elastomere in aktorischen, sensorischen und integrierten sensomotorischen Systemen. Dissertaton. Friedrich-Alexander-Universität, Erlangen
28. Menning JDM, Prokopchuk A, Ewert A, Schlecht B, Henke EFM, Wallmersperger T (2023) Modeling and simulation of deformation and capacitance of a substitue system of a sensor-integrated jaw coupling, in 10th ECCOMAS Thematic Conference on Smart Structures and Materials, pp 1611–1622 https://doi.org/10.7712/150123.9933.443570
29. Menning JD, Ewert A, Prokopchuk A, Schlecht B, Henke M, Wallmersperger T (2023) Finite element based modeling and simulation of an elastomer gear rim. Proc Appl Math and Mech 23(1):e202200141
30. Mhenni F, Choley JY, Penas O, Plateaux R, Hammadi M (2014) A SysML-based methodology for mechatronic systems architectural design. Adv Eng Informatics 28(3):218–231
31. NoMagic Inc SysML Plugin Documentation. https://docs.nomagic.com/display/SYSMLP190. Accessed 20 Oct 2023
32. Prokopchuk A, Ewert A, Menning JDM, Richter A, Schlecht B, Wallmersperger T, Henke MEF (2023) Multi-layer capacitive strain sensor based on dielectric elastomers, in 10th ECCOMAS Thematic Conference on Smart Structures and Materials, pp 1657–1668 https://doi.org/10.7712/150123.9937.445520
33. Prokopchuk A, Ewert A, Menning J, Richter A, Schlecht B, Wallmersperger T, Henke MEF (2023) Influence of manufacturing parameters on the quality of electrodes of a multi-layer capacitive strain sensor based on dielectric elastomers. In: Active and Passive Smart Structures and Integrated Systems XVII, vol 12483. SPIE, pp 554–563
34. Schirra T, Martin G, Puchtler S, Kirchner E (2021) Electric impedance of rolling bearings. Consideration of unloaded rolling elements. Tribol International 158:106927
35. Seiler FM, Krause D (2020) A multi-dimensional configuration algorithm for modular product algorithm for modular product architectures, Proceedings of the Design Society. DESIGN Conference, vol 1, pp 2405–2414 https://doi.org/10.1017/dsd.2020.283
36. Seltmann S, Campanile LF, Hasse A (2022) Topology-Optimization Based Design of Multi-Degree-of-Freedom Compliant Mechanisms (Mechanisms with Multiple Pseudo-Mobility). J Intell Mater Syst Struct 34(5):609–628. https://doi.org/10.1177/1045389X221111535
37. Seltmann, Muhammedi B, Hasse A (2023) Topology optimization-based design of a sensor-integrating feather key, in10th ECCOMAS Themat. Conf. Smart Struct. Mater., Patras, Greece. Dept. of Mechanical Engineering & Aeronautics University of Patras, pp 1669–1680 https://doi.org/10.7712/150123.9938.451778
38. SysML.org What is SysML? https://sysml.org/sysmlfaq/what-is-sysml.html. Accessed 20 Oct 2023
39. Stücheli M, Meboldt M (2013) Mechatronic machine elements: on their relevance in cyber-physical systems, in Smart Product Engineering: Proceedings of the 23rd CIRP Design Conference vol 2013. Springer, Bochum, pp 263–272
40. Vazquez-Santacruz JA, Portillo-Velez R, Torres-Figueroa J, Marin-Urias LF, Portilla-Flores E (2023) Towards an integrated design methodology for mechatronic systems. Res Eng Des 34(4):497–512
41. Vorwerk-Handing G, Gwosch T, Schork S, Kirchner E, Matthiesen S (2020) Classification and examples of next generation machine elements. Forsch Ingenieurwes 84(1):21–32
42. VDI/VDE 2206:2021-11 (2021) Development of mechatronic and cyber-physical systems. Beuth Verlag, Düsseldorf
43. Zheng C, Hehenberger P, Le Duigou J, Bricogne M, Eynard B (2017) Multidisciplinary design methodology for mechatronic systems based on interface model. Res Eng Des 28:333–356
44. Zuefle M, Kuechenhof J, Berschik M, Krause D (2023) Enhancing Collaborative Modular Product Development: Interface Allocation and Associated Responsibilities, Proceedings of the 25nd International DSM Conference (DSM 2023). Gothenburg, Sweden https://doi.org/10.35199/dsm2023.01