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Procedia CIRP 136 (2025) 522–527

www.elsevier.com/locate/procedia

35th CIRP Design 2025

Design Support and Strategies for Integrating Sensing Functions into Machine Elements

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Abstract

Sensing functions in machine elements allow early failure prediction and enhance system reliability. The problem is that the integration of sensing functions while maintaining mechanical functions leads to a conflict of objectives between mechanical and electrical domains, which is currently not supported methodically. This paper aims to overcome this conflict by methodically supporting the design of sensing functions in machine elements using the example of bolts as a case study. The V-model as an established process model for product development is expanded by sensor specific processes and further combined with the methodology of testing to overcome the conflicts arising in the design. Patterns of testing activities are found that lead to successful sensor integration into machine elements. This case study supports engineers as a reference to gather high-quality measurement and process data, which are crucial for data-driven methods like failure prediction and enhance system reliability.

Keywords: Testing, design knowledge, V-model, VDI 2206, methodology, sensor, integration, domain interaction, conflict of objectives, machine element, bolt

1. Introduction

In industry, there is a need to obtain high-quality data in order to facilitate big data analytics, condition monitoring, or predictive maintenance. Measuring data in-situ, at locations relevant to the process, is advantageous for data quality. Standardized machine elements are often situated at such locations, making it advantageous to obtain measurement data on them [1, 2]. By integrating smart sensing functions into machine elements, standardized sensor nodes with high-quality data become available. However, integrating novel sensory functions into a product that is fully developed and standardized is an ambitious matter. Specifically challenging is the conflict of objectives between a high performance of the machine element and high-quality data from the integrated sensors.

While single- and multi-axis force sensors for bolts represent a state-of-the-art technology, they are not designed to fulfil the requirements of a completely integrated and self-sufficient sensor system that would enable the bolt to be used as before and maintain the standardization [2]. Moreover, there is a lack of support for development of sensor integrating machine elements, specifically addressing interactions between domains for resolving the conflict of objectives between mechanical and sensory function [2–4].

In prior work, the system of the sensor integrating bolt for multi-axial force measurement is presented [5–8]. This contribution outlines the process for developing a sensor-

10.1016/j.procir.2025.08.090

integrating bolt for multi-axial force measurement, building on the previous work.

The literature on sensor integration presents two distinct approaches to product development: an empirical approach and a general, non-specific procedure model [4]. Methodologies exist that support development on a generic process level (VDI 2206, VDI 2221, State Gate). For example, the VDI 2206 with its V-model [9] was employed in the integration of acceleration sensors into gears [10]. However, the sensor system was not fully integrated, resulting in a protrusion on the side of the gears. In this instance, the methodology was employed merely as a general guide, rather than for the resolution of specific issues or the provision of detailed support. While the VDI 2206 [9] is a generally applicable framework, it has yet to be specified for the purpose of integrating novel sensory functions into products that have already undergone standardization.

Furthermore, the domain development is only described as a parallel procedure, interactions between domains as strongly needed for sensor integration are not addressed sufficiently.

Iterative testing, which it is intertwined in the development, can support the acquisition of specific knowledge about a certain product [11]. A methodology already exists about how to apply testing in a meaningful way to gain this specific knowledge [12][7].

The knowledge gap lies in the lack of a structured testing methodology to systematically gain knowledge for synthesizing embodiment solutions in the case of sensor integrating bolts, specifically for integrating novel sensory functions into standardized machine elements, addressing domain interactions to resolve the conflict between high mechanical performance and high-quality sensor data.

The following research question is posed: *How can the acquisition of knowledge in sensor integration into standardized machine elements be methodically supported so that the necessary design knowledge for synthesizing embodiment solutions is available and the conflicts of objectives between mechanical and sensor function are overcome?*

2. Methods

This contribution covers the development of a sensor integrating M20 bolt as an example case. Bolts as one of the most widespread machine elements are standardized in geometry, usually within the force flow and highly stressed up to their yield strength and above which offers very little design freedom for integration of sensors. Thus, they provide a challenging example case. As general procedure for development the VDI 2206 is used. A 4th domain for sensors is added between mechanics and electronics, to emphasize the importance of the sensor aspect in this development. In a similar way this was successfully done by Ley et al. [13] at the example of an optical domain.

The problem solving process is based on the micro-level cycle of problem solving [14, 15], integrated into the VDI 2206, in combination with the methodology of testing [12] which is customized to the particular problems as in a design process [16].

The situation analysis of the problem-solving process contains the specification of the **missing knowledge** needed for synthesizing embodiment solutions that have an intended behaviour. Based on that a **testing objective** is specified: *explore*, *narrow-down* or *check*. Further, one or more testing-**hypotheses** are formulated using *if*, *then*, *because* wherever applicable. Afterwards, the **activities** are planned and categorized in *literature research*, *model-based (analytical)* and *empirical* (Figure 1). For the last two, a virtual or physical testing object is operated, observed and evaluated. The analysis is concluded by an interpretation of the results. Based on the objective this leads to a generation of new hypotheses (*explore*), reduction of hypotheses (*narrow-down*) or a confirmation or rejection of a hypothesis (*check*). Each testing step is described using these categories. The results chapter contains a graphical overview of the case study's procedure (Figure 1) and a description of a subset of the steps that are within the focus of this paper, the interactions between domains and resolving the conflict of objectives between high mechanical performance and high-quality sensor data. The information technology domain is omitted in this work. Table 1 gives an overview of the sequence to identify patterns of testing activities.

3. Results

The methodology of testing is applied in a VDI 2206 based development process for the example case to acquire the missing knowledge. In the case study, 30 testing steps were conducted, mapped into the V-model (Figure 1). The sequence of testing steps is outlined in Table 1 to detect patterns. In the following, an excerpt of the steps is described in detail focusing the interactions between domains, aligned to the focus of this paper which was outlined in chapter 2.

The development objective for this example project is the development of a sensor integrating bolt, that

- maintains its primary, mechanical function (clamping force) and outer geometry, and
- provides lifetime multi-axial force measurement with minimal error.

3.1. Case study: Examples of the development steps and acquired knowledge

Step 1-3: Identify design space for sensor

In step 1 **Knowledge** is **missing** where to place sensors and electronics inside the bolt in order to maintain the max. force and the outer geometry. The **Testing-Objective** is to *explore* the critical locations of a standard metrical bolt in a *literature review* (**activity**) of applicable standards and publications. **Hypotheses** are generated: If there are critical locations like notches, then they increase mechanical stress excessively and therefore should be avoided with sensors and electronics. The acquired knowledge is the location and effect of the notches, the most critical notch is at thread/nut, followed by head/shaft.

In step 2 it becomes clear that **knowledge** about the shape of the design space for sensor and electronics and its effect on the stress distribution is **missing**. The **Testing-Objective:** *Explore* the stress distribution in a cross section of the bolt considering possible shapes of sensor and electronics. **Activities** are *analytical* calculations of tensile, bending and torsional stress with respect to the radius and the notch effect. **Hypotheses** are generated: If cavities for sensors and electronics are centered, cylindrical, and far away from notches, then stress increase is low, because the low stressed regions of the bolt are used.

In step 3 the design shape dimensions are *narrowed-down* by using the hypotheses from before and adding cavities to the *analytical* calculations. To avoid all notches is not possible. **Knowledge** is **missing** on how the notch effect changes due to cavities. The **activity** consists of *analytical* calculations, expanding the stress formulas with cavity diameters. The hypotheses are reduced: The notches relevant to the design space shape and location are identified and their effect estimated. Above a certain cavity diameter the notch head/shaft becomes most critical [7].

Step 10: Check energy consumption of measurement circuit

Following on the sensor concept from step 6 and the electrical parts and schematic (model) from step 9 **knowledge** is **missing** on the energy consumption which is important for the development objective of providing lifetime measurements. *Checking* the energy consumption of a prototype combining electronics and sensorics domain is the **Testing-Objective**. The **hypothesis**: If the strain gauge (SG) in combination with the measurement electronics do not exceed a certain limit, then lifetime measurement is enabled because energy can be acquired faster than be consumed. A *model-based* simulation of the circuit (step 9) with SG characteristics (step 6) is performed as **activity**. The hypothesis is rejected: The energy consumption with the SG is too high, SG with higher nominal resistance are needed to reduce consumption.

Step 12: Check sensor concept in bolt (empirical)

Following up on step 6 the sensor concept is integrated into the bolt (mechanical structure), combining two domains. **Knowledge is missing** if the analytical proven considerations are transferable to a real setup with SGs. From this the **Testing-Objective** of *checking* the sensor concept under multi-axial load is derived. The **hypothesis**: If the real sensor behaves as the formulas predict, then the model was sufficiently accurate and the sensor concept is valid. The **activity** is *empirically*

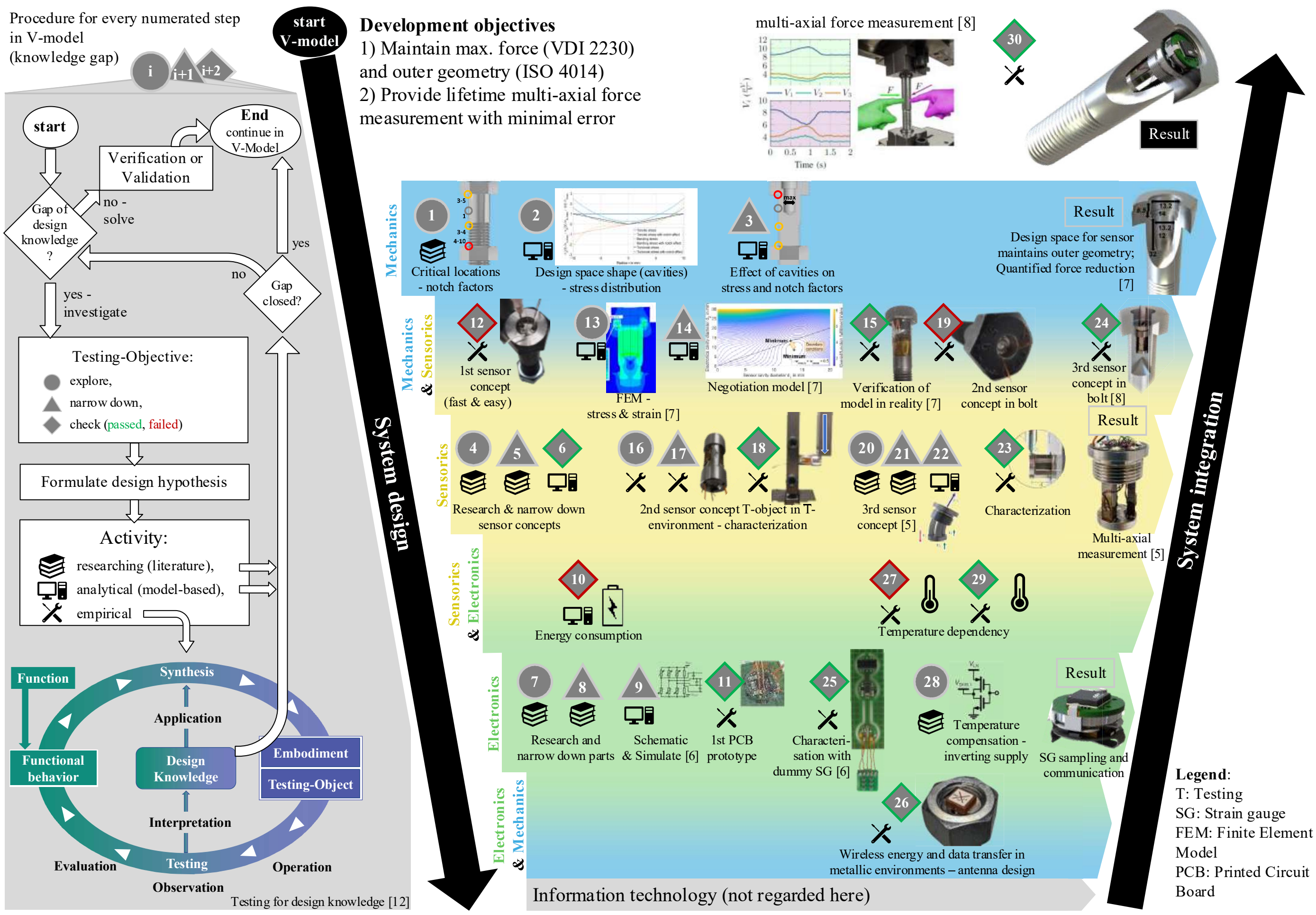

Figure 1: Overall procedure of the case study, combining the V-model and the methodology of testing to develop sensor integrating bolts.

conducting measurements using an easy to manufacture Testing-object composed of 3 cylindrical SGs (TB21, HBM) with a small volume that are glued into three drilled holes of a M20 bolt. The bolt is loaded axially and with bending torques in a testing-environment. The SG measurements in comparison to the applied load is analysed with focus on sensitivity and linearity. The hypothesis is confirmed only partly: The sensor concept works in a real setup. However, the model did not take the asymmetrical orientation of the SG into account, a high uncertainty occurs. They are also not temperature stable because the glue layer is difficult to control. A deformation body with flat SG (i.e. sensor body) is needed to reduce uncertainty. Therefore, quantitative design space considerations are necessary.

Step 13: Explore the effect of design space parameters

To reduce uncertainty in the sensory function a sensor body is needed that requires space inside the bolt. This will weaken the mechanical function because a conflict of objectives exists between mechanical and sensory domain. **Knowledge** of the effect of the sensor body's design space parameters on the mechanical and sensory functional behaviour **is missing** to identify an optimum. The **Testing-Objective:** *Explore* the effect of varying design space parameters on the functional behaviour. The **Activity** contains a *model-based* FE simulation. The v. Mises stress for mechanical functional behaviour and strain at shaft for sensory functional behaviour is analysed. **Hypotheses** are generated: More design space leads to a higher sensory and a lower mechanical functional behavior and vice versa, because both functions share the same material resulting in an opposing behaviour of the two functions. [7]

Step 14-15: Narrow-down design space parameters and check confidence of virtual model

Regarding the opposing behaviour of the functional fulfilments, **knowledge is missing** on design space parameters to resolve the conflict of objectives. Hence, the **Testing-Objective** to *narrow-down* the design space options to achieve a compromise between mechanical and sensory functional behaviour is set. This leads to the **Testing-Activity**: *Modelling* an optimization function that uses the FE data to negotiate between mechanical and sensory functional behaviour using weights. The **Hypotheses** are *narrowed-down*: If mechanical and sensory functional behavior are opposing, then there is an optimum in the usable design space range of the bolt which resembles a compromise between mechanical and sensory functional behaviour. Weights can be used to adjust the optimum according to application cases. [7]

In step 15 the confidence of the virtual model is *checked* by *empirical* testing. Certain parameter sets are picked that allow easy application of SG to reduce uncertainty. The hypothesis that the empirical data resembles the model within an error margin is confirmed.

Step 19: Check sensor concept #2 in bolt - subsystem mechanics and sensors

Building on the failed check of the sensor concept from step 11 and the design space from step 14 a sensor concept with sensor body for press fit and flat SGs is considered. In steps 16-18 this was carried out empirically, resulting in measured characteristics of the sensor.

Knowledge of the influence of mounting the sensor body in the bolt (combining mechanics and sensorics) on the characteristics determined before **is missing**. Hence, the **Testing-Objective** is derived: *Check* the SG measurement characteristics and compare them to step before. Based on that the **hypothesis** is stated: If the measurement characteristics change only in a linear way after mounting of the sensor body, then the press fit succeeds as a mounting method. As a **Testing-Activity** an *empirical* testing of the bolt with mounted sensor body in the tensile testing machine is conducted. The hypothesis is rejected, the characteristics change in a non-linear way, a hysteresis occurs. The tolerances of the press fit are too uncertain; therefore, a new mounting method needs to be explored. Also, the sensitivity for bending torques is too low, because the SG are adapted to the much higher strain of axial forces. A deformation body with different sensitivities for axial and bending strain is required.

Steps 20-24: Sensor concept iteration #3

A new deformation body is *researched* in an *explorative* way. This time also a *model-based narrow-down* is carried out to determine suitable design parameters for the split sensitivities, resulting in a sensor body with 3 bending beams. Similar to sensor concept #2 an empirical *check* is performed in the domain sensors to characterize the sensor behaviour, before integrating it into the bolt (mechanics domain).

Now, **knowledge is missing** on the influence of the mounting, this time glue, on the SG characteristics determined before. Hence, the **Testing-Objective** is to *check* the SG characteristics. A similar **hypothesis** is formulated: If the measurement characteristics change only in a linear way after mounting of the sensor body, then the glue succeeds as a mounting method. The **activity** is the *empirical* testing of the sensor body integrated in bolt, with axial and bending loads. The hypothesis is confirmed, this time no exceedingly big hysteresis occurred. The different sensitivities for axial force and bending torques enables the measurement of high axial forces while still being able to detect small bending torques [8]. However, the glue is prone to long-term instability, therefore the hysteresis needs to be watched closely.

Step 26: Check wireless data and energy transmission

Combining electronics and mechanical domain, **knowledge** is **missing** on the effect of the metal of the bolt on the wireless data and energy transmission. Hence, the **Testing-Objective** is to *check* the effect and parameterize it, deciding if the effect is bearable. The **hypothesis**: If the antenna is mounted in the head close to the outside, enough electromagnetic waves can be transferred to enable sufficient communication and energy transfer, because the antenna is only partly shielded. The **activity**: Empirical measurements of a breakout board antenna in a milled section of a bolt's head as a testing-object with the dimensions for electronics narrowed-down from step 14. The hypothesis is confirmed, enough energy and data can be transmitted, if the sender is visible from the bolt head and within a certain distance.

Step 27: Check temperature dependency of measurement
Following the successful electronics testing with evaluation boards in step 11 and the design space from step 14, a PCB is designed, manufactured and checked successfully for its electrical characteristics like power consumption and SNR on generated input signals in step 25. To continue and combine the sensor with electronics, **knowledge is missing** on the interaction of the SG and the measurement characteristics of the electronics (Printed Circuit Board, PCB), focusing temperature dependency. The **Testing-Objective:** *Checking* the temperature dependency. The **hypothesis**: If the sensors and electronics are subjected to temperature change without changing load, the measurement output does not change. This follows in the **activity** of *empirically* conducting measurements with the subsystem of electronics (PCB) with dummy SG in climate chamber. The hypothesis is rejected: A not neglectable temperature drift occurred. Strategies are needed to optimize PCB for less temperature dependency which are explored in step 28 and checked again in step 29.

The last step 30 is a combination of all domains. The sensor and the electronics are integrated into the bolt. Similar to steps 19 and 24 the characteristics of the multi-axial measurements are analysed, this time focusing the influence of the electronics on the measurement characteristics and possible changes in error or sensitivity.

3.2. Patterns and observations of the testing sequence

Table 1 shows the categorization of the sequence of objectives and -activities to gain the necessary specific design knowledge. At the outset, the *testing objective* is mostly to *explore* solution space represented as hypotheses using *activities* in *literature research* or *models* and *analytical equations*. The next step is to *narrow-down* the hypotheses (solution space), which is done *model-wise/analytical* (e.g. step 3, 9), by applying requirements in *literature research* (e.g. step 5, 8) or even *empirical* (e.g. step 15). After *narrowing-down*, *checks* are conducted *model-based* (e.g. step 6) and *empirical* (e.g. step 11). That allows to decide if the *check* passed or failed, that means if the hypothesis is confirmed or rejected, and hence if an iteration is needed. Most of the failed checks appear in the interaction of the domains (red rhombuses in Figure 1). As the project progresses, the testing activities shift from *literature research* to more *model-/ analytical-based* and *empirical* testing (Figure 1, Table 1).

In the mechanical domain (steps 1-3), no empirical tests were performed until the integration phase with the sensor (step 12). The first empirical testing was in electronics using evaluation boards of the chips that were researched (step 11). Empirical Testing-Objects in electronics are rather cheap compared to mechanical or sensory ones in this project. Afterwards, the empirical testing activities focused either on the sensor concepts (steps 16-18, 23) or on integration (steps 15, 19, 24), combining two or more domains. Due to uncertainties with SGs, empirical testing in the sensor domain is necessary to validate the sensor concepts. This process of first checking within the domain, then integrating and rechecking in combination with other domains, was successfully followed throughout development (steps 6&12, 18&19, 23&24, 25&26).

In this project, a model-based approach (negotiation model) was used in the first integration phase of mechanics and sensor (step 13ff.), which led to a successful empirical verification of the design space. In steps 16-18 the sensor concept #2 was explored, narrowed-down and checked empirically, however the integration test with the bolt (step 19) failed due to the unforeseen interactions of the mounting of the sensor body. When integrating to the next level, the interactions of the domains become apparent, and need to be checked by testing activities.

4. Discussion

The research question posed in the introduction can be answered: Utilizing the V-model [9] as a framework, complemented by a rigorous testing methodology [12] to acquire the missing knowledge throughout the process, we successfully developed a working prototype of a sensor-integrating bolt. The systematic formulation of missing knowledge, the creation of testable hypotheses, and the definition of testing objectives and activities facilitated efficient knowledge acquisition. Consequently, the case study was successful. The testing steps adhered to repeating patterns throughout the process, which are elaborated upon in the subsequent paragraphs. Moreover, the following sections discuss the generalizability, transferability, and limitations of the findings.

A strength of the process used is that it emphasizes the use of existing information about bolts and force sensors. Consequently, analytical equations and models can be employed to acquire knowledge pertaining to the mechanical and sensory functions. This is something generally transferable to other sensor integrating machine elements projects where information of a mechanical and sensory nature exists.

Table 1: Sequence of testing objectives and -activities showing patterns; blue, yellow and green represent the domains mechanics, sensors, electronics; Gradients indicate interactions/integrations; The shapes circle, triangle, rhombus indicate the testing-objectives *explore*, *narrow-down*, *check* like in Figure 1. The symbols book, computer, tool indicate activities *researching*, *analytical*, *empirical* like in Figure 1.

Another strength is the early and iterative suggestion of checking the embodiment solutions virtually and physically. This helps to identify and resolve conflict of objectives at an early stage, particularly in the interactions of domains. There most of the failed checks happened in the case study because of unforeseen dependencies. Conflicts of objectives between domains are likely, especially when the sensor is integrated into an existing machine element that interferes with the primary mechanical function. To solve this conflict, knowledge about the interaction is acquired by use of a negotiation model.

Furthermore, the importance of the occurrence of empirical testing in the sequence is emphasized due to its cost. If it is premature, the testing objects are expensive due to the huge solution space. If it is late and the testing fails, the iteration cost is high. Here, the first empirical testing followed a literature research and a narrow-down by analytical / model-based testing where knowledge was acquired. Hence the solution space is small and the iteration is within one domain, which keeps costs low. It can be followed that empirical tests should only be conducted when the solution space is sufficiently small, that the costs for the testing objects needed does not rise over the cost of an iteration (e.g. costs of a late change of sensor concept).

A weakness of the approach is a grey zone in defining the Testing-Objectives, one step could fit in more than one category depending on how the missing knowledge and hypothesis is formulated. Also, the synthesis of design parameters based on the acquired knowledge is only described very briefly in this contribution, which needs to be highlighted in future works.

As limitations the following points need to be mentioned: The sequence of testing activities is dependent on the missing knowledge, which is system specific. The findings are best transferable to machine elements with similar cylindrical geometry and force flows, e.g. shafts, bolts, couplings as could be shown for the part of the negotiation model in [17]. For other machine elements and sensor concepts it may vary. Therefore, in future the patterns need to be compared to sensor integration projects of other machine elements.

In conclusion, this contribution shows the development process of a sensor integrating bolt based on the V-model and expanding it by focusing on repeatable patterns of testing steps for sensor integration, which helped to acquire knowledge in order to successfully build a working prototype of a sensor integrating bolt. These patterns may help in future projects to more efficiently acquire knowledge by conducting the costly testing activities.

The unique contribution of this paper lies in supporting the integration of novel sensory functions into standardized machine elements by resolving the conflict between high mechanical performance and high-quality sensor data. That is enabled by a structured testing methodology that formulates missing knowledge, creates testable hypotheses, and synthesizes embodiment solutions by employing a negotiation model to balance mechanical and sensory functions.

Acknowledgements

This work was funded by the Deutsche Forschungsgemeinschaft (DFG, German Research Foundation) – 466650813 within SPP2305 - 441853410

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