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Development Method for Enabling the Utilisation of a Sensory Function in a Central Component Based on Its Physical Properties

B. Kraus ✉, J. V. Schwind and E. Kirchner

Technical University of Darmstadt, Germany

✉ benjamin.kraus@tu-darmstadt.de

Abstract

In the context of condition monitoring and predictive maintenance, collecting accurate data from technical systems is an important corner stone of the advancing digitalization. For gathering precise data of the current state of a system, measurements from within the process can be utilised. To measure in process without disrupting the system is a challenge that can be tackled by using the physical properties of the components of the system. In this paper a method to systematically find such possible sensory utilizable components (SuC), based on their inherent physical effects is presented.

Keywords: effect catalogue, design methods, sensor development, design research, methodical design

1. Introduction

Regarding the technical advances in digitalising the industry more specific requirements for technical systems arise. One key component for the digitalisation is the ability of a machine, system or product to inform the user or the control system about its current status (*Smart Engineering*, 2012; Fleischer *et al.*, 2018). For those status reports, which can be used for condition monitoring and subsequent condition based or predictive maintenance it is essential, that the system provides high quality data (Ehrlenspiel and Meerkamm, 2017). This data should be as reliable, accurate, and free of uncertainties as possible (Welzbacher *et al.*, 2021) To achieve those goals, one solution is to measure close to the process and the desired variable or to even measure inside the process itself also known as in-situ measurements (Kirchner *et al.*, 2018). In-situ measurements can be done by a conventional sensor, a specialised sensing machine element (SME) or even a sensory-utilisable component (SuC) as shown by (Kraus *et al.*, 2021). While there are plentiful ideas for those measurement systems, for example presented by Petko and Uhl (2004), Groche and Brenneis (2014), Jung and DeSmidt (2018), Großkurth and Martin (2019), Schirra *et al.* (2021) etc., a comprehensive methodology to implement sensor functions into a system is still missing, especially concerning SuCs. To present such a method for developing central SuCs, based on the short rough outline of the development process given by (Kraus *et al.*, 2021), and the not formalised process shown by (Harder *et al.*, 2021) for SMEs is the aim of this paper.

2. State of the art

2.1. Development methods for mechatronic systems

The "general model of product development" according to the VDI 2221 guideline is used as the underlying model of the method (Verein Deutscher Ingenieure, 2019). The sensory utilization of central components in technical systems corresponds to a function integration. Accordingly, the entire product development process is not run through. The relevant activities are the search for principle solutions and their structures as well as the evaluation and selection of feasible solution concepts. According to the VDI 2222 guideline, the development of principle solutions makes use of existing knowledge in the form of design catalogues and solution collections (Verein Deutscher Ingenieure, 1997). For the presented developed method, the effect matrix and the effect catalogue according to Vorwerk-Handing (2021) are used. The method can also be classified in the V-model for the development of mechatronic systems according to the VDI/VDE 2206 guideline (Verein Deutscher Ingenieure, 2021). It corresponds to the "system design" step. Operating principles for the integration of a sensor function into existing components are worked out. The method does not provide for a more detailed design and calculation of the solution concepts found. However, the domain-specific design of the SuC must necessarily follow the method in order to prove the functionality of the solution concept by measurements on prototypes as well as simulations.

2.2. Identification of physical effects

2.2.1. Multi-pole modelling strategy for physical domains

Multi-pole modelling provides an approach to represent the different elements of mechatronic systems across domains on a common abstraction level and is closely related to the through and across or Trent analogy (Trent, 1955). For this purpose, the circuit laws of electrical networks (Kirchhoff's laws) are transferred to general technical systems via analogy considerations. The basic building blocks of modelling are so-called concentrated network elements (cf. Figure 1, left). These elements are clearly distinguished from each other and are defined by the number of interfaces (poles) that enable coupling to other elements. The energy exchange between the network elements can be unambiguously described by two variables, the so-called power conjugate variables:

Flow variables (f) must flow into the element at one point and out at another point. The measurement can be done in one network point.

Effort variables (e) are always present between two poles of a network element. Two different network points are necessary for their measurement.

The product of flow and effort variable has the physical dimension of a power (Janschek, 2010). The flow and effort variables represent intensive state variables, i.e. they are not dependent on the size of the system. For a complete energetic description of a system, the stored energy must also be considered. This is done by introducing two extensive, i.e. dependent on the size of the system, state variables. These are referred to as the "primary variable" and the "extensum". The mathematical relationships between the four system variables of a physical domain are formed via two laws. On the one hand, via a temporal derivative or integration. On the other hand, via shape parameters, which are generally defined by material and/or geometric characteristics. (Vorwerk-Handing, 2021; Janschek, 2010)

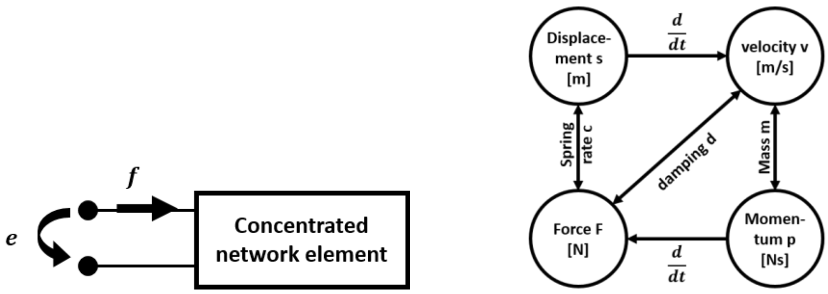

Figure 1. left: Concentrated network element with a flow and effort variable (Janschek, 2010) right: Representation of the four system variables from the domain mechanics (Vorwerk-Handing, 2021)

Figure 1, right shows the relationships between the four system variables of the physical domain "mechanics" according to multi-pole modelling. The force F and the velocity v represent the elementary power conjugate variables (intensive state variables), which are linked to each other via the shape

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parameter of the damping d. They determine the energy exchange with neighbouring systems. The displacement s (extensum) and the momentum p (primary variable) describe the energy stored in the system as extensive state variables.

2.2.2. *Effect matrix and catalogue by Vorwerk-Handing*

A systematic identification of potentially usable physical effects for the sensory detection of a state variable can be done by using the effect matrix and effect catalogue according to Vorwerk-Handing (2021). The basic structure consists of the effect matrix and organises the physical effects as shown in Figure 2. The structure of the effect matrix is based on the described multipole modelling. For the application, the measurand is inserted into the effect matrix as an input variable (cause). For the fulfilment of the sensor function, physical effects are filtered column by column, which have an electrical output variable (effect). The cells of the matrix contain the potentially usable effects. (Vorwerk-Handing, 2021)

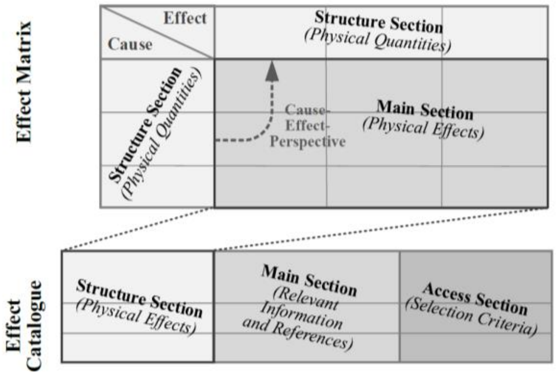

Figure 2. Base structure of the effect catalogue using the effect matrix by (Harder *et al.*, 2021) based on (Vorwerk-Handing, 2021)

The procedure for applying the effect matrix is shown in Figure 2. The effect catalogue is used to check whether the identified effects can be used in a specific technical system. Here, a differentiation is made between component-dependent (e.g. material, geometry) and system-dependent (e.g. kinematic) properties of the effect. For the former, the component can be specifically adapted to realize the effect and develop a SuC. The latter must necessarily be satisfied in the system and thus form a necessary condition for further consideration of an effect. An example of using the effect catalogue is given by (Harder *et al*., 2021), but doesn't include a formalised process.

2.3. The C&C² approach and its extension to identify potential measurement locations

The C&C2 approach can be used to create analysis models for existing or to-be-developed technical systems and products. The purpose of modelling is to identify relations between form and function in the system. For this purpose, all components relevant for the main function are modelled by three core elements, so-called shape function elements (Matthiesen, 2021):

- Working Surface Pairs (WSP) are formed by the interaction of two general surface elements.
- Channel and Support Structures (CSS) are general volume elements that connect two pairs of active surfaces and determine the direction of flow variables in the system.
- Connectors (C) represent the system environment as surface elements.

A model can also be actively adapted. There are three options to change the shape of an existing system and thus integrate new functions: WSP and/or CSS can be added or removed. In addition, the physical properties of these two elements can be adapted (Matthiesen, 2021; Albers et al., 2004).
The C&C² approach was extended to the load path and node model to support sensor integration into technical systems (Vogel, 2021). The aim is to identify and evaluate potential measurement locations for the detection of a flow quantity. The load path describes the path of the flow variable through the system and thus links the model elements. The number of splits as well as the number of model elements to be considered is used as a quality criterion for the identified measurement locations.

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2.4. Sensing machine elements (SME) and their sub-category sensory utilizable machine elements (SuME)

Sensing machine elements are a subcategory of mechatronic machine elements and can be further categorised by their functionalities based on the function model by (Pahl and Beitz, W. Gericke, K., 2021) as done by (Vorwerk-Handing *et al*., 2020). SME generally add a sensory function to a classic machine element and can therefore provide information from within a technical system with little to no extra building space for additional sensors (Kirchner *et al*., 2018).

For this work the subcategory of sensory utilizable machine elements is of special interest, since their underlying idea of utilizing the physical properties of a machine element can be applied to a component that is directly connected to the main function of a system as shown by Kraus *et al*. (2021) & Harder *et al*. (2022). Both categories share similar benefits regarding the ability to provide in-situ measured data for the user and face similar challenges during their implementation (Kraus *et al*., 2021). An example of a SuME are sensor utilizable ball or plain bearings, which use the physical properties of a ball bearing and respectively a sliding bearing to measure loads applied on the system directly from within it (Schirra *et al*., 2021; Harder *et al*., 2021). A formalised method of enhancing components with an additional sensory function by utilising their physical properties will be shown in chapter 3 and is the main concern of this work.

3. Method for enabling the utilisation of a sensory function in a central component

The method for enabling the utilisation of a sensory function in a central component to create so called sensory utilizable components (SuC) is composed of four major steps, which are shown in Figure 3 and will be presented in this chapter. The starting point of the method is the building structure together with the desired target variable for determining the current state of the system. Assuming both as already given by previous steps of the development process.

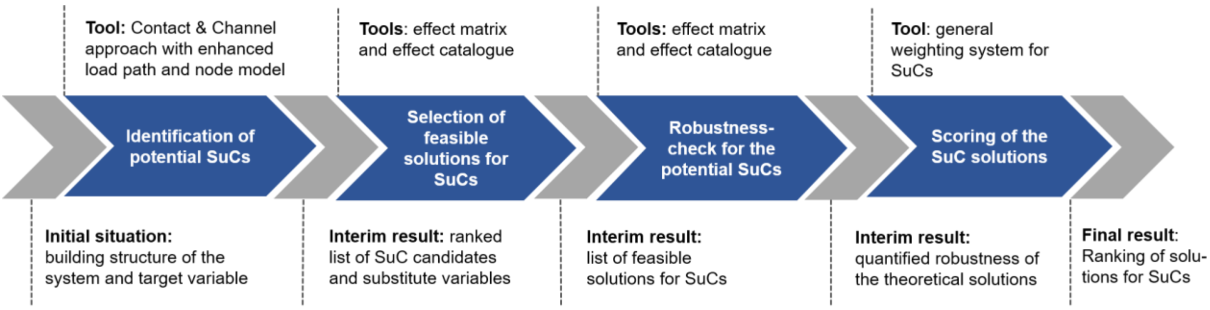

Figure 3. Overview of the four steps to methodically find possible SuCs

3.1. Problem description and background theory

The general development of this method was loosely based on the steps of the "Design Research Methodology" (DRM) by Blessing and Chakrabarti (2009). During step 1 & 2 (research clarification & descriptive study I) and their iterations, it was found that limit the possible solution space can be limited by the in section 2.1 described methods, and some requirements as for example the necessity of reaching the physical domain of elektro-magetism to generate a feasible sensor signal were identified. In terms of the c-k-theory (Le Masson *et al*., 2017), especially the "breadth first" approach in the concept-space used by the Pahl/Beitz model, on which the VDI 2221is based, in conjunction with the V-model approach of splitting up different domains during the design process, can lead to unwanted limitations of the solution space. Therefore, the proposed method aims to first provide the designer with an additional sub-knowledge-space in form of the effect catalogue, and by that guiding to a wider space of possible solution concepts. Afterwards, the concept space is systematically narrowed down by accessing the knowledge-space provided by the designer and the analysed system. The herby found prescriptive study (step 3 of DRM) will be described in the following sections.

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3.2. Identification of potential central sensory utilizable components

The first step is to identify a list of potential central components, which might have utilizable sensory properties. The complete flow chart of this step is shown below (cf. Figure 4). For this purpose the given target variable is matched with its physical domain based on the multi pole modelling strategy. This gives a first impression of the target variables metrological characteristics and enables the usage of the effect matrix and effect catalogue.

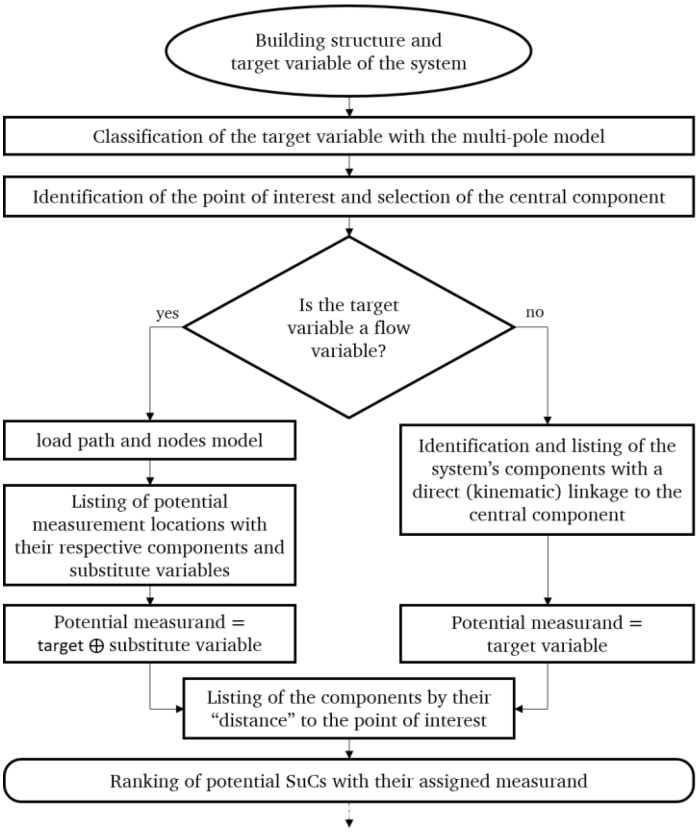

Figure 4. First flow chart to identify potential central sensory utilizable components

The building structure of the system is then used to locate where in the system the target variable originates. The origin is defined as the point of interest and the components directly in or at the point of interest are the first entries in the list of potential SuC candidates. To identify further SuC candidates, it is important to distinguish whether the target variable is a flow variable or not according to the multi pole model presented in chapter 2. If the target variable is a flow variable (left path), it is possible to use the methods of the contact an channel model as well as its extension presented in chapter 2 to identify possible feasible measurement locations and components. Those identified components are then listed as potential candidates based on their proximity to the point of interest together with the substitute variable, which is determined by the transitions between the target quantity and the measurement location. That means in detail, that each node or transition in the "flow path" decreases the proximity to the point of interest, e.g. a component that is reached by two transitions between components or through nodes is ranked lower than a path that is reached by only one transition. The substitute variable can, but does not have to be the target variable.

If the target variable is not a flow variable (right path), the target variable can only be transferred to other components by a direct (kinematic) connection between them. For this method, only components that have a fixed, rigid connection to the components next to the point of interest will be analysed. They are also ranked by their proximity to the point of interest in this case based on the physical distance to it. Their substitute variable is hence always the same as the target variable.

The result of this step is therefore a ranked list of SuC candidates based on their proximity to the point of interest together with their respective substitute variables.

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3.3. Selection of feasible solutions for SuCs based on their inherent physical effects

The second step uses the ranked list to select possible solutions for a SuC based on the physical properties of the components, the flow chart of the second step can be seen below (Figure 5). To achieve this, each component's assigned measurement variable is used as the entry argument for the physical effect catalogue. The catalogue provides possible effects, which connect the measurement variable with other physical variables. To find a feasible sensor solution it is required that the physical variable, found by this step, is inside the domain of electricity, so that the electric variable can be measured and processed automatically. This can be achieved by filtering the solutions by effects, which directly connect the measurement variable with a variable inside the electric domain.

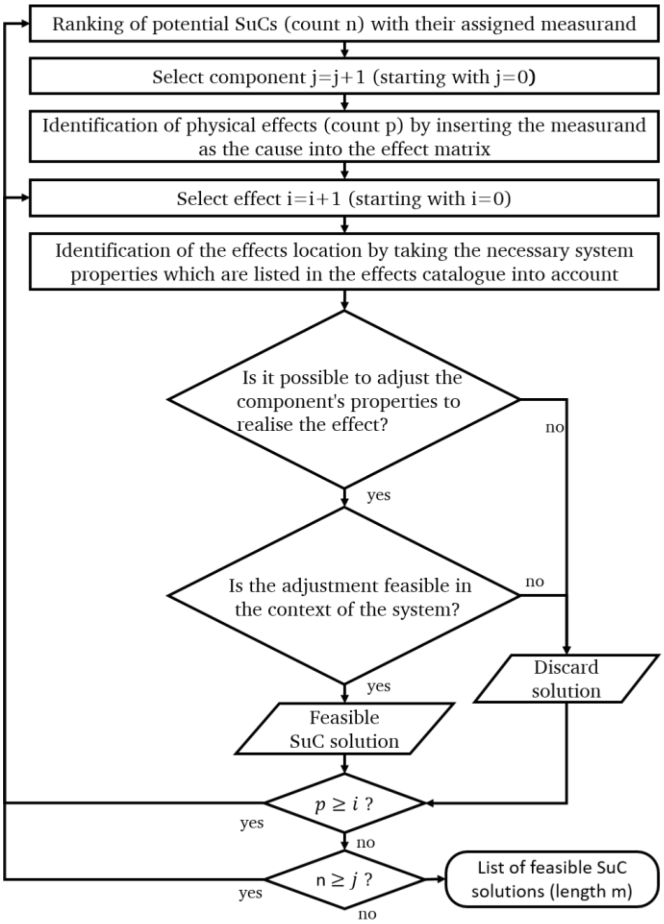

Figure 5. Second Flow Chart for selecting theoretical solutions for SuCs

For each effect found, suitable effective surfaces (or lines or spaces) must be identified within the component. The identification of such active surfaces must take into account the necessary system-dependent (kinematic) properties of the effect. Subsequently, it can be checked whether the component or the effective surface itself is suitable as an effect carrier. For this purpose, an adaptation of the component-specific (material) properties can be examined in order to meet the necessary requirements for the realisation of the physical effect. Both the identification of effective surfaces and the adaptation of the physical properties of the component can be supported by the access part of the effect catalogue. The modification made to the system must be critically considered with regard to its feasibility. Component tolerances as well as installation space restrictions must be taken into account. The physical measurement function must also be reversible.

The result of this step is therefore a list of principle solutions for components that can be used with sensory functions (SuC).

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3.4. Robustness-check for the theoretical SuCs

In a third step (cf. Figure 6), the robustness of the principle solutions to the influences of disturbance variables must be assessed. This step is necessary because of the rough environmental conditions in machines during in-situ measurements. Solutions must be found that are less susceptible to the influence of disturbance variables. The systematic identification of potential disturbance variables is carried out via the effect matrix. For each principle solution, the underlying physical effect (intended effect) is examined with regard to potential indirect superpositions. Such indirect superpositions are physical effects that are causally based on a disturbance variable. If the effect of the disturbance corresponds to the input or output variable of the intended effect, the disturbance can influence the transmission behaviour of the sensory component (Vorwerk-Handing, 2021). It is assumed that n potential disturbance variables have been identified for a principal solution of a SuC. All potential disturbances are assigned the value $D_n = 1$. An examination of the concrete system environment of the SuC provides information on whether the potential disturbance is present. If the disturbance is present in the immediate vicinity of the SuC, such an influence must be anticipated, and the factor E_n is set to 1, and if not, to 0. The environment-dependent robustness coefficient is calculated by the equation:

$$R_k = \frac{1}{1 + \sum(D_n \cdot E_n)}$$

That means, the more disturbance variables influence the transmission behaviour of a sensory component, the less robust it is. (Mathias, 2016)

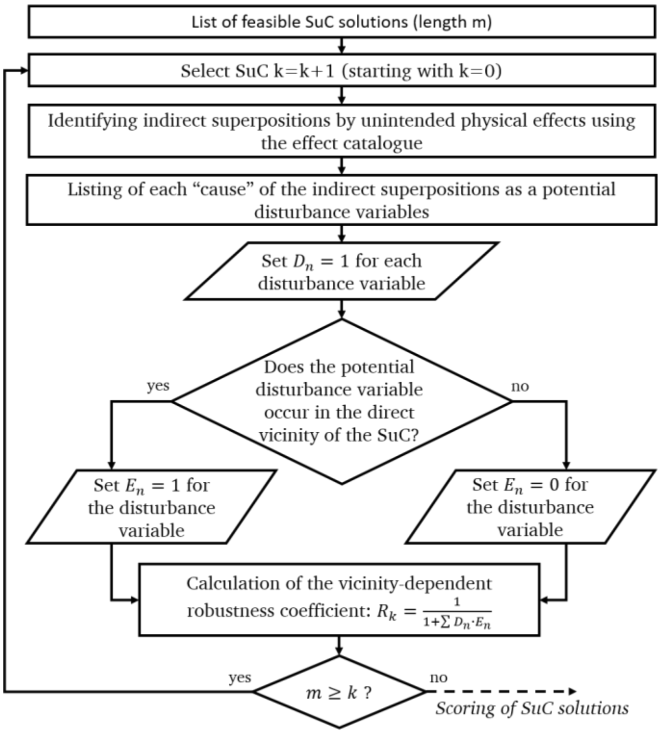

Figure 6. Third flow chart to check the possible SuCs for their robustness

3.5. Scoring of the solutions

A utility value analysis is carried out for the evaluation of the principle solutions (Kirchner, 2020). The analysis is based on a weight sum model. For sensory usable components, a general weighting system was created for the derivation of evaluation criteria. The four different criteria are:

Effort of integration $g_1 = 0{,}2$
Sensitivity of the underlying model equation $g_2 = 0{,}2$
Distance to the point of interest $g_3 = 0{,}3$
Robustness $g_4 = 0{,}3$

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The last two criteria can be seen as a quantification of the solutions inherent uncertainty, which increases with a more complex model as well as the number of disturbances from inside and outside the system. The individual weights of the criteria form suggestions for the value analysis. By assigning a score to each criteria (e.g. from 1 to 4) and multiplying it with its respective weight g_i and then summing up all the weighted scores, it is possible to rank the SuC solutions. For scoring the robustness, the robustness coefficient R_k from the previous step and for the sensitivity the derivation of the effects physical model is used. By performing this final step, the developer acquires a list of feasible ranked solutions for SuCs and can decide whether he or she wants to integrate one of the found solutions into the system.

3.6. Example of found SuCs in a valve system

The procedure described will be illustrated using the example of an electromagnetic valve drive. The system is shown in figure 7 on the right. The valve movement is actuated by two electromagnets, between which an armature moves. The kinetic energy is stored in the valve and actuator spring.
In the first step, the potential SuCs need to be identified. In the example, the opening status of the valve must be detected in order to enable an optimum gas exchange at any time. This is determined by the displacement of the valve disk relative to the valve seat. The valve seat is defined as the point of interest. The valve represents the central component. The displacement to be detected (target variable) corresponds to the extensum from the physical domain of mechanics. Two system points are necessary for its measurement. One system point must be located at the moving measurement object, respectively the potential sensory utilizable component. According to the first step of the method, all components that have a direct kinematic coupling to the movement of the valve are suitable. These are the valve spring, the armature as well as the actuator spring. The second point must be located at a non-moving component. For this purpose, the valve seat, the valve guide or the valve housing can be considered. For all identified components, the measurand corresponds to the displacement.
In the second step, it must be checked whether the identified components can be adapted for the detection of the valve displacement via a specific modification. The best four principle solutions of the valve assembly are shown in figure 7 on the left. The underlying physical effects convert the measurand into an electrical output signal. The displacement can affect the electrical capacitance of a plate capacitor by changing the plate distance. The valve feather mount can be used as a movable measuring electrode, and the valve housing as a fixed counter electrode (solution no. 1). The change in electrical resistance due to displacement is applied to potentiometric sensors. In this case, it can be checked whether the electrical properties of the valve shaft can be used as a potentiometer. A sliding contact would have to be attached to a fixed component (solution no. 2). For the use of magnetoresistive effects for displacement measurement, the electrical measurement signal is not directly present at the SuC. The magnetic field of a permanent magnet is converted into a displacement-dependent signal by applying a tooth structure to the ferromagnetic valve shaft (solution no. 3). The displacement can also affect the electrical capacitance via a change in the covering area of the capacitor plates. As a necessary system-dependent property for determining the effect location, the displacement vector must be perpendicular to the normal vector of the plate surfaces. This condition is fulfilled for the effective surface pair „valve shaft“ and „valve guide“. The effective surfaces can be modelled as a cylindrical capacitor, with the intervening lubricant forming the dielectric. To generate a displacement-dependent capacitance signal, a modification must be made, for example by applying an additional dielectric on the valve shaft, which moves out of the guide during valve movement and thus leads to a change in the electrical capacitance (solution no. 4). The two converging steps three and four of the method are essentially based on already validated procedures and are therefore not further elaborated in the following. The robustness check is based on the systematic identification of disturbance variables on physical effects using the effect matrix. For the evaluation of the solutions, a “utility analysis” is performed using the evaluation criteria presented in section 3.4.
The presented example illustrates that by applying the method, a wide range of solutions for SuCs can be developed. Notably, SuC solutions need certain adjustments to the system such as components for energy and signal transfer, to implement them into the system. A detailed description of all the other found solutions and their scoring won't be presented here to not exceed the limitations for this paper.

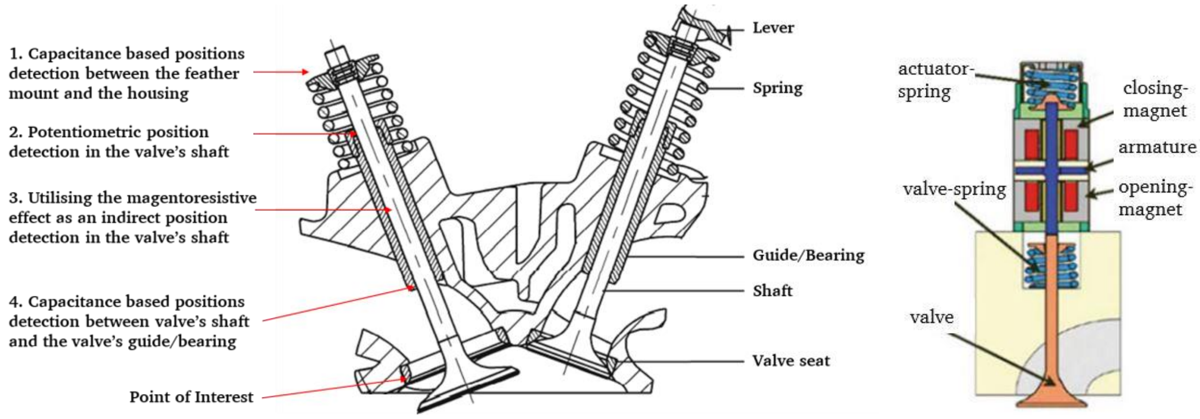

Figure 7. Valve system with the found possible SuC solutions (right) & full actuated valve assembly (left) both based on (Mahle GmbH, 2013)

4. Discussion and Outlook

As shown above it is possible to develop a formalised method for purposefully finding possible SuC solutions in a technical system. The method is based on a good understanding of the multi pole modelling strategy and gives an algorithmic structure to identify, select and score different SuCs inside a system. To apply this method it is necessary to already have a structure of the physical system in place and know the desired target variable. While the method seems feasible on paper a few challenges still need to be overcome to reduce the complexity for the developer. For example, the effect catalogue needs to be updated and provided as open source for developers. Another stepping stone is the necessity to be familiar with the multi pole model. This can be addressed by providing a preferably digital supporting tool for the developer which combines the multi pole theory with the effect matrix and lets the user interact with the provided knowledge space.

Gericke *et al*. (2020) mention several key challenges for methods developed in academia, one of those is the "lack of focus on validation", to address this, the next step to further mature the proposed method is to do a thorough DRM step 4 study. Afterwards, to further refine the method a few steps should be carried out in the future. Firstly, the validation results and feedback should be integrated and secondly the definitions for the method should also be reworked and tested for continuity and simplicity. Thirdly, the method should be verified through more examples and refined based on the results of those verifications. Furthermore, the third and fourth step of the method should be better defined to minimise the necessary knowledge and familiarisation time of a user. And finally a study with experienced developers should be carried out, to analyse the benefit of this method versus a conventional sensor integration.

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