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A Procedure Model for the Systematic Sensor Selection and Integration into Technical Systems

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Abstract

New sensor solutions are under development in the context of digitalization in order to integrate sensory functions into systems. When integrating sensors, the three domains of mechanical, electrical and information engineering must be considered. This results in complex development processes that require suitable procedure models. However, specific procedure models for sensor selection and integration are missing. This contribution proposes a procedure model for sensor selection and integration on the basis of the Munich Procedure Model (MPM) and gives an outlook on open research questions.

Keywords: *design methodology, product development, design methods, sensor selection, sensor integration*

1. Introduction

Today's megatrend of digitalization of products and processes is driving the fourth industrial revolution, also known as Industry 4.0. It describes the networking of products and processes with the help of modern information and communication technologies. A foundation of this development is the availability of high-quality and reliable product and process data, in many cases recorded by suitable sensors. (Hirsch-Kreinsen et al., 2019; Zhou et al., 2015)

A trend towards sensor integration as close as possible to the point of occurrence of the quantity of interest with minor design changes, no additional design space requirements and a low level of measurement uncertainty can be seen in industry and research. This is achieved by integrating sensory functions deep into technical systems in order to overcome prevailing uncertainties and to gain access to new applications of measurement principles. So-called Sensing Machine Elements (SME) provide one approach for this. (Vorwerk-Handing et al., 2020)

Examples for SME are load measuring bearings (cf. Schirra et al., 2018), timing belts (cf. Großkurth and Martin, 2019) or screws (cf. Brecher et al., 2016). The ongoing trend towards the development of new sensor integration approaches can be seen in the setup of the priority program SPP 2305 with the title "*Sensor-integrating machine elements - Pioneer of comprehensive digitalization*" by the German Research Foundation (DFG, *Deutsche Forschungsgemeinschaft*) (cf. SPP 2305 and FZG, 2020).

For the acquisition of measurement data, different quantities can be measured at different locations with a variety of measurement principles and sensor concepts (cf. Czichos, 2018). The development and integration of sensor technology represents a highly complex interdisciplinary field of tension in product development between the domains of mechanical, electrical and information engineering (Nattermann and Anderl, 2010). However, according to Kirchner et al. (2018), an empirical approach to the selection and integration of sensor technology into technical systems is still common.

In the context of this contribution, the term *sensor* is used to refer not only to the actual sensor element that converts a physical input quantity into an electrical output quantity. Rather, the term sensor is used to refer to

the complete *sensor system*, which, in addition to the actual sensor element, can also contain analog-digital signal processing, power supply and communication interfaces. (cf. Hunter et al., 2010; Berger et al., 2016)
In this contribution, the state of the art of existing procedure models for sensor selection and integration is briefly reviewed. Based on the review results, the essential procedure steps for sensor selection and integration are derived. In the next step, a suitable procedure model is developed using the Design Research Methodology (DRM). The contribution concludes with an initial verification example, a discussion of the proposed procedure model and an outlook on further research activities.

2. Fundamentals of systematic approaches to sensor selection and integration

A comprehensive, effective and efficient use of sensors in technical systems requires suitable systematic selection and integration approaches. In the context of new product development or product generation development, questions about sensor selection and integration must be answered in order to determine an optimized sensor solution. For this purpose, e.g., the "*Guideline Sensors for Industrie [sic] 4.0*" describes seven general technical and economic guiding questions and supporting toolboxes (Fleischer et al., 2018). However, such general guiding questions alone are not sufficient to select and integrate suitable sensors into a technical system. In literature, different procedure models for the systematic selection and integration of sensors are proposed. In the following, an overview will be given for this purpose, whereby no completeness can be achieved due to the limited available space. Sensor selection algorithms are not considered in this literature review, as these are specific methods for the sensor selection step within the overall procedure.
As early as the 1980s, Eversheim and Hausmann (1985) proposed a procedure for planning the use of sensors in assembly systems. In a first step, the monitoring requirements are to be derived from the assembly task. Then the monitoring task is described and a monitoring concept as well as a monitoring strategy are defined. In parallel, the available range of sensors is analyzed in order to finally compile the technical solution alternatives. After an economic evaluation, a sensor solution is selected.
Based on these considerations, Classe (1988), Zeller (1995) and Löpelt et al. (2019) have further developed the sensor selection procedure. In addition to the main procedure steps, they also introduce subdivisions of the procedure steps, thereby contributing to the systematization of sensor selection. The systematic approach according to Löpelt et al. provides two phases. In the preparation phase, the measurement task should first be identified, followed by the definition of a requirements list, which is further detailed and concretized throughout the procedure. This is followed by the determination of potential measurement locations and potential measurement quantities. In the second phase, the selection phase, potential measurement principles are selected, the selection is narrowed down and finally a measurement principle is determined. In the end, a suitable sensor can be selected.
In a much more general form and based on the general product development procedure, as also described by Pahl et al. (2007), Regtien (2005) divides the selection of sensors into the procedure steps of requirements definition, selection of the measurement principle, selection of the sensing method and the subsequent sensor selection.
Czichos (2018) describes the procedure for the selection of sensors in a similar general way. In the first step, the quantity of interest is defined and the environment is described. Subsequently, all potential sensors are listed and the best solution is selected. This is followed by a validation of the selected sensor and a calibration of the sensor before commissioning.
As a last example, the work of Jones et al. (2018) is mentioned. The authors divide the overall procedure into a five-step system analysis and the actual sensor selection. In the system analysis, an understanding of the overall system and its fundamental processes is created. Subsequently, the quantities to be measured and the requirements necessary for this are defined and the environment and thus potential disturbance factors are considered. Finally, the costs for implementation of the sensor are estimated. After this system analysis, the authors propose a detailed sensor selection method, which concludes the described procedure.
In addition to these approaches for a systematic sensor selection and integration, the literature offers various experiences of sensor integration projects that have already been carried out. In the following, three representative example projects and their methodological approaches are presented:

- Vasilevitsky and Zoran (2016) empirically integrate sensor technology into additively manufactured machine elements. They first integrate the sensor technology into CAD models of their components, then carry out FEM analysis and validate the integration by means of test runs of additively manufactured components. No context specific methodological approach is followed.
- Schirra et al. (2021) describe their procedure for developing sensing rolling bearings. They begin with a case study in order to determine and evaluate the requirements for a sensing bearing. Afterwards, the sub-functions to be realized are identified, conceptual solved and combined into an overall solution. This solution is prototyped and the degree of fulfilment of the requirements is evaluated. The chosen procedure suggests that the standard VDI 2221 (2019) was chosen.
- In their development, integration and verification of a sensory gear, Peters et al. (2021) use the procedure model according to standard VDI 2206 (2020). They extend the procedure by an additional integration step, since the sensor is first developed independently and then integrated on the gear wheel. The authors do not make any statement about the reason for using this procedure model and possible challenges or deficits in its application.

This list represents only an abstract of sensor integration projects. More sensor integrations are described in literature that choose either an empirical approach or a general, non-specific procedure model of product development. This underlines the statement of Kirchner et al. (2018), that in practice empirical approaches are still regularly used for sensor selection and integration. In other words, often no appropriate methodological approach is used for the whole procedure of sensor selection and integration, which can be attributed to the lack of methodical knowledge of the developers (cf. Lindemann et al., 2011). It can therefore be concluded that there is currently still a lack of specific or adapted procedure models to support product designers, which are not sensor experts, in a systematic sensor selection and integration that considers all three domains of mechanical, electrical and information engineering. These procedure models are necessary to control uncertainty during development as well as application of sensors, which enables an increase of quality of the sensors, of the provided measurement data and finally of the product.

3. Research method

The previously formulated deficits of common approaches to sensor selection and integration as well as the missing specificity of conventional procedure models for this purpose need to be countered by developing a specified procedure model that is designed for sensor selection and integration. This should lead to a reduction of uncertainty in the context of sensor selection and integration, which stems from deficits in the existing knowledge as well as in the methodological competences of the developers, and make the integration process manageable. The procedure model should be able to be used for the development of new products with integrated sensors as well as the integration of sensors into existing products, e.g., as part of a product generation development or as a retrofit solution.

For this purpose, the Design Research Methodology (DRM), proposed by Blessing and Chakrabarti (2009), is used. The DRM aims to make design research more efficient and effective. This also includes the development or adaption of procedure models. In the context of this contribution, Type 3 of design research projects is used. This type is recommended for developing a design support, like a procedure model, when there are none or only insufficient approaches described in literature.

After the identification and specification of the research topic as well as the formulation of a research plan and success criteria a comprehensive literature review is conducted. The reviewed literature includes sensor integration projects, especially of SME, and procedure models from product development of mechatronic products as well as sensor selection and integration, which can be classified as procedural meso- and macro-level models (cf. Wynn and Clarkson, 2018). Based on the review findings requirements for the procedure model are derived and the intended impact of the model to be developed is formulated. The most important requirements are the similarity to the formulated macro structure (cf. Section 4.1), the possibility to directly include supporting methodical tools into the model and the possibility not only to describe the macro-level of the sensor selection and integration, but also the micro-level. Furthermore, the model should be based on established procedure models of product development in order to increase its applicability and acceptance.

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First, a macro structure, which represents the main procedure steps of sensor selection and integration found in literature and by intuition, is developed. Subsequently, a utility analysis is carried out to compare the suitability of different existing procedure models regarding the formulated requirements and identified main procedure steps. This is done in order not to create yet another new procedure model and utilizing the developers' acceptance and knowledge of existing procedure models (cf. Wynn and Clarkson, 2018). After this selection process, the most suitable procedure model for the specific use case of sensor selection and integration is adapted. Conclusively, for an initial evaluation of the procedure model, the model is verified by applying it to a theoretical example. A comprehensive validation is still subject to further research. This contribution is intended to introduce the topic and provide a first potential approach to the scientific discussion.

4. Methodology for a systematic sensor selection and integration

In this chapter, the general procedure steps of sensor selection and integration are systematically derived from the literature and intuitive assumptions. Subsequently, a procedure model for the presented systematic approach is proposed. Finally, the procedure model is initially verified in the context of a simplified example.

4.1. General procedure steps for a systematic sensor selection and integration

The aim of this section is to identify the relevant procedure steps in the context of sensor selection and integration and to summarize them in one model. This is primarily done using the literature already presented in Section 2, but also the experience of the authors.

As already shown in Section 2, different - but in many respects similar - procedure descriptions for sensor selection and integration are available in literature. The procedure models show very similar structures and differ only in detail. For example, the description depths differ or individual procedure steps are omitted, added or combined. The presented procedure models describe thereby mainly the procedure from the clarification of the measurement task up to the selection of potential sensors. The step of the subsequent sensor integration into a new or existing technical system is not mentioned in literature. Finally, some references mention the validation and calibration as the end of a sensor selection.

The procedure models from literature typically represent sequential models, although this form of representation is not useful as it does not capture reality. The procedure model to be developed explicitly does not describe a sequential procedure model, since the steps can be run through in different order or iteratively depending on the specific application. This is one reason for the systematic identification and adaption of a suitable and established procedure model in this contribution.

Based on these findings, the procedure steps can now be summarized in a general model. This model is shown in Figure 1. The derived model is divided into three sections. The system analysis, the system synthesis and the system validation. The system analysis describes the procedure steps of clarification of the measurement task and determination of the quantity of interest, determination of potential measurement locations, determination of potential measurable quantities and determination of potential measurement principles. System synthesis includes the two procedure steps of sensor selection and conceptual sensor integration. The third section describes the validation of the selected and integrated sensor solution. Simultaneously with the three sections, the sensor selection and integration are continuously analyzed and verified. The individual steps are described in detail in Section 4.2.

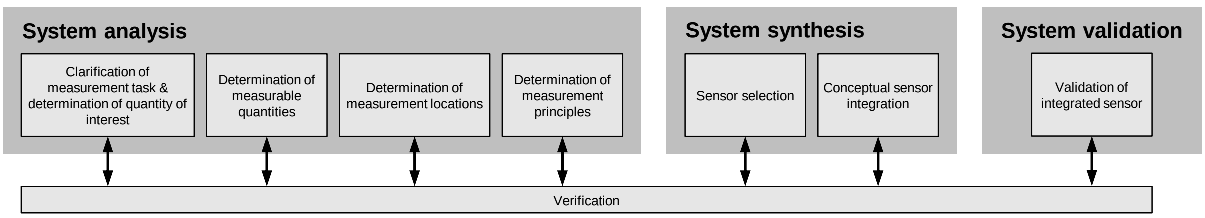

Figure 1. The sensor selection and integration procedure steps grouped into the three sections of system analysis, synthesis and validation and the parallel verification

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4.2. Procedure model and supporting methodical tools for a systematic sensor selection and integration

As defined during the research clarification, the main objective of this research is the development of a procedure model aiming to support developers lacking the required experience to select and integrate sensors intuitively. For achieving this, one of the formulated requirements claims to adapt an existing procedure model (cf. Section 3). On behalf of checking the usability of existing meso- and macro-level procedure models the requirements are weighted and a utility analysis is conducted. The most important requirements are the similarity to the formulated macro structure (cf. Section 4.1), the possibility to directly include distinct methods into the model and the possibility not only to describe the macro-level of the sensor development and integration, but also the micro-level. In this analysis the Munich Procedure Model (MPM) turned out to be a promising procedure model for the sensor selection and integration and will be used as the basis for the procedure model to be developed in this contribution. Although the degree of establishment was rated still low, the MPM offers high potential to represent the macro structure without sequential character and to differentiate the procedure steps. In this way a flexible application and the linking to supporting tools is possible.

Analogous to the MPM, the proposed procedure model for a systematic sensor selection and integration (Figure 2) consists of defined elements (circles) which represent potential procedure steps. These elements can be connected by the developers with situation- and process-specific paths (dashed lines). Since the elements cannot always be clearly separated from each other, they are represented by overlapping circles. For a detailed description of the MPM and its application please refer to Lindemann (2009).

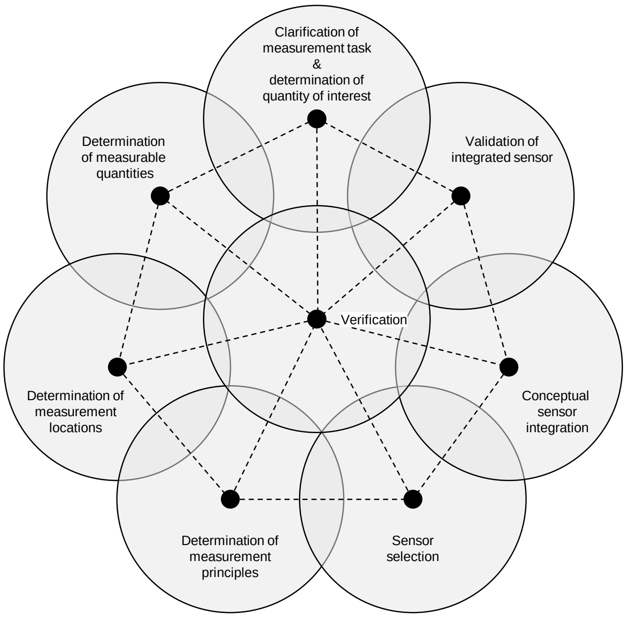

Figure 2. Procedure model for a systematic sensor selection and integration based on the Munich Procedure Model (MPM)

In principle there is no definite entry step for the sensor selection and integration. This is due to the broad variety of possible contextual factors. But following Pahl et al. (2007) the most promising first step is to clarify the measurement task and determine requirements. Also, it is recommended to end a design process with a validation, to ensure that the defined task is fulfilled. Between these elements, the other elements can be accessed in varying order, iterated or omitted. Edges can be passed through bidirectionally. The decision for a specific path must be made context-dependently and can vary during a sensor selection and integration process. However, standard procedures can also be developed experience-based.

The individual elements of the procedure model are briefly described in the following. Furthermore, potential supporting methodical tools are suggested for each element or, if no suitable tools are available in literature, the deficits are pointed out. The methodical support within a procedure step is essential for the successful application of the procedure model.

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In the step of the **clarification of the measurement task and determination of the quantity of interest**, the aim of the measurement is analyzed and defined. This also includes the definition of the quantity of interest. The quantity of interest is subject to the measurement (e.g. an acting force F). Since this measurement can be done indirectly, i.e. via substitute quantities, as well as directly, it is proposed to not call it the measurand in order to distinguish it from the quantity that can actually be measured by the selected sensor, the measurable quantity (e.g. a resulting elongation ε) (cf. Hausmann et al., 2021b). For the derivation of the quantity of interest from the measurement task, no specific method has been found in literature. As this procedure step is similar to the task clarification, requirements for the sensor selection and integration must be identified and formulated (cf. Pahl et al., 2007). Sensor selection and integration adds additional requirements to the mechanical, electrical and information domain. Requirements can be identified with the help of suitable methodical tools, e.g. checklists, and collected in a requirements list. In the further course of sensor selection and integration, these requirements have to be continuously verified and detailed.

The step of the **verification of the system**, including the detailing of requirements, is placed in the center of the procedure model, as it is highly linked to all other steps of the procedure model. Depending on the previous step in the procedure model or the current state of sensor selection and integration, the system can be analyzed subject to different objectives. After analyzing the system and gaining new knowledge about it, the requirements can be verified. Then requirements can be further detailed and a following procedure step can be selected. It is also possible to iterate a previous step.

Analogous to the general product development process, a conceptual design of the sensor must be developed before the development can enter a more detailed level. The next four steps are part of this conceptual design development. As described before, in many cases it is not possible to measure the quantity of interest directly. Therefore, a **determination of potential measurable quantities** must be carried out. The relationship between the quantity of interest and potential measurable quantities can be described on an abstract level by physical effects. The task is to identify the most suitable effect chain, which is associated with a low level of uncertainty and can be realized in the system. For this purpose, one potential methodical tool are the effect catalogues proposed by Vorwerk-Handing (2021).

To enable the measurement of a quantity related to the quantity of interest in complex systems, a **determination of potential measurement locations** must be carried out. At this step it is decided whether the quantity of interest is measured in-situ, i.e. directly at its point of origin, or ex-situ, i.e. distant from it (cf. Hausmann et al., 2021a). One possible methodical tool for this task is the Load Path and Node Model proposed by Vogel (2021). This model can be used specifically to investigate the channel, change and variation of flow variables. This makes it possible to effectively estimate at which location a sensor should be placed in order to be able to sense the measurable quantity with a low level of uncertainty.

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Beside the determination of potential measurement locations and measurable quantities, also a **determination of potential measurement principles** must be carried out. For this the effect catalogues proposed by Vorwerk-Handing (2021) as well as the toolboxes proposed by Fleischer et al. (2018) can potentially be used. The selection of a measurement location, a measurable quantity and a measurement principle cannot be made independently and therefore not in a sequential procedure.

During the **sensor selection**, the conceptual results regarding a measurement location, a measurable quantity and a measurement principle are to be transferred into an embodiment design of the sensor. This also includes the selection of additional aspects of the sensor as the energy supply, the communication interface and potential analog-digital signal processing units. The literature offers various selection methods for this purpose, such as the three-sieve selection tool proposed by Jones et

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[al. (2018)]. These selection approaches are always based on a consideration of the defined requirements.
A further step is the **conceptual sensor integration** into the technical system. Within the scope of this step, the available design space, interfaces and other requirements must be considered to create a first concept for the integration of the sensor. This concept is transferred to the overall product development process so that the sensor can be considered in further product development. For the integration step, the literature does not yet provide suitable methodical support and contextual factors. In many cases, this integration process is carried out on an empirical or simulative basis. Schirra et al. (2021) propose initial design rules for the integration of sensing rolling bearings into gearboxes. However, these only represent an excerpt of the whole integration process and do not yet consider all relevant domains, such as power supply and signal transmission.
The final step involves a **validation of the integrated sensor**. The level of fulfilment of the requirements as well as the requirements itself must be evaluated before the sensor selection and integration can be successfully completed. For this purpose, evaluation criteria should be defined in the clarification of the measurement task and evaluated in this step. In many cases, prototypes are developed or simulations are carried out for this purpose.

4.3. Initial verification of the procedure model based on an example application

For the initial verification of the developed procedure model, it must be evaluated whether the requirements defined for the procedure model are fulfilled. For this purpose, a part of the development of a sensing timing belt for the measurement of the span-specific belt force is used as an illustrative example here (cf. Großkurth and Martin, 2019). Figure 3 shows the sensing timing belt on the left and a segment of the procedure model on the right, which will be considered below. A complete validation of the procedure model, e.g. with the help of suitable studies, is ongoing in further research, but could not yet be carried out due to time constraints.

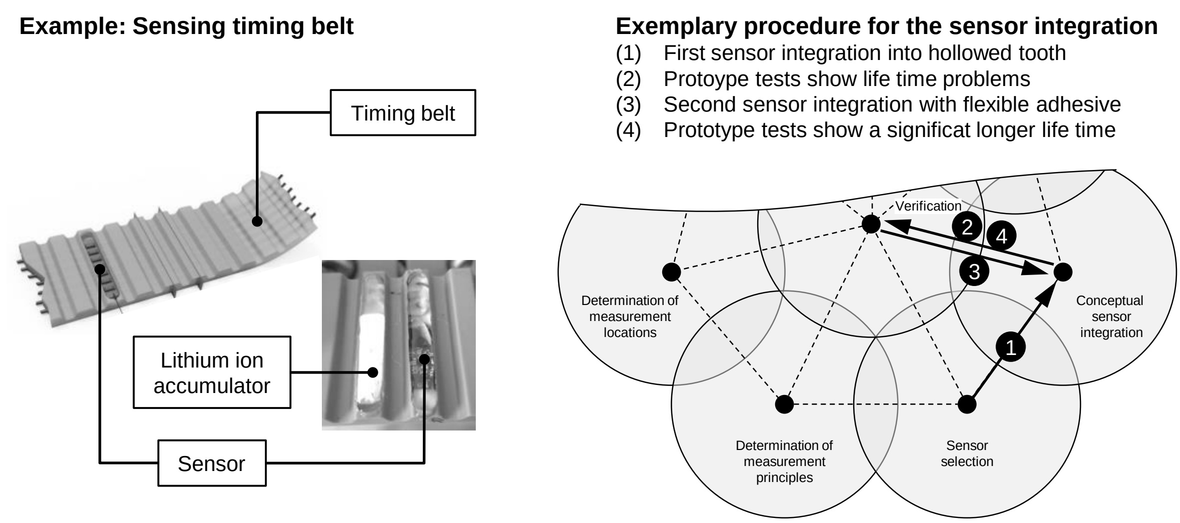

Figure 3. Sensing timing belt as sensor integration example and the exemplary procedure for a iterative sensor integration (left: cf. Welzbacher et al., 2021)

The example used here describes the selection and integration of a sensor directly in a timing belt in order to determine the span-specific belt force in-situ, as described in by Grosskurth and Martin (2019). In the system analysis the measurement location directly in a tooth is determined, whereby the span-specific belt force as quantity of interest is determined by the eigenfrequency of the timing belt as measurable quantity. MEMS accelerometers are used to measure vibrations and thus the eigenfrequency. In the system synthesis the selected sensor is now to be integrated into a tooth (1). For this purpose, a tooth is hollowed out and the sensor is embedded. During a subsequent verification (2), prototype tests showed that the sensor is subjected to the same degree of bending as the timing belt

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due to the high stiffness of the adhesive used. The sensor cannot withstand these loads. On the basis of this verification, a suitable next procedure step can now be identified in the model. An iteration of the integration seems promising and is carried out (3). By using a different adhesive with more flexible properties, a significantly better life time can be achieved in a subsequent verification phase (4).
The example shows that the iterative and complex procedure for sensor selection and integration can be described and potentially supported with the help of the proposed procedure model. The procedure model fulfills the essential requirements that were set at the beginning. These include the similarity to the macro structure and existing procedure models - in this case the MPM. Furthermore, supporting methodical tools can be provided for the individual procedure steps, which also enables a detailing of the micro structure.

5. Discussion

The intention of this contribution is the proposal of a suitable procedure model for sensor selection and integration based on a literature review on existing procedure models in product development and sensor selection and integration. However, the proposed procedure model has not yet been validated. This is planned in the context of further research. With the help of a comprehensive validation the quality, applicability and acceptance of the procedure model can be evaluated and potential improvements can be identified.
During the development of the procedure model, deficits in the available supporting methodical tools for the individual procedure steps were identified, which need to be addressed in future research. For example, suitable approaches for the determination of suitable quantities of interest from the measurement task have not been proposed so far. But also, in the context of the conceptual integration of a selected sensor into a technical system, supporting methodical tools for a systematic and efficient integration that is not exclusively experience-based are still missing. Furthermore, design guidelines in the context of the Design for X approach, a "*Design for Sensor Integration*"-approach, should therefore be developed.
For a comprehensive validation, an integration of the described procedure into the general product development process of technical systems is still missing. The question must be answered as to when which steps can or should be carried out. For this purpose, the relevant contextual factors must be identified and described. This is also subject to current research.

6. Conclusion

This contribution presents different approaches for sensor selection and integration from literature and thereby identifies the main procedure steps. These are transferred into a procedure model for a systematic application in product development. This procedure model is based on the Munich Procedure Model (MPM) and is suitable for the iterative and cross-domain development tasks in the context of sensor selection and integration. Finally, an initial verification of the procedure model is presented and the need for further research activities is specified in the discussion, such as a comprehensive validation of the presented procedure model.

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References

Berger, C., Hees, A., Braunreuther, S. and Reinhart, G. (2016), "Characterization of Cyber-Physical Sensor Systems", *Procedia CIRP*, Vol. 41, pp. 638–643. https://doi.org/10.1016/j.procir.2015.12.019.

Blessing, L.T.M. and Chakrabarti, A. (2009), *DRM, a Design Research Methodology*, Springer, Dordrecht. https://doi.org/10.1007/978-1-84882-587-1.

Brecher, C., Jasper, D., Schmidt, S. and Fey, M. (2016), "Methodik zur Ermittlung der Schraubenzusatzkräfte von Schraubenverbindungen", *Konstruktion*, Vol. 68 No. 6, pp. 78–82.

Classe, D. (1988), Beitrag zur Steigerung der Flexibilität automatisierter Montagesysteme durch Sensorintegration und erweiterte Steuerungskonzepte, [PhD Thesis], Carl Hanser Verlag, Munich.

Czichos, H. (2018), Measurement, Testing and Sensor Technology: Fundamentals and Application to Materials and Technical Systems, Springer, Cham. https://doi.org/10.1007/978-3-319-76385-9.

Eversheim, W. and Hausmann, A. (1985), "Planung des Sensoreinsatzes für flexibel automatisierte Montagesysteme mit Industrierobotern", *VDI-Z*, Vol. 127 No. 1/2, pp. 37–40.

Fleischer, J., Klee, B., Spohrer, A. and Merz, S. (2018), *Guideline Sensors for Industrie 4.0. Options for cost-efficient sensor systems*. [online] VDMA-Forum Industrie 4.0. Available at: https://vdma.org/viewer/-/v2article/render/1132021 (accessed 16.02.2022).

Großkurth, D. and Martin, G. (2019), "Intelligenter Zahnriemen", in *20. GMA/ITG-Fachtagung Sensoren und Messsysteme 2019: Tagungsband*, *25.-26.06.2019*, *Nuremberg*, AMA Service GmbH, pp. 738–743. https://doi.org/10.5162/sensoren2019/P2.14.

Hausmann, M., Koch, Y. and Kirchner, E. (2021a), "Managing the Uncertainty in Data-Acquisition by In Situ Measurements. A Review and Evaluation of Sensing Machine Element Approaches in the Context of Digital Twins", *International Journal of Product Lifecycle Management*, Vol. 13 No. 1, pp. 48–65. https://doi.org/10.1504/IJPLM.2021.115700.

Hausmann, M., Welzbacher, P. and Kirchner, E. (2021b), "Development of a General Sensor System Model to Describe the Functionality and the Uncertainty of Sensing Machine Elements", in *Proceedings of the International Conference on Engineering Design (ICED21), 16.-20.08.2021, Gothenburg, Sweden*, Cambridge University Press, Cambridge, pp. 1243–1252. https://doi.org/10.1017/pds.2021.124.

Hirsch-Kreinsen, H., Kubach, U., Stark, R., Wichert, G. von, Hornung, S., Hubrecht, L., Sedlmeir, J. and Steglich, S. (2019), *Key Themes of Industry 4.0. Research and Development Needs for Successfull Implementation of Industry 4.0*. [online] Research Council of the Plattform Industrie 4.0. Available at: https://en.acatech.de/publication/key-themes-of-industrie-4-0/ (accessed 18.02.2022).

Hunter, G.W., Stetter, J.R., Hesketh, P. and Liu, C.-C. (2010), "Smart Sensor Systems", *The Electrochemical Society Interface*, Vol. 19 No. 4, pp. 29–34.

Jones, P.M., Lonne, Q., Talaia, P., Leighton, G.J.T., Botte, G.G., Mutnuri, S. and Williams, L. (2018), "A Straightforward Route to Sensor Selection for IoT Systems. A straightforward three-sieve selection tool facilitates the selection of sensors for IoT systems", *Research-Technology Management*, Vol. 61 No. 5, pp. 41–50. https://doi.org/10.1080/08956308.2018.1495965.

Kirchner, E., Martin, G. and Vogel, S. (2018), "Sensor Integrating Machine Elements. Key to In-Situ Measurements in Mechanical Engineering", in Schützer, K. (Ed.), *23° Seminário Internacional de Alta Tecnologia: Desenvolvimento de Produtos Inteligentes: Desafios e vovos requsitos*, Piracicaba.

Lindemann, C., Hippler, K.-R. and Koch, R. (2011), "Requirements Engineering. Ein Ansatz auch für die klassische Produktentwicklung?", in Reussner, R., Pretschner, W.A. and Jähnichen, S. (Eds.), *Software Engineering 2011: Workshopband, 21.-25.02.2011, Karlsruhe, Germany*, Gesellschaft für Informatik, Bonn, pp. 205–216.

Lindemann, U. (2009), Methodische Entwicklung technischer Produkte: Methoden flexibel und situationsgerecht anwenden, VDI-Buch, 3., korrigierte Aufl., Springer, Dordrecht.

Löpelt, M., Wilsky, P., Ruffert, J., Göhlert, N., Prielipp, R. and Riedel, R. (2019), "Sensorauswahl für Bestandsanlagen", *ZWF Zeitschrift für wirtschaftlichen Fabrikbetrieb*, Vol. 114 No. 5, pp. 273–276. https://doi.org/10.3139/104.112087.

Nattermann, R. and Anderl, R. (2010), "Approach for a Data-Managmenet-System and a Proceeding-Model for the Development of Adaptronic Systems", in *Proceedings of the ASME 2010 Internetional Mechanical Engineering Congress and Exposition: Volume 3: Design and Manufacturing*, *Parts A and B, 12.-18.11.2010, Vancouver*, ASME, pp. 379–387. https://doi.org/10.1115/IMECE2010-37828.

Pahl, G., Beitz, W., Feldhusen, J. and Grote, K.-H. (2007), *Engineering Design: A Systematic Approach*, 3. ed., Springer, London.

Peters, J., Ott, L., Dörr, M., Gwosch, T. and Matthiesen, S. (2021), "Design of sensor integrating gears. Methodical development, integration and verification of an in-Situ MEMS sensor system", in *Procedia CIRP: 31st CIRP Design Conference* 2021, Elsevier, pp. 672–677. https://doi.org/10.5445/IR/1000133745.

Regtien, P.P. (2005), "Selection of Sensors", in Sydenham, P.H. and Thorn, R. (Eds.), *Handbook of Measuring System Design*, John Wiley & Sons, Chichester, pp. 778–780.

Schirra, T., Martin, G. and Kirchner, E. (2021), "Design of and with sensing machine elements. Using the example of a sensing rolling bearing", in *Proceedings of the International Conference on Engineering Design (ICED21), 16.-20.08.2021*, *Gothenburg, Sweden*, Cambridge University Press, Cambridge, pp. 1063–1072. https://doi.org/10.1017/pds.2021.106.

Schirra, T., Martin, G., Vogel, S. and Kirchner, E. (2018), "Ball Bearings as Sensors for Systematical Combination of Load and Failure Monitoring", in Marjanović, D., Štorga, M., Škec, S., Bojčetić, N. and Pavković, N. (Eds.), *Proceedings of the DESIGN 2018 15th International Design Conference, May, 21-24*, *2018*, *Dubrovnik*, *Croatia*, Faculty of Mechanical Engineering and Naval Architecture, University of Zagreb, Croatia; The Design Society, Glasgow, UK, pp. 3011–3022. https://doi.org/10.21278/idc.2018.0306.

SPP 2305 and FZG (2020), *Sensor-integrating machine elements. Pioneer of comprehensive digitalization*. [online] SPP 2305 and FZG. Available at: https://www.spp2305.de/ (accessed 27.10.2021).

Vasilevitsky, T. and Zoran, A. (2016), "Steel-Sense. Integrating Machine Elements with Sensors by Additive Manufacturing", in Kaye, J., Druin, A., Lampe, C., Morris, D. and Hourcade, J.P. (Eds.), *Proceedings of the 2016 CHI Conference on Human Factors in Computing Systems*, *07.-12.05.2016*, *San Jose*, *USA*, ACM, New York, pp. 5731–5742. https://doi.org/10.1145/2858036.2858309.

VDI (2019). VDI 2221-1:2019-11: Entwicklung technischer Produkte und Systeme -- Modell der Produktentwicklung, Beuth Verlag, Berlin.

VDI/VDE (2020). VDI/VDE 2206:2020-09: Entwicklung cyber-physischer mechatronischer Systeme (CPMS) -- Draft, Beuth Verlag, Berlin.

Vogel, S. (2021), Das Lastpfad und Knotenmodell. Eine Erweiterung des C&C²-Ansatzes zur Bewertung von Ersatzgrößen in der Produktentwicklung mechatronischer Systeme [PhD Thesis], Technical University of Darmstadt, Darmstadt.

Vorwerk-Handing, G. (2021), Erfassung systemspezifischer Zustandsgrößen. Physikalische Effektkataloge zur systematischen Identifikation potentieller Messgrößen [PhD Thesis], Technical University of Darmstadt, Darmstadt.

Vorwerk-Handing, G., Gwosch, T., Schork, S., Kirchner, E. and Matthiesen, S. (2020), "Classification and examples of next generation machine elements", *Forschung im Ingenieurwesen*, Vol. 84, pp. 21–32. https://doi.org/10.1007/s10010-019-00382-1.

Welzbacher, P., Schulte, F., Neu, M., Koch, Y. and Kirchner, E. (2021), "An Approach for the Quantitative Description of Uncertainty to Support Robust Design in Sensing Technology", *Design Science*, Vol. 7 No. 18. https://doi.org/10.1017/dsj.2021.19.

Wynn, D.C. and Clarkson, P.J. (2018), "Process models in design and development", *Research in Engineering Design*, Vol. 29 No. 2, pp. 161–202. https://doi.org/10.1007/s00163-017-0262-7.

Zeller, F.-J. (1995), *Sensorplanung und schnelle Sensorregelung für Industrieroboter*, [PhD Thesis], Carl Hanser Verlag, Munich.

Zhou, K., Liu, T. and Zhou, L. (2015), "Industry 4.0: Towards Future Industrial Opportunities and Challenges", in Tang, Z. (Ed.), 2015 *12th International Conference on Fuzzy Systems and Knowledge Discovery: FSKD 2015 15-17 August*, *Zhangjiajie, China*, IEEE, Piscataway, pp. 2147–2152.