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Integration of Measurement Functions in Existing Systems – Retrofitting as Basis for Digitalization

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Abstract

In the current situation of a rapidly progressing digitalization has to be noticed, that still a lot of technical systems exist which were developed without taking the particular requirements of digitalization into account. An essential requirement of a digital system, which can not be achieved by most of those existing (analogous) systems, is to provide the relevant physical quantities, e.g. real time measurement of process related forces in mechanical structures. In many cases a new development or replacement of those existing systems would lead to prohibitive cost or is not feasible due to limited human resources. One promising approach to provide the relevant physical quantities without a new development or replacement of the whole system is the integration of measurement functions by retrofitting or rather by locally further developing the existing system. This paper therefore introduces an approach for sensor integration in existing systems. Based on application dependent goals, a methodical procedure is described which leads in individual steps to a retrofitting concept for integrating measurement functions in existing systems. After clarifying the application dependent goals, the first step of the method consists of a system analysis and focuses on defining and structuring the solution space of potential concepts. This step includes a systematic capture of potential measurement places, potential quantities to be measured and the corresponding models between the relevant physical and the potentially measured quantities. Based on this, the concept synthesis in the second step pursueses the goal of developing promising concepts and to evaluate these. During this step the potential of substituting conventional machine elements with mechatronic machine elements is discussed. All steps described above are verified by developing and implementing a measuring system for providing real time data of wheel forces in an existing formula student racing car. The application of the described approach in an industrial cooperation project has shown that it is necessary to extend the approach by the option of a local further development of the existing system. For this reason three optional steps which allow local modifications but prevent a complete new development are introduced. Generally the first optional step and the base for the following ones, is to analyse the existing system to ascertain the main restrictions regarding the implementation of a measurement system. Derived from these restrictions, additional requirements for the integration of measurement functions are defined and compared with the initial requirements of the system. If a contradiction occurs in this step, this restriction

prevents an integration of a measurement function in this area. Otherwise both, the initial requirements of the system and the detected requirements for the integration of measurement functions form the basis for a local further development to continuously improve the system of interest.

Keywords: Product Design, Digitalization, Measurement Function, Retrofitting

1 Introduction

The progressive digitalization in the field of mechanical engineering as a part of the development towards Cyber-Physical-Systems (CPS) requires a solid data basis of the functional and process relevant physical quantities (Abramovici & Herzog, 2016; BMWi, 2016). Due to long development and/or life cycles, a lot of technical systems exist which were developed without taking account of this particular requirement. As a consequence those systems can mostly not provide such a data basis. Examples are the provision of currently occurring forces in (analogous) mechanical structures, cf. Chapter 3, or process parameters in existing production facilities (Harting, 2017). Since in many cases a new development or replacement of those existing systems would lead to prohibitive cost or is not feasible due to limited human resources (Harting, 2017), the question occurs, how to integrate these systems in a digital environment. To achieve the mentioned integration, in a first step these systems have to be enabled to provide the relevant physical quantities. Therefore the integration of measurement functions by retrofitting or rather by locally further developing the existing system provides a step to build the needed basis for digitalization. This superordinate goal can be considered from two different perspectives: The product developer/manufacturer gets the chance to optimize the product due to a deeper understanding and to open potential additional business fields or the customer/user could take the advantages of the functional extension of the system such as intelligent automatization based on in-situ measured data.
The essential questions which are not yet answered deal with the issue how to integrate the required measurement functions in an efficient and methodical way in existing systems. The first question is, for which reason a specific physical quantity is needed, which implies the required target quantity or target information. Based on this, the question which physical quantities could be measured to get the required (target) information has to be clarified. This point includes the creation of a physical model to correlate the measured quantity and the target quantity. Directly related is the question where to measure the identified measurand. Besides finding potential measuring locations, the evaluation of these and the decision criteria are important aspects which have to be considered as well. Finally the question which kind of sensor (principle) is appropriate to measure the intended measurand under the given boundary conditions has to be answered.
To support product developers in a methodical way, this paper introduces an approach for sensor integration in existing systems which focusses on the question which physical quantity should be measured to get the required information and where to measure. Therefore a methodical procedure is developed and described which leads in individual steps to an upgrading concept for integrating measurement functions in existing systems. To verify and illustrate the approach in Chapter 2, the example of developing and implementing a measuring system to provide information about the current wheel forces in an existing formula student racing car (Figure 1) is used. Chapter 3 provides an outlook on the application of the developed approach in an industrial cooperation project.

2 Development of a Methodical Approach for Integrating Measurement Functions in Existing Systems

Generally the developed approach is seen in the methodical context of product development, for example described in the VDI-Guideline 2221 (1993) or by Pahl and Beitz (2007). The following approach assumes that an existing system is not able to provide the needed information about certain physical quantities, a new development or replacement of the existing system is not intended or not feasible and consequently an integration of measurement functions in the existing system is striven for. Furthermore, the method assumes that the problem definition is completed. That includes the precise definition of the application dependent goals in form of requirements. Among others, the target quantity has to be clarified. In the exemplary case, the current wheel forces of the formula student racing car in x-, y- and z-dimension are defined as target quantities (Figure 1).
The first step of the following method consists of a system analysis and focuses on defining system boundaries and structuring the system. This step contains an abstraction of the problem and has a diverging character according to Pahl and Beitz (2007). Based on this, the concept synthesis in the second step pursues the goal of developing promising concepts and to value these. Therefore the second step has a convergent character.

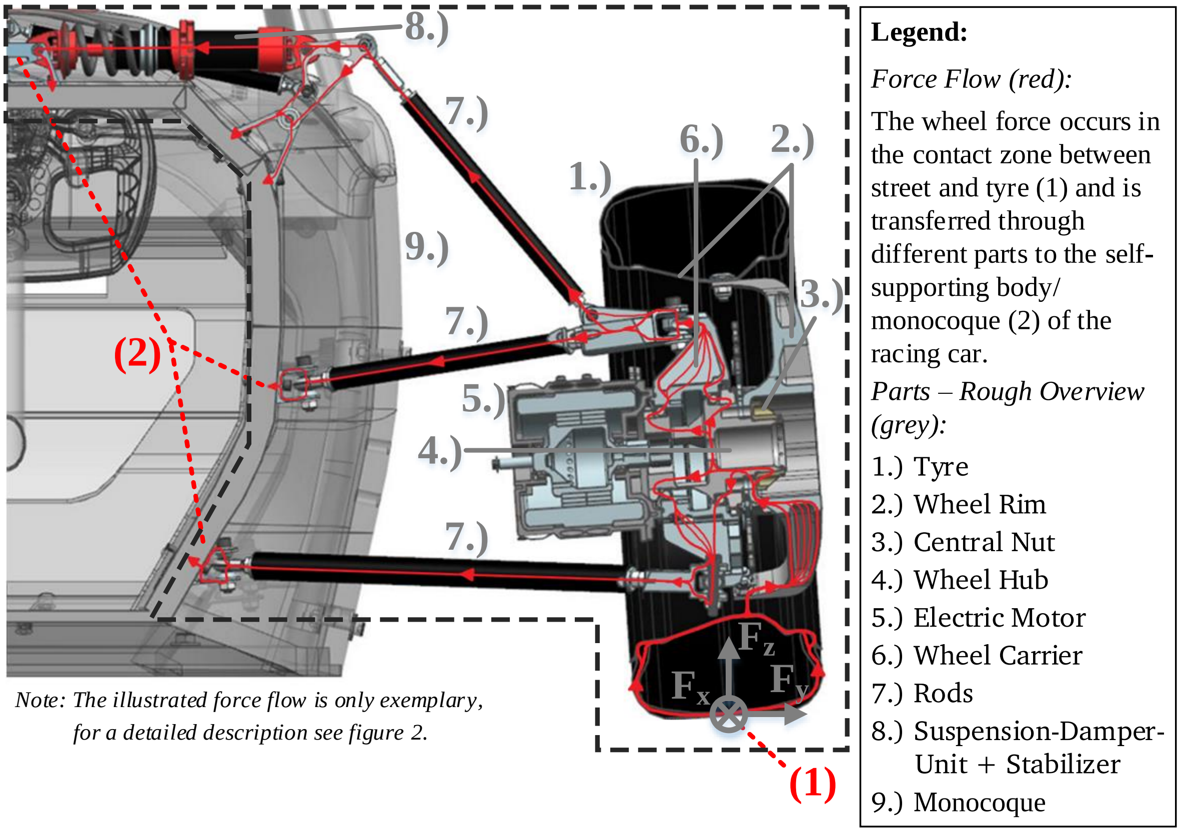


Figure 1. Considered subsystem of the formula student racing car

2.1 Analysis of the System

The main objective of the system analysis is to establish a reliable basis for the concept development. To achieve this objective two results are needed: Delimitation and structuring of the system and based on this a comprehensive detection of all physical quantities which could be used to define the target quantity. Potential measurands and the corresponding models to determine the target quantity are derived subsequently.

2.1.1 Delimitation and structuring of the solution space

Delimitation and structuring of the system depend on the considered system and the particular goals. Therefor it is not possible to describe a uniform approach which is appropriate in all cases. As a result of this step the scope and limits of the system have to be clarified and the potential content should be in a structured form for the further considerations.

To illustrate this step of the mentioned approach it is applied for gathering forces in mechanical structures in general and wheel forces in a formula student racing car in particular. The operational wheel force occurs in the contact zone between street and tyre (Figure 1 (1)) and is transferred through different parts to the self-supporting body (monocoque) of the racing car (Figure 1 (2)). Since the individual wheel forces are superimposed in the monocoque, it is not possible to measure these individually afterwards. Thus the system boundary is defined by two interfaces: The contact zone between street and tyre (Figure 1 (1)) and the interface between chassis and monocoque (Figure 1 (2)). To structure the system in a methodical way it is promising to consider the force flow (Figure 1 and Figure 2). In this way it is ensured that all components which are involved in the force flow, and therefore are potentially appropriate to be used for measuring the occurring forces, are captured. The intensive investigation of the force flow also leads to a deeper understanding of the system. As seen in Figure 2, on the one hand the force flow splits up partially in up to five parallel paths and on the other hand there are components which concentrate the force flow. During the following development process various paths have to be observed depending on the measuring point. At least a model of the force distribution between the observed path and potential parallel paths has to be integrated in the measurement and analysis process.

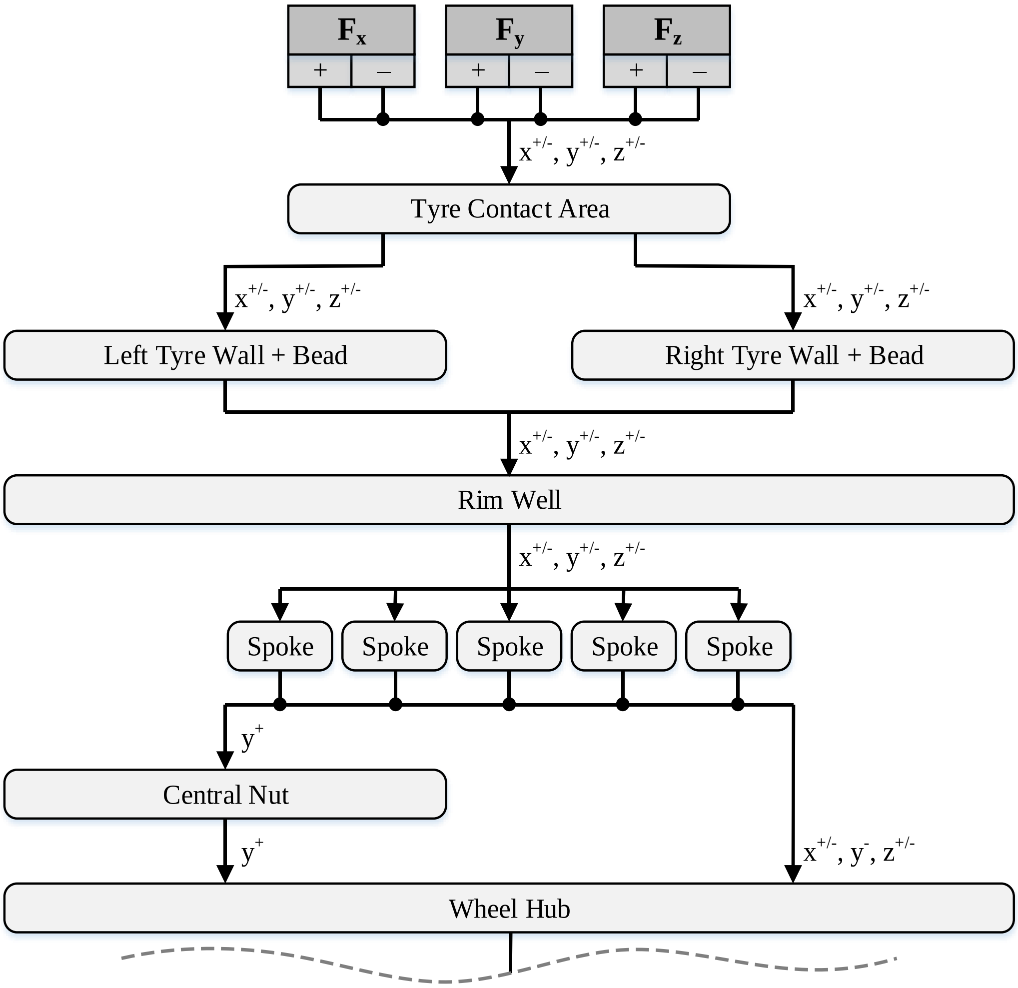


Figure 2. Section of the force flow, illustrated in a flow chart

2.1.2 Detection of potential measurands

For the example of gathering forces in mechanical structures, a methodical way to delimit and structure the system is described above. The second part of the analysis aims at a comprehensive detection of all potential measurands which could be used to determine the target quantity. This step requires a systematic differentiation between the target quantity, which is actually the quantity of interest and therefore the general objective of all efforts, and a variety of quantities which are unequivocally related to this target quantity and therefore potential measurands. Of course in the simplest case the target quantity is directly measureable and is therefore the measurand. The mentioned unequivocal relation between the target quantity and the measurand(s) does not require unequivocalness in a single component of the system. Instead, as mentioned above, the combination of all gathered information by analysing the measurand(s) has to be in an unequivocal and determinable relation to the target quantity. The relation between the combination of all gathered information and the target quantity has to be depicted in an underlying model. The methodical detection of all potential physical quantities which could be used, or rather which are needed, to define the target quantity and the underlying models is an essential step in the whole approach. A result of this step could be a network of interactions originating from the target quantity. These interactions could occur in an intended, but also in an unintended form in the perspective of the fundamental function of the system. Since this step also depends on the considered system, its components and the particular goals, quite different approaches could be appropriate. A promising approach for the considered case of gathering forces in mechanical structures is illustrated below, using the continuous example of measuring wheel forces in a formula student racing car.

Since this step is based on finding existing physical relations between the target quantity, in this case a mechanic force, and potential measurands, it is useful to rely on existing knowledge collections for example in form of design catalogues (Koller, 1998). Originating from a chosen principle, in this case a force, the mentioned design catalogue relates dependent physical quantities and the correlating physical effects. In principle this step is iterated based on the detected dependent physical quantities for all parts of the system. It has to be mentioned that after the first part, in this case the tyre, further physical quantities besides the force are transferred through the individual parts and the interfaces between these parts. Consequently these physical quantities have to be considered in the following steps also. In Figure 3 the grey lines between the physical quantities illustrate these relations. Considering Figure 3 it is further on notable that the detected dependencies are reiterating. The reason for this reiteration is founded in the pure mechanical coupling between the individual parts which is only able to transfer the same physical quantities to the connected parts. Furthermore on this level of abstraction the physical properties of the individual parts are relatively similar. The gained information is illustrated in a tree diagram in Figure 3. The additional information about the physical effects which underlie the dependence between the physical quantities could be used later as origin for developing the models between the measurand(s) and the target quantity.

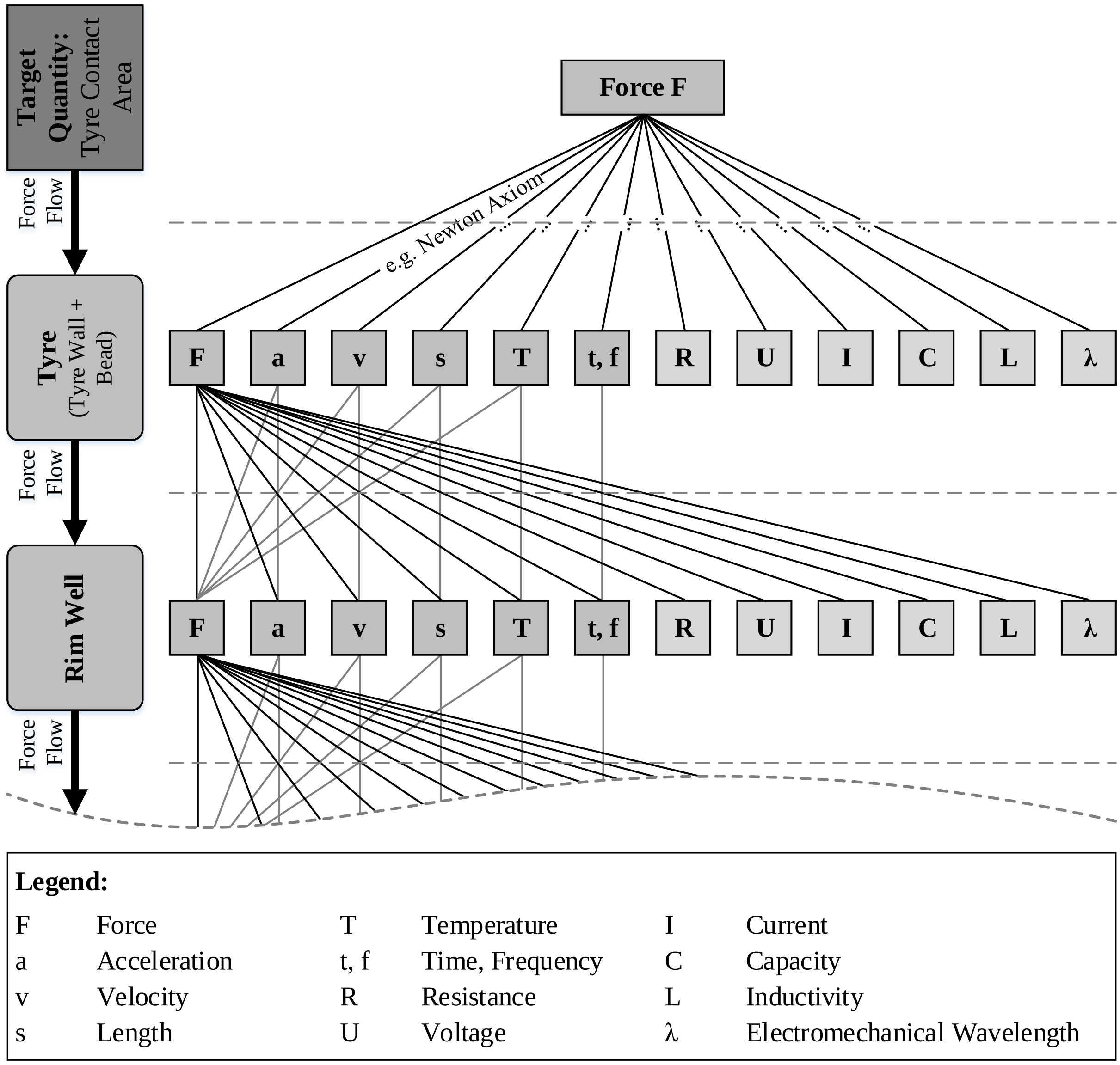


Figure 3. Physical relations between the target quantity (mechanic force) and potential measurands derived from a design catalogue

2.2 Synthesis of Concepts

Based on the structured system and the detection of potential measurands as an outcome of the system analysis, the concept synthesis focusses on a methodical and efficient development of concepts and the evaluation of these. To achieve this objective two main steps are applied: Systematic variation of decisive distinguishing characteristics and a parallel review and valuation process of the generated concepts. Since the decisive distinguishing characteristics and also potential review and evaluation criteria are depending on the considered system, its components and the particular goals, the approach is again applied for gathering forces in mechanical structures in general and wheel forces in a formula student racing car in particular. According to the structuring of the solution space, all components which are involved in the force flow are potentially appropriate to be used for measuring the occurring forces. In the current stage of development it is neither prescribed nor clear which component of the considered system has to be used or is the most appropriate for measuring the occurring forces. Furthermore it is possible to add additional components only for measuring purpose. These mentioned components could be placed in the interfaces between the existing components and thus be placed in or parallel to the force flow. For this reason the question where to measure, which includes a consideration of the individual components of the system and also the option of measuring between these components by adding additional components, represent the first variation criterion. Not included in this consideration is the exact measuring point on an individual component. Since in general a successive concretisation minimizes the necessary effort in a development project (Pahl & Beitz, 2007), the exact localization has to be determined in a following development stage. As introduced above, the systematic differentiation between the target quantity and potential measurands leads to the recognition that a variety of quantities which are unequivocal related to the target quantity are possible measurands. Therefore the second variation criterion is derived from the detection of potential measurands during the analysis stage. As introduced the considered component and potential measurands are dependent on and influenced by each other. For this reason a combination of these variation criteria is not merely useful, but essential. A schematic representation of the variation step is visualized in Figure 4.

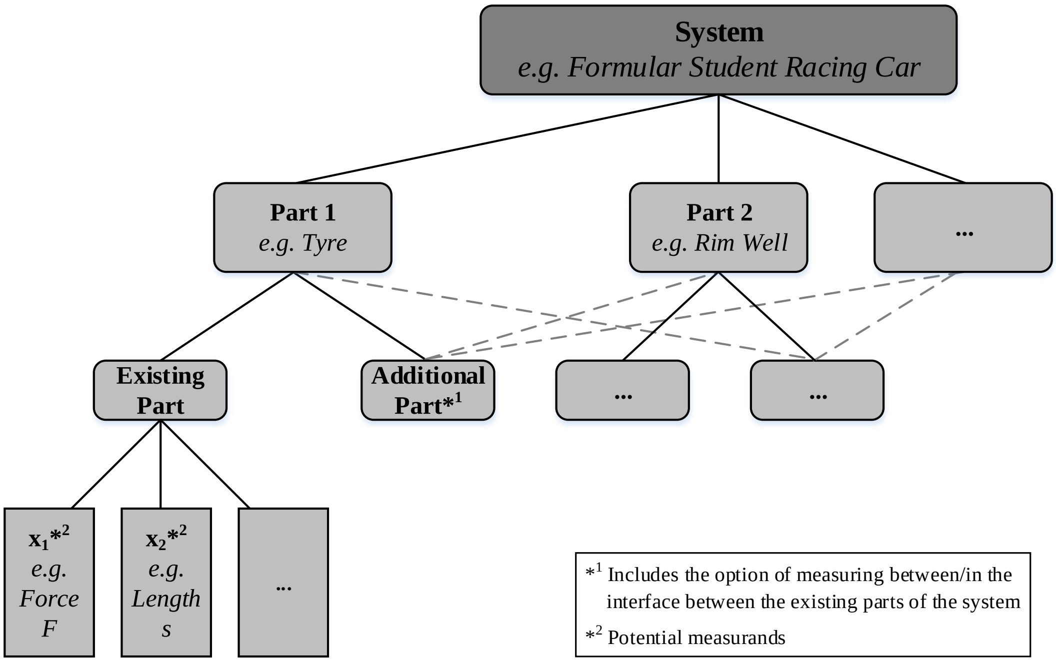
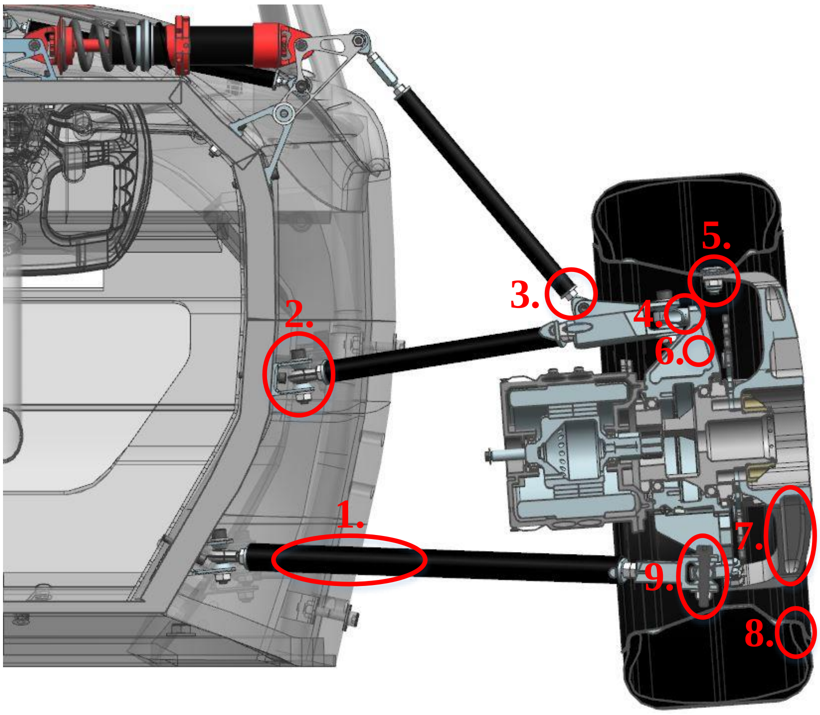


Figure 4. Schematic representation of the variation step

To minimize the necessary effort, the schematic variation process is extended by a preceded analysis of similarities between the variation criteria and a potential formation of clusters. The components of the exemplary system can be clustered in two groups. On the one hand there are recurring components which are used several times to fulfil the same basic function. Examples are screws, nuts, washers, bearings or joints. On the other hand are individual components which are developed to fulfil a specific function under specific requirements. The first group are standardized parts with similar characteristics. Therefore it is mostly sufficient to variate each of these parts only once with all potential measurands and to transfer the results in form of potential principle solutions to similar parts. A promising approach is the development and application of Mechatronic Machine Elements (MME). Mechatronic Machine Elements are standardized parts which are derived from conventional machine elements but extended in their function by implementing for example sensory components (Martin, Schork, Vogel, & Kirchner, 2018). In this way measurement functions could be potentially realized in existing systems by substituting conventional machine elements by Mechatronic Machine Elements.

As a result of the introduced approach an exhaustive solution space is generated in a methodical way. To ensure an efficient development of promising concepts a review and selection process, based on the formulated requirements is integrated in the variation process.
The application of the introduced approach for gathering wheel forces in a formula student racing car has shown promising results, finally in form of nine concepts. An overview of the developed concepts is shown in Figure 5. After a validation step following VDI-Guideline 2225 (1998), the two most promising concepts in form of measuring the occurring force directly or rather the strain in the rods, were built up in a first experimental setup (Figure 6). First static and dynamic measurements were performed with this setup by applying forces on the monocoque while the respective wheel was placed on a triaxial force sensor. First results of measurements have demonstrated that the developed concepts are functional. In this way the introduced approach is verified initially.



Legend:
1. Rod – Strain
2. Rod – Screw Connection
3. Rod – Force
4. Wheel Carrier – Force
5. Wheel Rim – Screw Connection
6. Wheel Carrier – Strain
7. Spoke – Position
8. Rim Well – Force
9. Wheel Carrier – Screw Connection

Figure 5. Overview about the developed concepts

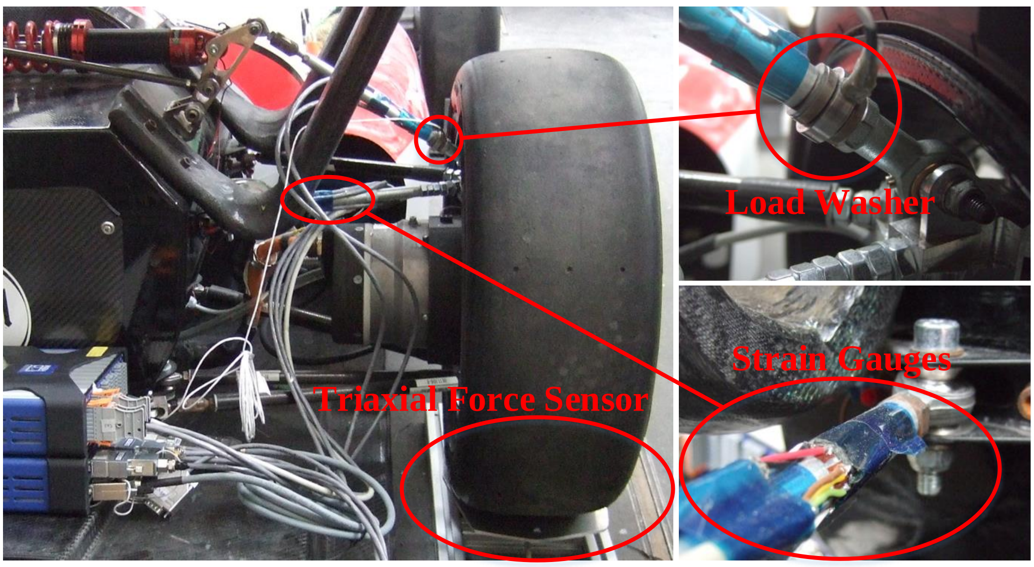


Figure 6. Exemplary experimental setup

3 Application of the Approach in an Industrial Cooperation Project

The introduced approach for sensor integration in an existing system was applied in an industrial cooperation project. The main objective of this project is the concept development for sensor integration in an existing assembly of a commercial vehicle. Overarching goals are for example in the field of progressive automation in form of autonomous driving, safety and/or comfort aspects as well. Since the project is still running and the results are subject to confidentiality, the following explanations are focussed on the applied approach on a methodical level.

3.1 Project Overview

The basic boundary conditions in this project are similar to the ones from the example of gathering the current wheel forces of a formula student racing car in chapter 2. An existing system is unable to provide the needed information in form of occuring forces in an analougus mechanical structure, a new development of the whole existing systems is not intended and consequently an integration of measurement functions in the existing system is striven for. The precise definition of the application dependent goals in form of requirements, among others the target quantity, is completed in a preceded step. Based on this initial situation the introduced approach has been applied successfully. By delimitation and structuring of the system along the force flow and based on this a comprehensive detection of all potential measurands the basis for the concept development is created. Through a systematic variation of decisive distinguishing characteristics and a parallel review and valuation process potential concepts are generated. Considering the developed concepts it is notable that finally all concepts are focussed on one part of the assembly. By analysing the reasons why all concepts are focussed on one part of the assembly, it is striking that the boundary conditions of the existing system limit the finally founded solutions in this case drastically. Since the preservation of the current system should not be an end in itself and a potential new or further development of the system could entail significant advantages, it is interesting to get more detailed information about potential concepts without these restricting boundary conditions. Therefore it is reasonable or rather necessary to extend the approach by local further development of the existing system. For this reason three optional steps, which allow local modifications but prevent a complete new development are introduced in chapter 3.2.

3.2 Extension of the Method – Local Further Development

To take the mentioned aspect of locally further developing the system into account, the initial step of the potentially three following ones has to be the analysis which boundary conditions mostly restrict the solutions in the previous steps. In the considered case, the most important examples for such restricting boundary conditions are the prescribed geometries/force flows and the indefinable material properties of some parts. To analyse the whole system in a methodical and therefore efficient way it is useful to follow the structuring which is developed in section 2.1.1, in this case along the force flow. Derived from these restrictions in a second step additional requirements to circumvent the detected restrictions in the respective part are defined and compared with the initial requirements of the system. If a contradiction between the derived and the initial requirements of the system occurs in this step the respective restriction prevents an integration of a measurement function in this area. Otherwise both, the initial requirements of the system and the detected requirements for the integration of measurement functions, form the basis for a local further development. The local further development, in this case focused modifications of the existing system, are implemented in the third step which is orientated towards methodical product development, for example described in the VDI-Guideline 2221 (1993) or by Pahl and Beitz (2007).

4 Methodical Approach for Integrating Measurement Functions in Existing Systems

Chapters two and three of this paper have introduced an approach for sensor integration in existing systems. Based on application dependent goals, a methodical procedure is described which leads in individual steps to a concept for integrating measurement functions in existing systems. These individual steps are summarised in Figure 7, which illustrates the main outcome of this paper. Based on the target quantity the "Analysis of the System", as shown in Figure 7 on the left, comprises the delimitation and structuring of the system and the following identification of potential measurands. Figure 7 on the right represents the "Synthesis of Concepts" and focusses on a methodical and efficient development of concepts and the evaluation of these. The three optional steps, which allow local modifications but prevent a complete new development (cf. chapter 3) are illustrated in the lower part of Figure 7.

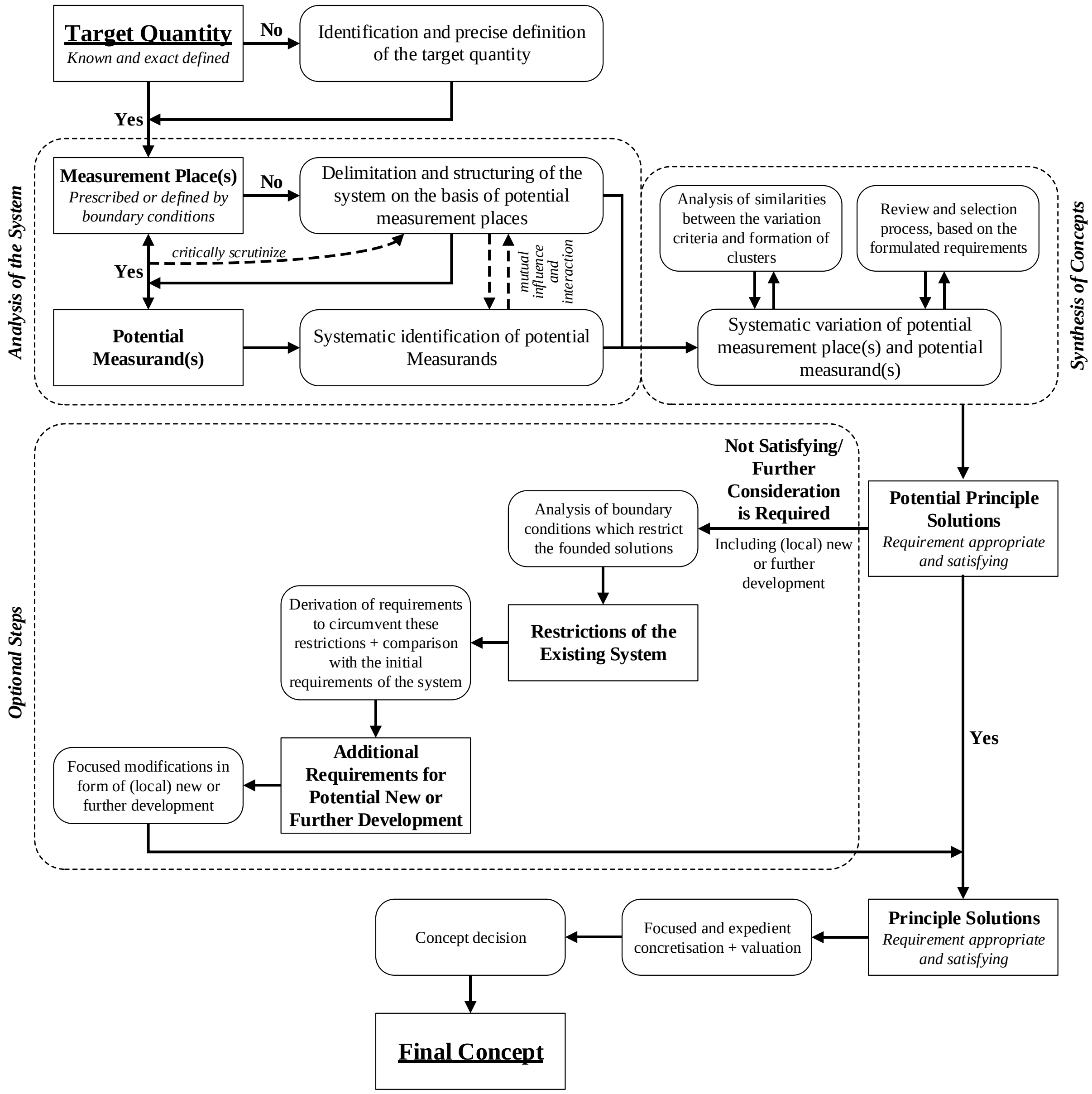


Figure 7. Methodical approach for integrating measurement functions in existing systems

5 Conclusion and Further Research

This paper introduces an approach, which supports the product developer with the integration of measurement functions by retrofitting or rather by locally further developing existing systems. The approach focusses on the question which physical quantities could be measured to get the required information and where to measure these. The presented approach is verified initially by applying it for gathering wheel forces in a formula student racing car and forces in an existing mechanical assembly of a commercial vehicle.

To identify potential measurands the opportunity of using existing knowledge collections in form of design catalogues is successfully applied. It has been shown that these catalogues are not only useful for finding solutions in their original sense, but also for analysing existing systems and identifying dependencies which could be used to derive potential measurands. In this way the method could support the developer to approach the integration of measurement functions in existing systems more systematically, which increases the prospects of success. It has to be noticed that in the considered case of measuring forces in mechanic structures the iteration of this step for all parts of the system is not necessary. The relevant dependencies could be detected in a single step by considering one single component of the system. Nevertheless, for other applications it is generally reasonable to iterate this step for all parts of the system. Potential concepts are generated by a systematic variation of decisive distinguishing characteristics. In the case of gathering forces in mechanical structures the individual components of the system and the option of measuring between these components by adding additional components are proposed as a first variation criterion. As a second variation criterion the potential measurand is identified. The essential advantage of this approach is the methodical development of a solution space. Particular because the integration of sensors in existing systems is often different compared to the initial requirements of fulfilling the main function. Based on the knowledge that the preservation of the current system is not an end in itself and a potential new or further development of the system could entail significant advantages, three optional steps, which allow local modifications but prevent a complete new development of the existing system, are introduced. Based on the analysis which restrictions mostly limit the finally founded solutions in the previous steps, additional requirements to circumvent the detected restrictions are defined and compared with the initial requirements of the system. If these derived requirements are compatible with the initial requirements of the system both, the initial requirements of the system and the detected requirements for the integration of measurement functions form the basis for a local further development. In this way a focussed further development of the existing system is achieved with the aim of reducing the needed effort as much as possible.

The main focus of further research will be on the application and verification of the introduced approach under different boundary conditions for example other target quantities (except forces). Also the relations between target quantity and potential measurand, including modelling the relations, will be investigated further on. The explicit inclusion of further boundary conditions such as disturbance variables or uncertainty lets further questions arise as well.

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