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Procedia CIRP 119 (2023) 1041–1046

www.elsevier.com/locate/procedia

33rd CIRP Design Conference

A method for optimizing product architectures for the management of disturbance factors

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Abstract

The demand for a better product and process quality is ever increasing in the globalized world. To satisfy this demand the management of disturbance factors in mechatronic systems is essential. The applicability and efficiency of strategies targeted at the management of these factors depend on the components, the source of the disturbance factors and the systems building structure. Therefore, a method is developed to derive a building structure of a system, which supports the management of disturbance factors, from an existing functional structure. This support lowers the effort, necessary to manage disturbance factors, and thereby aids in increasing the quality of the product and the associated process. Finally, the presented method is applied on to a sensor integrating timing belt to demonstrate its usability and practicality.

Keywords: Robust Design ; Disturbance Factors ; Disturbance Variables ; Modularization ; System Architecture Design ; Sensor Integrating Machine Elements ; Product Development ; Product Design

1. Introduction and motivation

In an increasingly globalized world, the demands on product quality are rising [1]. Companies must thus improve the quality of their products. In the case of mechatronic systems, one aspect related to product quality are the disturbance factors acting on the system. These can affect any component of the system, regardless whether it is functioning as an actuator, sensor or its function is purely mechanical. These disturbance factors can originate either from the environment or from the product itself [2]. There are multiple approaches to manage these disturbance factors [3]. The necessity and success of these approaches depend on a number of influences. It is the premise of this publication that these influences do not need to be taken as given. One of these influences is the building structure of a product, since it determines which components are grouped and which interact with each other. For a system of low complexity the consideration of disturbance factors in the development of a building structure can be carried out intuitively. For more complex systems, on the other hand, a methodical approach is useful to identify potential synergies and negative interactions between components and thus enables the building structure to be optimized accordingly. The aim of this paper is to present such a method and demonstrate the methods potential by using the example of a sensor integrating timing belt.

10.1016/j.procir.2023.02.179

2. State of the art

In the following subsections, the state of the art relevant to this contribution is presented. First, an introduction to existing robust design strategies is given. Then, the product architecture design is explained. The focus here is on creating a uniform understanding of the relevant terms for the paper, so that existing methods are only discussed in passing. Finally, it is explained how the consideration of disturbance factors in the development of product architectures has been methodically considered so far.

2.1. Robust design

Based on Taguchi, a product or process is robust, when it has limited or reduced functional variation, even in the presence of disturbance factors, whereas the discipline to design these products and processes is called robust design [2]. A number of methods exist for designing such a robust system, the goal of which is to reduce the influence of disturbance factors into the process or function of a product [3].
These strategies, which differ in the point at which they prevent the influence of the disturbance factor into the process, can be divided into three basic categories [3]:

- Eliminate disturbance factor: The occurrence of the disturbance itself is prevented.
- Reduce/eliminate disturbance factor influence: The disturbance factor occurs, but the system is designed in a way preventing the disturbance factor to affect the process or product.
- Eliminate/reduce disturbance factor impact: The existence of the disturbance factor and its influence on the system is inevitable, but the system is designed so that the impact of the disturbance factor does not limit the functionality of the process or product.

Mathias et al. state that the effectiveness or feasibility of individual measures does not have to be present in every case [3]. Therefore, the applicability and efficiency of any measure depends on a number of influences. Amongst others, one of these influences is the building structure of the product, since this determines into the interaction of the different components.

2.2. Product architecture design

According to Kotler, a product is everything that can be offered to a person to fulfil a wish or a need [4]. According to Alisch, products can be divided into tangible goods, intangible services and energy services [5]. In the context of this paper the term product is restricted to systems with technical functions, which do not exclusively include sensory and actuator functions.
A product is composed of the assemblies contained in it and the components built into the assemblies. The physical structure of the assemblies and components is called building structure. The components perform the various partial functions, whereby the sum of the partial functions of different levels represents the overall function of the system. The representation in Fig. 1 is a simplification, since the fulfilment of a partial function can be implemented by several components and at the same time a single component can be used to fulfil several partial functions. The functional structure describes how the overall function is derived from the partial functions. Functional structure and building structure can be represented together in the product architecture, which is shown in Fig. 1 [6]. Depending on how the product architecture is designed, various synergies or negative interactions result. For this reason, strategies have already been developed that aim to generate advantageous product architectures, such as the Modular Function Deployment by Erixon [10]. However, previous strategies of product architecture design are not able to include the interaction of components specifically for different disturbance factors.

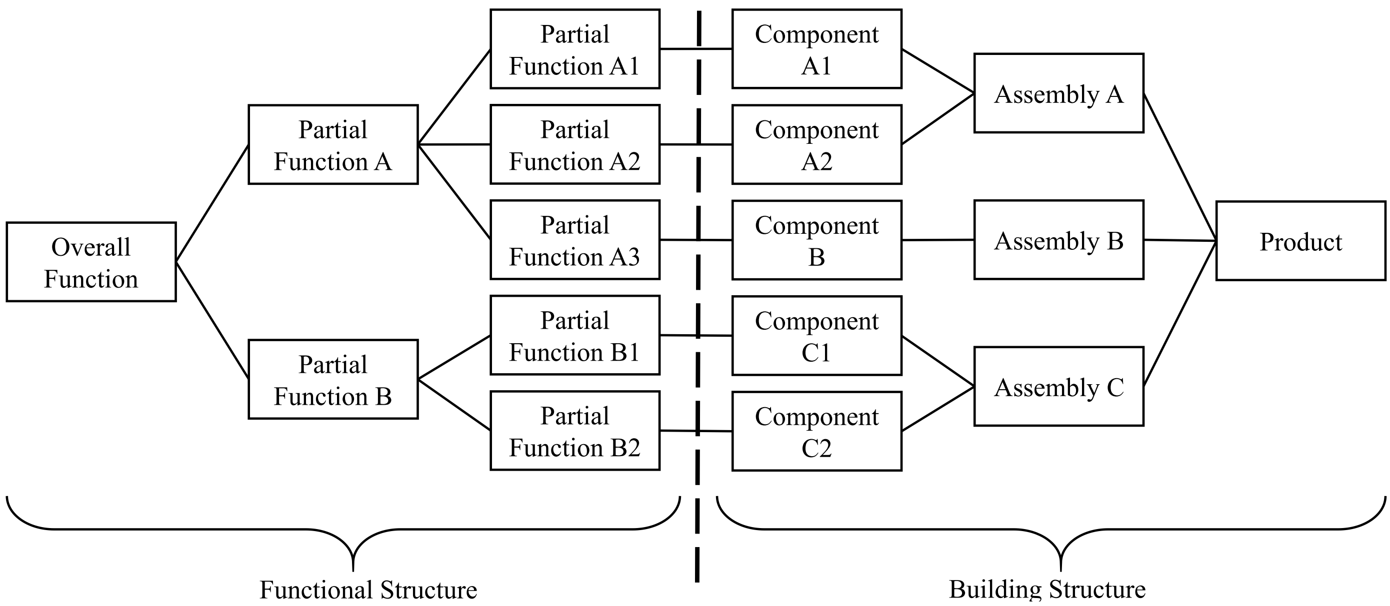

Fig. 1. Schematic representation of a product architecture, translated from [1]

It is important to note that the presented method can be applied both in the general design of a building structure as well as in the development of a modular product structure. The term assembly used to describe the method is thus not a restriction on applicability and is merely used for linguistic consistency within the contribution.

2.3. Disturbance factors in the development of product architectures

In the development of mechatronic products, field effects emanating from actuators, sensors and components for control and data management can be a significant disturbance factor. Electromagnetic effects, thermal fields, etc. may be necessary to perform desired product functions, and undesirable fields may damage other components [7]. Sanaei et al. consider field effects in Design-Structure Matrices by investigating the impact of field effect constraints on product architecture during modularization. The designer is assisted during modularization by applying constraints with interactive algorithms to form and evaluate module clusters to find an improved product architecture [8].
Otto et al. present guidelines for considering field effects in the product development process. Functional structures are used as visual support for the guidelines, which aim to identify, for example, isolating components or components that are able to transform and transfer fields and move them across module boundaries to find more feasible and innovative design solutions [7].

3. Methodical support to handling disturbance factors

The method presented in this contribution is based on the assumption that components can be assigned to one of four different roles regarding every individual disturbance factor:

- Emittor, which means that a component emits a disturbance factor,
- Affector, which means that a disturbance factor has a negative effect on a component
- Sensor, which means that a component is used to detect a physical quantity in the system on which a disturbance factor is based
- Irrelevant, which means, that the disturbance factor has no meaningful impact on the component in this specific system

These roles are derived from five characteristics, which were developed for this contribution and represent design strategies aimed at the management of disturbance in mechatronic systems. These characteristics do not necessarily replace the strategies presented in the fundamentals, but might only serve as enablers for these strategies. These characteristics are as follows:

- Pairs of components in which one is the sensor for a disturbance factor affecting the other component must be spatially separated from each other.
- Components that are detrimental to each other due to their emitted disturbance factors must be spatially separated from each other.
- Pairs of components in which the one emits the disturbance factor affecting the other component must be spatially separated from each other.
- Components that are affected by the same disturbance factors shall be spatially grouped.
- Components one of which has the task of monitoring the other shall be spatially grouped. This can be necessary to monitor disturbance factors affecting specific components.

These characteristics can be stated for any disturbance factor, occurring in the system. Therefore, the characteristics can be displayed in a matrix, in which the role of each component regarding the different disturbance factors is recorded. This form of representation has proven effective in a number of methods in the design of building structures, such as the Design-Structure Matrix [9] and the Modular Function Deployment [10]. The resulting matrix is displayed in Fig. 2. The components in the system are shown at the top of the matrix and the disturbance factors are shown in the left hand column. The individual roles of the components with respect to the disturbance are shown in the centre of the matrix, where the corresponding rows and columns cross. There is one exception, since the fifth characteristic does not involve any disturbance factors. To address this characteristic, these components can be clustered in the matrix by positioning them in adjacent columns. Within the method these components can then be treated as a single entity. How this matrix representation can be derived and how it is used to develop a product structure, is illustrated in the block diagram in Fig. 3 and explained in the following.
In the first step of the method the system is divided into its individual components. Depending on whether the product at

	Component 1	Component 2
Disturbance Factor A	Relation A1	Relation A2
Disturbance Factor B	Relation B1	Relation B2

Fig. 2. Component Disturbance Factor-Relation Matrix

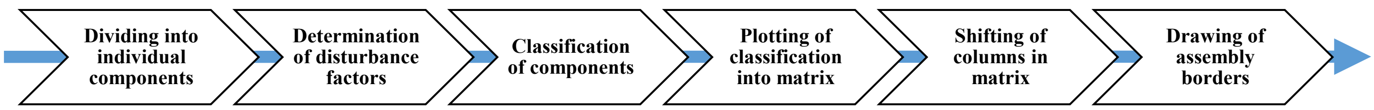

Fig. 3. Block diagram of the method to optimize product architectures for the management of disturbance factors

hand is a new design or a redesign, the components come from an already existing system or are partial solutions for partial functions of the system. Subsequently, the disturbance factors occurring within the system itself are determined. The identification of disturbance factors in a system requires its own methods. Since the development of such methods is not the aim of this contribution, reference is made here to the work of Welzbacher et al. [11]. Disturbance factors can be physical quantities in terms of a transferred energy, but also, e.g., grease or dust or other material. The components in the system are then assessed with respect to the disturbance factors. Each component has either of the roles previously presented in regards of each individual disturbance factor. This classification is entered into the matrix. Whether a component must be classified with respect to a disturbance factor as an emittor or an affector, or whether the influence can be neglected, is left to the discretion of the designer and depends on the specific system. For example, there are temperature and acceleration compatibility limits for almost every component. However, depending on the system, these limits may be considered relevant or irrelevant and thus negligible. In order to fulfil characteristic five, the interdependent components are grouped. Thereupon, the components, and thus the columns in which they are located, are shifted to form clusters of components with the same relation to the disturbance factors. Afterwards the borders between assemblies are drawn between the components, which exhibit different relations to disturbance factors. If the sorting of the components is not clear, different designs can be developed parallel and evaluated regarding their potential. Hence, a final design can be determined.

4. Application in an exemplary system

In this section, the previously presented method is applied on a sensor integrating timing belt as an exemplary case. The terminology is in line with the classification by Vorwerk-Handing et al. [12]

4.1. The sensor integrating timing belt

As the operating time of a timing belt progresses, it becomes elongated due to wear. The increase in wrap diameter leads to a looser pretensioning force by the belt pulleys, and thus to vibrations during operation. The analysis of these vibrations can thereby be used to draw conclusions about the pretensioning force and therefore the condition of the timing belt. This measurement is in-situ, which leads to reduced uncertainty [13, 14]. For this purpose, the following research was carried out by Großkurth and Martin as part of a cooperative project with BRECO Antriebstechnik Breher GmbH & Co. KG and CONTECS Engineering Services GmbH. Sensors for detecting the vibrations of the timing belt were installed directly in a tooth of the belt. The energy supply is provided by a Li-Polymer battery, which is located in the adjacent tooth of the timing belt. [15]. The prototype developed in this project is displayed in Fig. 4 a.

In a follow-up project, a successor version with a revised concept for the energy supply was presented by Großkurth et al. For this purpose, use was made of the fact that the traction means installed in the timing belt are wound up. This can be used as the coil of a transformer to transmit electrical energy into the timing belt. For this purpose, another coil is installed around the timing belt, that transfers the energy into the timing belt. [16, 17] The successor version is shown in Fig. 4 b.

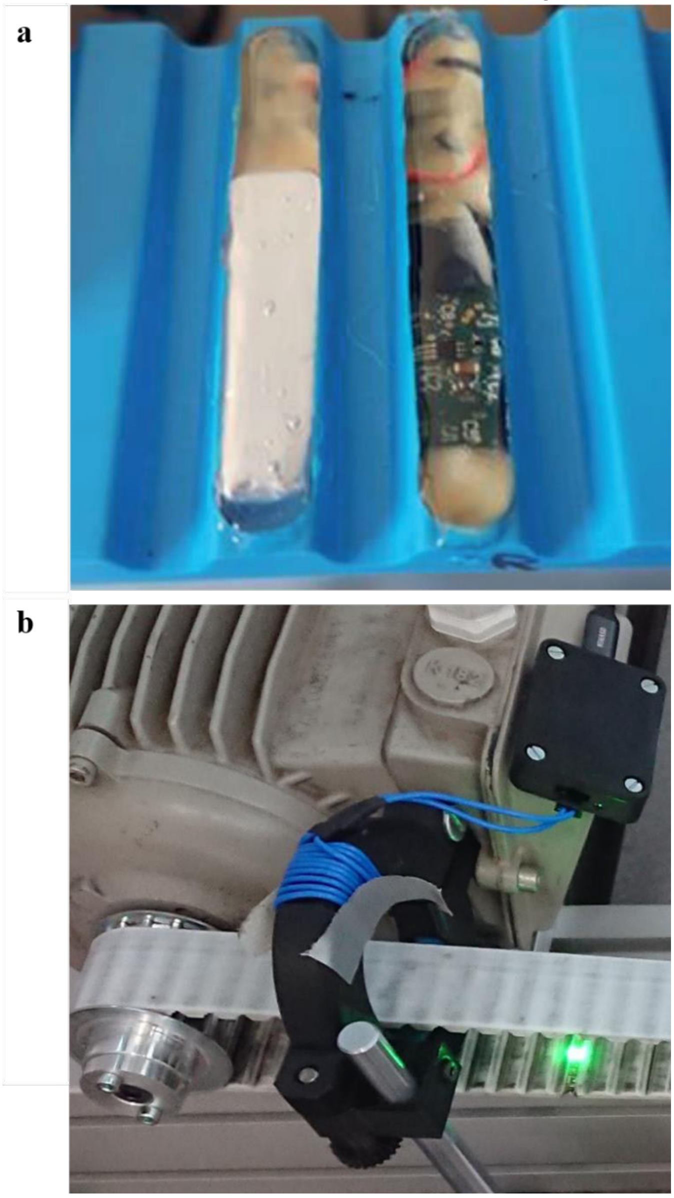

Fig.4. Prototypes of a sensor integrating timing belt, (a) with integrated battery [15], (b) with coil for energy transmission

4.2. Application of the method

In the following, the method described above is applied to the exemplary sensor integrating timing belt. For this purpose, the system is first divided into its components acceleration sensor, temperature sensor, microcontroller, Bluetooth-transmitter, power supply and timing belt. In a next step, these are compared with the possible disturbance factors temperature, static charge, vibration and deformation. According to the classification presented in section 3, the interactions between the components and possible disturbance factors are assessed with Emittor (E), Affector (A), Sensor (S) or Irrelevant (I). The result of the comparison and assessment is shown in Fig. 5. Subsequently, the entered components are sorted according to their relation to the occurring disturbance factors.

The filled matrix can be sorted. For this purpose, the rows are swapped in such a way that clusters of components result which have as similar a relationship as possible to the respective disturbance factors. The result of this sorting is shown in Fig. 6. In the resulting matrix, the borders between assemblies can be drawn. The resulting assemblies are color coded and also displayed in Fig. 6. The timing belt itself forms its own assembly (green), which emits the disturbance factors static charge, vibration and deformation in particular. A second assembly (blue) contains the power supply, which is affected by all disturbance factors. The remaining components acceleration sensor, temperature sensor, microcontroller and Bluetooth-transmitter are combined in a third assembly (yellow).

4.3. Result

Considering the improvement of the development step between the two versions of the sensor integrating timing belt, the changed energy supply principle is particularly noticeable. While in the first version the energy supply is ensured by an integrated battery, in the successor the energy supply takes place contact-free by a coil system. On a more abstract level, the energy supply has been placed in an assembly that is spatially separated from the remaining components. This result is in line with the findings that can be obtained from the application of the method.

5. Conclusion

In this contribution, a gap in the existing methods for robust design was identified regarding the design of a products building structure. To close this gap, five characteristics were developed, representing strategies, with which these building structures can be optimized considering the impact of disturbance factors. From these characteristics, four roles were derived that components in mechatronic systems assume in relation to disturbance factors. To map these relationships, a matrix was developed in which all relationships between components and disturbance factors in a mechatronic system are displayed. On the basis of this matrix representation, a method was developed that can be used to optimize the building structure of a mechatronic system with regard to disturbance factors. Finally, the applicability of the method was put to test by means of an example. With the method presented in this paper, it is possible to consider robust design at earlier stages of development than before. In addition to the earlier integration, the range of methods with which robust design can be implemented is also expanded.

6. Outlook

Following this publication, a number of steps are necessary to further develop the method and make it applicable in a real development context. The example system used in this paper

		Components					
		Micro-controller	Acceleration sensor	Power supply	Timing Belt	Bluetooth-Transmitter	Temperature sensor
Disturbances	Temperature	I	I	A	I	I	S
	Static Charge	A	A	A	E	A	A
	Vibration	A	S	A	E	A	A
	Deformation	A	A	A	E	A	A

Fig.5. Component Disturbance Factor-Relation Matrix for the sensor integrating timing belt

		Components					
		Acceleration sensor	Temperature sensor	Micro-controller	Bluetooth-Transmitter	Power supply	Timing Belt
Disturbances	Temperature	I	S	I	I	A	I
	Static Charge	A	A	A	A	A	E
	Vibration	S	A	A	A	A	E
	Deformation	A	A	A	A	A	E

Fig. 6. Method applied to the sensor integrating timing belt

has a low complexity due to the small amount of components and disturbances. This has the advantage that setting up the matrix and determining assemblies is simple. However, this means that the method must be tested on a more complex system. Furthermore, to apply the method in such a system, tools have to be developed to support the definition of assemblies. Once the method is applicable to complex systems, it must be integrated into the context of a methodology. Here, it must be clarified how the conflict of goals between the system architecture designs of methods with different aims can be resolved. Finally, the method must be applied in the development of a real product in order to evaluate the influence of the application of the method on the management of disturbance factors. Furthermore, the applicability of the method outside the context of mechatronics must be examined. In particular, it must be determined whether the characteristics postulated for the paper can be transferred to non-mechatronic systems. Subsequently, a review of the roles assigned to the components in the method must be carried out, cf. section 3.

Acknowledgements

The authors thank the Deutsche Forschungsgemeinschaft (DFG), which funded the research within the project “Microelectronic modular system for sensor-integrating machine elements”.
Funded by the Deutsche Forschungsgemeinschaft (DFG, German Research Foundation) – 466493340

The authors thank the Deutsche Forschungsgemeinschaft (DFG), which funded the research within the project “Derivation of analysis- and synthesis-methods to manage uncertainty in the development of mechatronic systems with sensor integrating machine elements”.
Funded by the Deutsche Forschungsgemeinschaft (DFG, German Research Foundation) – 426030644

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