

DESIGN FOR DIAGNOSIS

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ABSTRACT

Until now a large series of helpful guidelines for the design of products in the more concrete stages of design and product development were generated and published under the notion design for X, such as Design for Manufacture and Assembly (DFMA), Design for Cost (DfC), Design for Sustainability (DfS). Until now no special attention was given to design guidelines aiming at supporting designers to arrive at with products that allow and ease diagnosis – no special attention to Design for Diagnosis (DfD) guidelines. Only in the field of the design of highly integrated electronic modules attempts to employ DfD strategies were reported. The scope of the reported strategies is up to now limited to this field. The trend to ubiquitous computing and the first development steps towards cognitive systems as well as a general trend toward higher product safety and reliability lead to a higher importance of diagnosis, usually in order to detect possible faults in the products. Diagnosis is also a prerequisite for two additional approaches: monitoring and adaptive control. Complete conference series are devoted to the topic of diagnosis but in general the products are taken “as they are” and the diagnosis capabilities are added later on. In this paper a first attempt is made to formulate general valid guidelines how mechanical and electrical products can be designed in order to allow and to ease effective and efficient diagnosis.

Keywords: Design for X, Diagnosis, Monitoring

1 INTRODUCTION AND STATE OF THE ART

Diagnosis on its own carries the possibility to greatly enhance the reliability of products. However, it is also a means for two other promising approaches – monitoring and adaptive control which can additionally enhance efficiency and effectiveness of these products. In this section the three approaches diagnosis, monitoring and adaptive control are described and prior research into Design for Diagnosis is presented and discussed.

On a very general level **diagnosis** is usually understood as the process of estimating the condition of certain entities. More specifically, in technical applications the term diagnosis describes activities which aim at detecting and identifying faults. Over the last three decades, the growing demand for safety, reliability, and maintainability in technical systems has drawn significant research in the field of diagnosis. Such efforts have led to the development of many techniques; see for example the most recent survey works of Blanke et al. [1], Isermann [2], Witczak [3], Zhang and Jiang [4] and Korbicz et al. [5]. The application of a collection of these techniques gathered in one system [6] was analyzed in [7]. The next logical (large) step beyond products with diagnostic functionalities is cognitive products; several research teams investigate this topic e. g. Paetzold&Schmid [8].

For mechanical and mechatronic products the **main function** can be described as “*detecting and identifying product or process abnormalities*”. The ultimate aim is to inform a user or a group of users or a superordinate system about these abnormalities. The possibilities to inform are oriented on the senses of human beings and typical communication channels. The output (the message that any kind of abnormality is present and optionally the identification (description) of this abnormality) can be optical, acoustical, tactical, analog or digital (and theoretically olfactorical – appealing to the senses smell and taste). Analog outputs are sent to other systems (usually superordinate systems) and can be electrical (e. g. voltage beyond a certain threshold signals an abnormality) as well as using other physical parameters (e. g. a movement of a certain lever signals an abnormality). The term “digital output” summarizes all kinds of communication means between digital systems – usually BUS systems of any kind (e. g. CAN, Flexray) are used. Figure 1 summarizes the output possibilities of a diagnostic system.

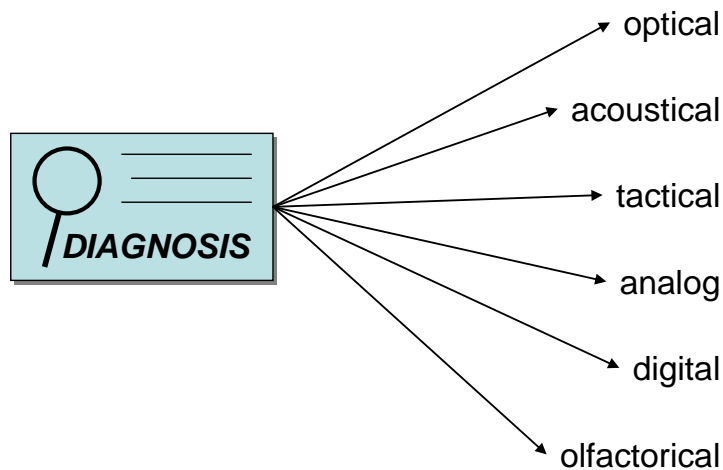


Figure 1: Output possibilities of a diagnostic system

The following list presents a few examples for diagnostic systems for mechanical and mechatronic products with increasing complexity:

- The characteristic of a car seat belt buckle to give a sound (“click”) in the moment the buckle is closed correctly already presents a diagnostic system in the widest sense.
- Very often locks for foldable car seats signalize either with a green indicator (correctly locked) or a red indicator (still not correctly locked) the state of the seat lock.
- Important safety systems such as anti-lock brakes, stabilization programs or airbags in cars usually signalize malfunctions with a warning lamp. It is important to note that today usually only the electronic components are covered by the underlying diagnostic systems.
- The control rooms of nuclear power plants and the cockpits of airplanes mainly offer diagnostic information (and the possibility to react when abnormalities occur). It is important to note that the typical checklists that are used prior to departure of planes can also be understood as part of the diagnostic system.

For the understanding of diagnostic system it is important to be aware that such systems either can detect or identify abnormalities when the system is not in use (stand-by diagnosis) or in use (operation diagnosis) or both. Furthermore, the abnormalities can either lead to malfunction at once (immediate malfunction) or the slow degradation of the product eventually leading to malfunction (creeping malfunction). This distinction is shown in Figure 2.

DIAGNOSIS	stand by diagnosis	operation diagnosis
	immediate malfunction	
creeping malfunction		

Figure 2: Distinct forms of diagnosis

The creeping malfunctions offer a promising field for diagnosis which can be called **predictive diagnosis**. The term “predictive diagnosis” is in contrast to “predictive control” rarely used in the technical domain (it is widely used e. g. in medicine). One example for the usage of this term is the presentation of an automated system for fault diagnosis based on vibration data recorded from a main power transmission [9]. For mechanical and mechatronic products predictive diagnosis (essentially in the meaning of failure detection and identification before these failures even occur) presents a

promising field of research, especially because many products are part of larger systems. A failure of the larger system which is caused by a failure of a single product usually leads to enormous consequences in terms of cost of idleness (e. g. of a whole production segment). Therefore preventive maintenance is desirable for many products; however such preventive maintenance today is aggravated by the fact the upcoming failures can usually not be detected. The only preventive maintenance systems available are time based but not state based. A predictive diagnosis system would allow scheduling maintenance and service in dependence of the current state of a product (wear of bearings, gear systems, etc.) and the state of sensors (wear and staining). In the car industry first advances towards state based service are already being made.

A strongly connected field concerns the **monitoring** of technical data. The notion monitoring summarizes all kinds of systematic observation, surveillance or recording of an activity or a process by any technical means. In leading industries such as computer chip production or car manufacturing today usually nearly all operation data of the productions systems are being monitored for the three main reasons safety, efficiency and planability:

- The safety of production systems can be enhanced because a reliable safety system with a fast reaction can be realized on the basis of a real-time monitoring system. The role of coincidence for detecting possibly dangerous faults is diminished if a continuous monitoring is in place.
- The efficiency of production systems can be enhanced because any kind of waste (of energy, time and production goods) will be detected and can subsequently be prevented or reduced.
- The planning possibilities and planning quality can be enhanced if accurate data from a real-time continuous monitoring system are available as realistic prognosis is enabled by such data.

The requirements of a monitoring system are usually the same as the requirements of diagnosis systems. Therefore the insights presented in this paper could additionally be used for “Design for Monitoring”.

The term “control” names certain activities with the aim to manage, command, direct or regulate the behavior of devices or systems and has been the core of extensive research for many decades. In the last four decades the techniques of **adaptive control** have found rising attention. Adaptive control usually relies on an aggregation of a conventional control methodology with some form of recursive system identification [10]. For this system identification the strategies, methods and tools of diagnosis can be applied. Consequently, also a Design for Adaptive Control may be an outcome of DfD. Figure 3 shows a summary of the notions diagnosis, monitoring and adaptive control.

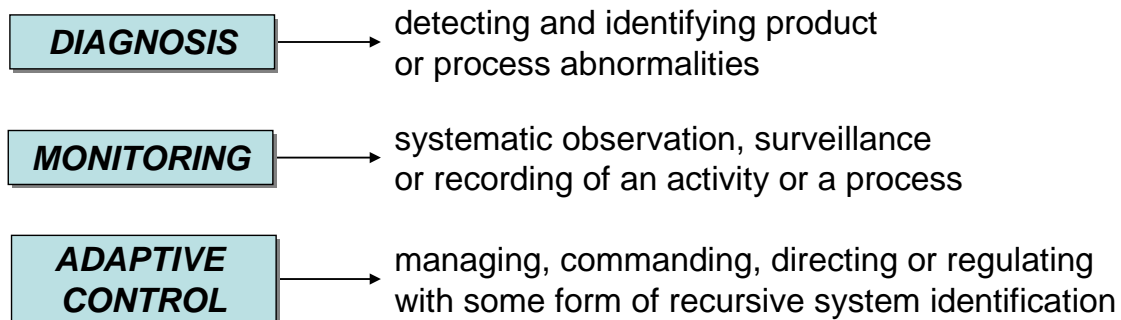


Figure 3: Diagnosis and related terms

Research into the topic of diagnosis is manifold. There are even designated conferences which only discuss the strategies, methods and tools of diagnosis (and adaptive control). Also in the field on mechatronic design diagnosis is well understood in the field of reconfigurable manufacturing systems [11] and the approaches towards Design for Reconfigurability (DfR) [12]. However, the question how products should be designed in order to allow and ease diagnosis is usually not addressed. Only in the field on complex electronic systems approaches to face this challenge are reported. Chen [13] uses the notion “Design for Diagnosis” for describing a technique to measure the delay and crosstalk noise for the testing and the diagnosis of on-chip bus wires. Wang et al. [14] propose a Technique for Diagnosing Integrated Circuit Faults. However, in both papers the DfD strategies, methods and tools are not elucidated at all and no systematic procedure or state of the art is given.

The present paper seeks to start the process of developing such systematic procedure. Three hypotheses are the basis for the presented work:

- Hypothesis 1: Complex products can only be reliable and safe if the user really knows that they function correctly.
- Hypothesis 2: Good mechanical or mechatronical design can distinguish good products from bad products in terms of diagnoseability.
- Hypothesis 3: Understandable guidelines can help designers to consciously or subconsciously design products that allow or ease diagnosis.

The nature of the research is still exploratory - the testing of the hypotheses is not yet the main goal. Instead the basis for guidelines for design for diagnosis is by laid using the following sources:

- The retrospective analysis of both authors on their time in industrial product development in automotive and robotics industry.
- The analysis of research works in adjacent fields – mainly in the field of product upgrading [15], cognitive systems [8] and product cycle management [16].
- Experiences in product development processes at two universities, e. g. the development of autonomous vehicles [17] and a formula student race car.
- Analysis of existing products and product elements and evaluation concerning their aptitude for diagnosis.

2 A PROCESS ORIENTED CONCEPT OF DFD

For the collection, development and sensible presentation of Design for Diagnosis (DfD) strategies, methods and tools a structure was needed to focus and substantiate the discussion. A structure concerning the level of abstraction can be found throughout the design methodology literature [20], [21], [22]. Design science has made clear that the model of the level of abstraction is not appropriate as a strict time line of a design process [23]. Still, the logical validity of the levels of abstraction has not been charged. This model of the level of abstraction essentially describes different view-points on the same product. The highest level of abstraction is the requirement model only stating what characteristics a product should provide. The distinction between requirements and functions is not always clear. Quite often, the main function of a product is also stated as a requirement. Still, function models (structure-oriented, flow-oriented, or relation-oriented) allow a first concretization how a product works, i. e. how the requirements are achieved. The next more concrete level is build up by the physical effects which describe how the product functions can be achieved. Even more concrete the geometry and the material describe how the physical (and chemical) effects are realized. One possible presentation is the Munich Model of Product Concretization (Figure 3).

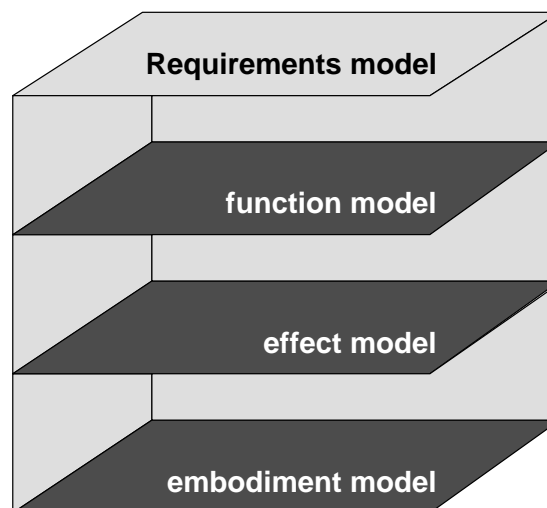


Figure 3: Munich Model of Product Concretization

The following discussion of DfD strategies, methods and tools follows this general structure.

3 DFD IN REQUIREMENTS MANAGEMENT

The term requirements management in general describes the activities “collection of (search for) requirements” and the ongoing “handling of requirements” including providing requirements to all stakeholders, updating requirements and tracking, numbering as well as versioning requirements. The importance of requirements and requirements management was highlighted frequently and is illustrated by the well-known “rule of ten”. The “rule of ten” specifies that it costs 10 times more to find and repair a failure at the next stage of realization. Thus, for example, it costs 10 times more to find a failure in the concept phase than during the phase “clarification of the task” which is aiming at requirements. This underlines the importance of requirements management for all kinds of engineering design.

The specific point concerning requirements management when aiming at Design for Diagnosis (DfD) is resulting from the fact that diagnosis is ultimately not necessary for the basic functions of the product under development. Consequently all kinds of diagnostic functions are somehow linked to the direct functionality of the product. For an example, a diagnostic function “detect failure of braking system” of a car is strongly linked to the direct function “brake car”. For a better overview it is therefore highly desirable that requirements concerning diagnostic functions can be linked to requirements describing the (direct) functionality that is being diagnosed as requirements and configuration changes of the direct function can very often influence the connected diagnostic function. Current tools for requirements management (e.g. Doors (compare e.g. [18])) allow to interlink requirements, but the insight to link requirements concerning diagnostic functions to requirements describing direct functions could be adapted by science and industry.

It is important to note that especially the Failure-Mode-and Effects-Analysis (FMEA) offers a straightforward possibility to identify demand for diagnosis. Usually in a FMEA three different estimations are being made (compare e. g. [19]):

- the severity evaluation assigning a level of severity to the effects of a failure,
- the occurrence evaluation assigning a level of probability for a failure to occur and
- the detection evaluation assigning a level of probability for a failure to be detected before the effects occur.

The detection evaluation can give important hints towards diagnosis demands. A “bad” evaluation of a certain fault (meaning that it is likely that a failure is not detected before the effects occur) points to characteristics of the product which should be diagnosed in order to reduce the probability that a failure is not detected. Such diagnosis demands can be identified early if a FMEA is started very early in the development of a product. The identified diagnosis demand can be formulated as requirement or an addition to a requirement.

The aspects of DfD concerning requirements management are summarized in Figure 4.

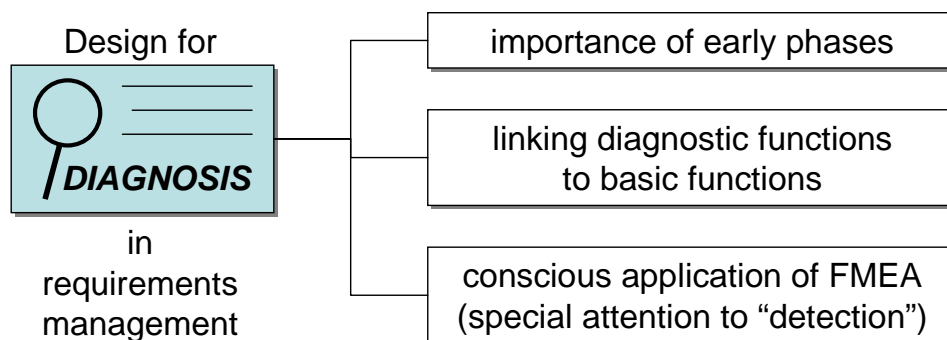


Figure 4: Design for Diagnosis in requirements management

4 DFD IN FUNCTION ANALYSIS

Certain requirements describe necessary functions of future products. By means of function analysis (and synthesis) it can be described on an abstract level how these functions can be realised. Many different approaches and models have been proposed for function analysis. The first one, which will be analysed with regards for its potential to support DfD is the function structure as proposed by

Ehrlenspiel [20]. The main advantage of this form of function analysis is the inclusion of states (input and output states of functions, compare also [15]) and the description of different types of linking possibilities of secondary flows to primary flows (types: condition state, process state, additional state). Figure 5 shows the notation and an example of the flow orientated function structure.

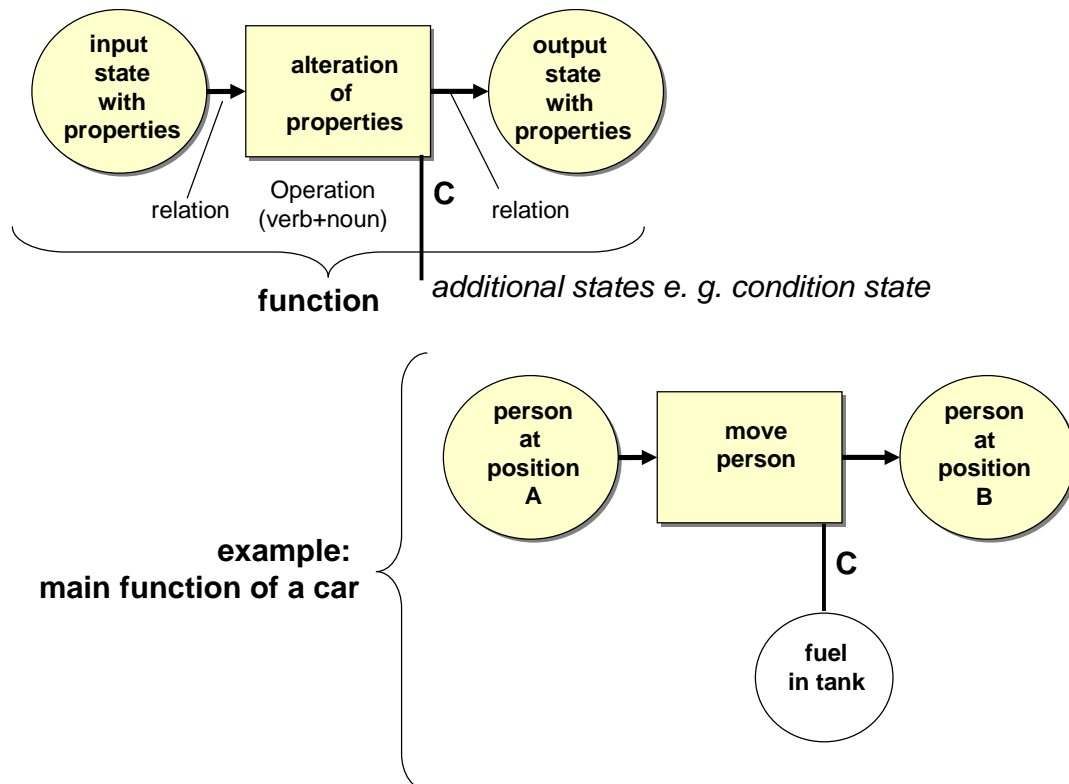


Figure 5: Flow oriented function analysis (compare [20])

In this function structure the direct functions and diagnostic function can be described in a consistent representation. Especially the link type „process state“ allows to assign a diagnostic function to a flow of matter, energy or information undergoing some kind of operation. By this type of function structure it is therefore possible to show exactly which entities are being diagnosed and to localise the diagnostic function on a functional level. Possible diagnostic functions could test, if the input states of a function are existing (matter, energy or information), if condition states are existing and could evaluate process conditions of the function carrier.

It was a central insight of research work concerning updating possibilities of products that the flows (matter, energy, information) insight a product to be updated need to be accessible [15]. The addition of diagnostic function is very similar to product updating; in fact very often products are updated by means of adding control or diagnostic functionality. Any flow oriented function structure is therefore appropriate for supporting DfD as these flows are made visible in this type of product representation.

Another well-known approach to analyse functions is based on the work of Altshuller and used in connection with the tools of TRIZ/TIPS (compare e. g. [24]). This kind of function structure is concentrating not on the flows but on the relations in a product. Figure 6 shows one notation example (other notation conventions exist) and a diagnostic example.

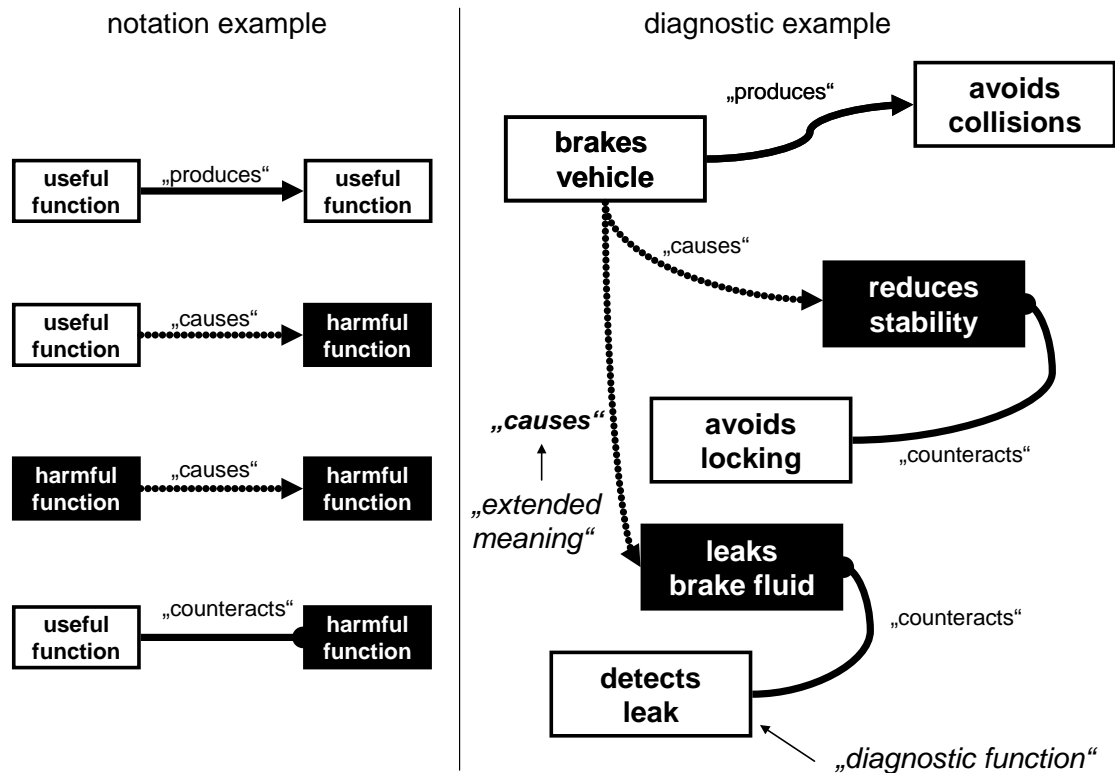


Figure 6: Function analysis based on TRIZ

As the results at the right side show, a relational function structure can ease the understanding of and overview over diagnostic functions and thus support DfD. It is only necessary to understand the relation cause also in a manner so that it may describe system failures (the function „brake vehicles“ may „cause“ the harmful function „leaks brake fluid“). Then the relation „counteracts“ can be used to identify diagnostic functions and to describe their meaning or purpose.

In summary, the functional domain and the different models used in this domain offer several possibilities to develop and explore diagnostic functionality.

Figure 7 summarizes the aspects of DfD concerning function analysis.

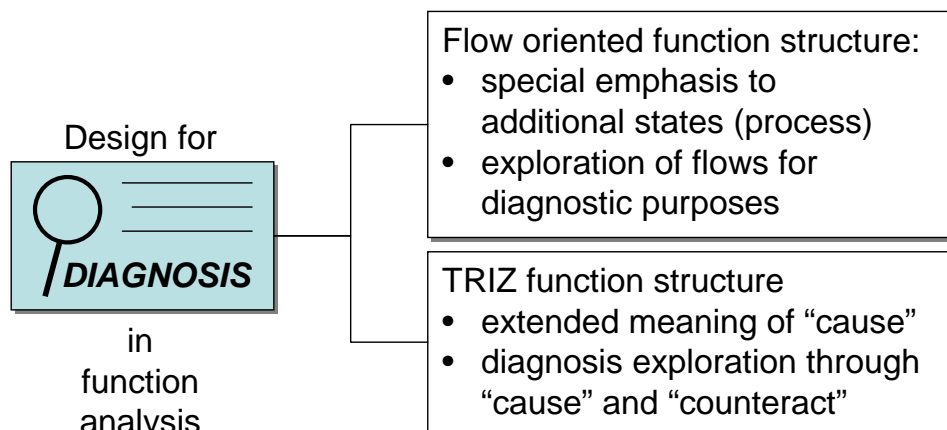


Figure 7: Design of Diagnosis in function analysis

5 DFD CONCERNING PHYSICAL EFFECTS

In general, the physical domain describes how functions of a product are realised in the most abstract physical sense. A number of authors, e. g. Ehrlenspiel [20] propose to describe the physical domain by means of elementary physical effects. These physical effects are listed in form of a catalogue also containing the most important input and output parameters. The advantage of this methodical approach is that with a rather small number of physical effects (approx. 90) any physical product realisation can

be described by means of effect chains. For DfD, the proposed collection of physical effects is also appropriate to describe the realization of diagnostic functions, because many physical effects can be used for sensory tasks.

The analysis of physical effect chains can furthermore help to develop effective and efficient diagnostic functionality. In order to approach this point it has to be assumed that a large share of diagnostic data processing is currently done digitally. Usually some kind of computer (industrial PC, embedded system, ...) is processing, filtering and storing diagnostic information by means of digital electric signals (especially in the expected age of ubiquitous computing). This fact can lead to a novel hypothesis for DfD: “The further away a sensory physical effect is from digital electricity (far in the meaning of the physical effect chain to transform the output signal of a physical effect into a digital electrical signal) the higher will be the expense for information conversion”. Based on this hypothesis, sensory physical effects which have electrical outputs are desirable for DfD. Additionally, when describing the realisation of diagnostic functionality by means of chains of elementary physical effects it is desirable to add two additional (pseudo-)effects - the conversion of analogous signals to digital signals and vice versa. Using these additional physical effects, any diagnostic functionality can be analysed from source (entity which is diagnosed by means of an elementary physical effect) to receiver (diagnostic computer resp. human being).

When looking at the physical domain it is important to note that in some cases diagnostic functionality may be achieved without any or at very low cost. This phenomenon will occur if actuators can simultaneously be used as sensors. Large expenditures for diagnosis can be saved if actuators are directly used as sensors. An actuator is typically a mechanical or electromechanical device which converts energy into motion or applies a force. A sensor is a physical tool that measures physical quantities. It sends the information in a form possible to read by the converter and next to the measuring device. The most popular sensors deliver information in the form one of the electric quantities voltage, resistance or intensity. There are approaches in the literature using direct measurements of signals applied to actuators. These approaches are made in order to get information about the actuator’s state of work. The advantage of using actuators as sensors is the possibility to ensure delivering additional information to the entire control system without making the system more complex. Usually in that way actuator load is measured. One example of using this method is described in Washington et al. [25].

The aspects of DfD concerning physical effects are contained in Figure 8.

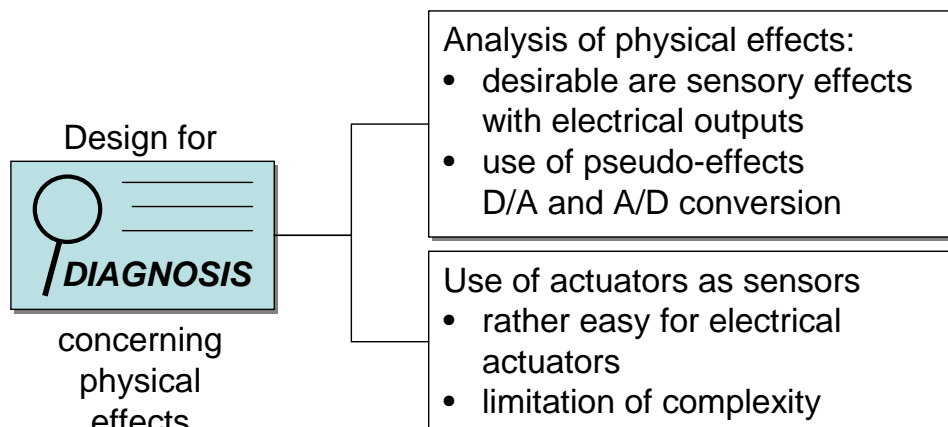


Figure 8: Design for Diagnosis concerning physical effects

6 DFD IN EMBODIMENT AND DETAIL DESIGN

The level “embodiment model” describes the product on the basis of its geometry - usually initial focusing on the effect geometry later on additional “connecting” geometry of the product. The methodical support of DfD at this level is similar to support of conventional design (variation of certain product characteristics, design for X, principles of optimum systems, ...). In this section two examples of products showing possibilities for DfD are given.

The first example concerns an industrial machine for the preparation of films for development (connecting the films for continuous development). Before a product update the machine could not

distinguish different kinds of film rolls (e. g. color and black-and-white) therefore frequently wrong rolls were mistakenly added and connected to the wrong film line. By means of a product update a diagnostic function was added. The main flow of the system (film rolls) was accessible at the input – a slot for films. A bar code reader (DX-reader) could add diagnostic functionality to this system (Figure 9 - compare [15]).

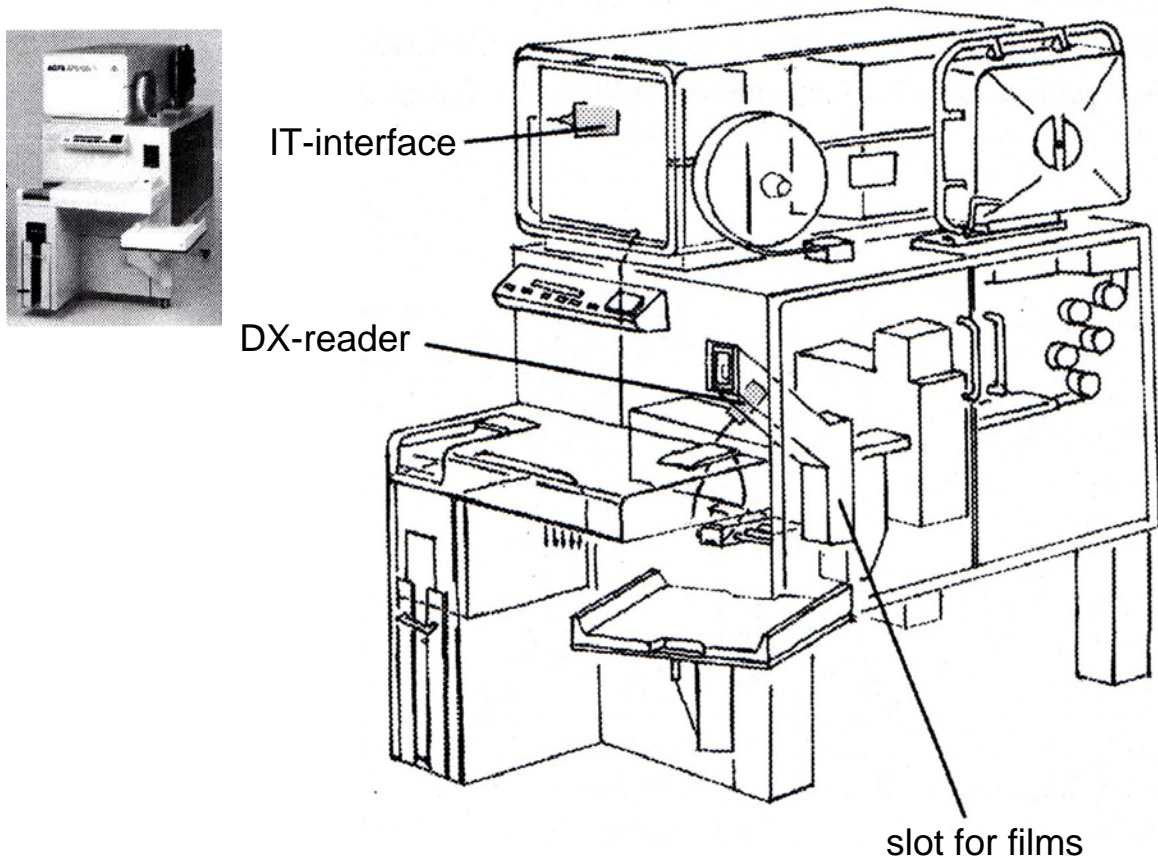


Figure 9: Film Auto-splicer with added diagnostic functionality [15]

This example shows three important aspects which should be part of a DfD methodology:

- Accessibility of main flow: the main flow of the Auto-splicer is a matter flow – the films – and can be accessed for diagnostic purposes at the slot.
- Spatial possibility to add additional entities: the design of the auto-splicers allows the addition of an additional device – the DX-reader. Obviously such spatial possibilities can only be provided, if the potential for additional diagnosis is detected in the design process.
- Open interfaces: the integration of a diagnostic device – the DX-reader – was only possible because the original design provided the possibility to use the open interfaces to the control system.

The presented example firstly describes an updating of a system due to additional or changed requirements but also allows exploring possibilities to enable or ease diagnosis in embodiment and detail design. Obviously, the three aspects listed above as well as a general consciousness concerning the specific requirement of diagnosis in embodiment and detail design can only be a first building block of a future DfD methodology.

The second example concerns a well known elastic coupling [26] with an integrated diagnostic function. If the elastic element of such coupling may fail as a consequence of e. g. strong overload, the coupling will be able to continue the basic function. However, any user (e. g. the driver of a car) will be warned by means of increased vibration (Figure 10).

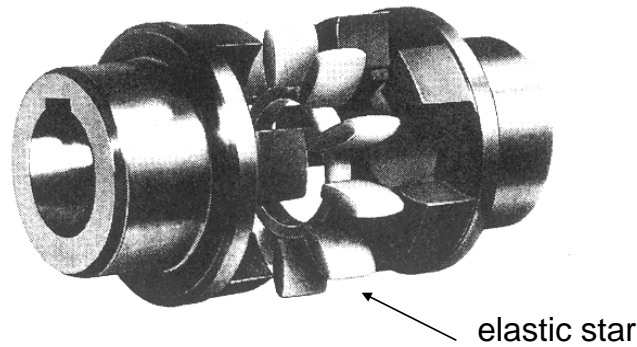


Figure 10: Elastic coupling with integrated diagnosis [26]

This example shows the close connection of design for diagnosis with fail-safe design. Two different philosophies of engineers are present in daily practice [27]. One general approach often used by engineers, who develop other systems which dispose of a large share of mechanical parts, can be characterized as “safe life”. The product is designed in a way that it will never fail under the circumstances which can be foreseen. On the contrary, complex mechatronic systems are usually designed “fail safe”. The basic principle of this philosophy is to accept the possibility of failure but to limit the effect of failure. This philosophy was first introduced by Westinghouse in 1872 [28]. The fail-safe philosophy needs to be accompanied by diagnostic functionality so that the limited failure is quickly detected and that the system usage is adapted to the given circumstances. Two possibilities can be distinguished for detecting failure:

- The sending of signals of any kind to the senses of the user, e. g.:
 - obvious changes of the appearance of a system (e. g. deformation of damaged bottle for the home preparation of carbonated water),
 - obvious changes of the acoustics of a system (such as in squeaking worn brake pads),
 - obvious changes of the vibrations generated by a system (such as in the elastic coupling in Figure 9) and
 - obvious changes in the smell of a system (e. g. a damaged car clutch).
- The sending of signals of any kind to any kind of sensors – the failure will act on something which will send a sensor signal, e. g. a mechanical overload sensor. This possibility is generally preferable as a diagnostic system can then analyze the sensor signals, can identify the failure and can start activities to compensate the failure or react to the failure up to a system shutdown and to the alarming of emergency help. In some cases the failure can be detected and compensated without notice of the user (who is usually also the customer).

Figure 11 contains the aspects of DfD concerning embodiment and detail design.

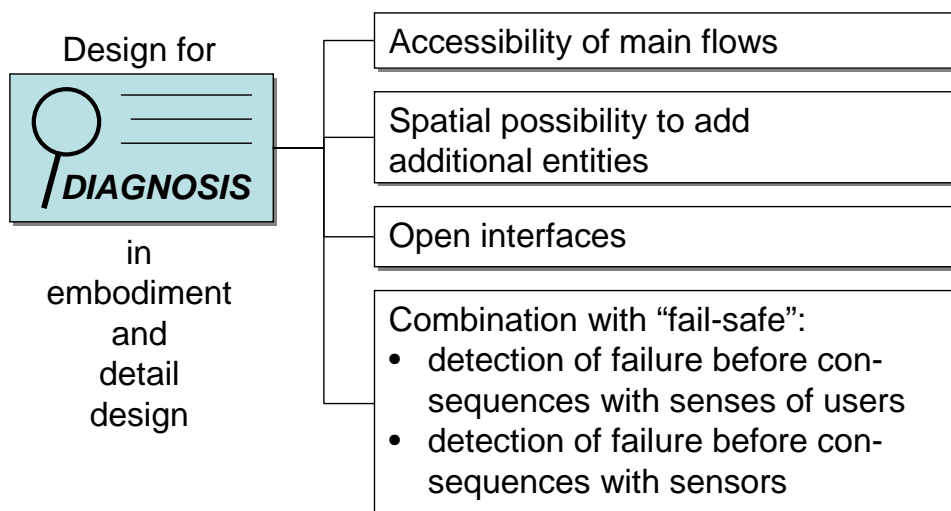


Figure 11: Design for diagnosis in embodiment and detail design

7 SUMMARY

Up to now in the field of design research comparatively little attention was given towards guidelines assisting designer to consciously include diagnostic functionality into products. This paper presents an investigation of the necessity of diagnostic functionality and the formulation of first building blocks for such guidelines summarized under the notion “Design for Diagnosis (DfD)”. The researched aspects span the design process from requirements analysis over function analysis as well as physical effects to embodiment and detail design. The point of main emphasis is laid upon the early phases, but some initial aspects for later phases could also be identified by means of product analysis. Further work will concern an expansion of the guidelines and an approach to explore and assess the applicability to industrial engineering design.

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