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DESIGN FOR CONTROL

Stetter, Ralf (1); Simundsson, Avery (2)
1: University of Applied Sciences Ravensburg-Weingarten, Germany; 2: University of Manitoba, Canada

Abstract

Currently, 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 to Cost (DtC), and Design for Sustainability (DfS). Until now, little attention has been given to design guidelines aiming to supporting designers in creating products that enable and ease control – no special attention has been given to Design for Control (DfC) guidelines. Some researchers have started to investigate DfC, but until now, the more conceptual stages of design were not the focus of their research. Additionally, recent research in the direction of Design for Diagnosis (DfD) has been initiated, which shares some common elements with DfC. In this paper, a first attempt is made to formulate hypotheses for how mechanical and electrical products can be designed in order to enable and to ease effective and efficient control.

Keywords: Control, Diagnosis, Design for X (DfX), Functional modelling, Mechatronics

Contact:
Prof. Dr.-Ing. Ralf Stetter
University of Applied Sciences Ravensburg-Weingarten
Mechanical Engineering
Germany
ralf.stetter@hs-weingarten.de

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1 INTRODUCTION

Currently, 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 to Cost (DtC), and Design for Sustainability (DfS). Until now, little attention has been given to design guidelines aiming to supporting designers in creating products that enable and ease control – no special attention has been given to Design for Control (DfC) guidelines. Initial research in the area of production economics has led to a so-called perspective "design for control" (DfC). However, the focus of this research was limited to the control of manufacturing and assembly. Some researchers have also started to investigate DfC, but until now, the more conceptual stages of design were not the focus of their research. Additionally, recent research in the direction of Design for Diagnosis (DfD) has been initiated, which shares some common elements with DfC. Complete conference series' are devoted to the topic of control but, in general, the products are taken "as they are" and the control capabilities are added in the post-design phase. In this paper, a first attempt is made to formulate hypotheses for how mechanical and electrical products can be designed in order to enable and to ease effective and efficient control. The attempt is based on a model of design processes in industrial companies, which is presented in the next section. Section 3 clarifies the notion of control, shows elements of modern control systems, and summarizes existing research into design for control. A sample product, which serves for explaining the hypotheses, is explained in Section 4. Section 5 is ordered according to the model presented in Section 2 and explains the hypotheses.

2 DESIGN PROCESSES IN INDUSTRIAL COMPANIES

It was decided to use a slightly different model in order to structure the discussion in this paper. This model was derived from a model of mechatronic product development used in prior research (Stetter and Pulm 2009). This model, shown in Figure 1, is proposed for the sake of an in-depth discussion of the most prominent aspects of systematic product development in today's industrial settings.

The centre of the model is the core process of companies involved in product development, production and assembly, as well as marketing and after-sales. Four groups of activities are important in every phase of this core process. The essential activities of the project management concern the planning and control of all schedules, as well as the assignment of resources. The most important aspects of project management revolve around people, time and money. The logical relationships of the product and the process are dealt with in "process management". Process management is often also referred to as Systems Engineering and can be defined as guidance for the functional design of complex systems, which is based on certain thinking models and principles (Daenzer and Huber 2002). Change Management is the process of requesting, determining attainability, planning, implementing, and evaluation of changes to a system. It has two main goals: supporting the processing of changes and enabling traceability of changes (Crnkovic et al. 2003). In order to allow this traceability, a version management is often part of the change management. The term "configuration management" is meant as an extension of variant management. Possible variants of a product have to be consciously configured so that each possible product variant (configuration) will fulfil the functional and physical requirements throughout its life, including compatible and working configurations during the design process. These possible configurations have to be considered during all phases of the core process of production companies. The notion "testing" summarizes a number of activities which have to be planned, carried out and controlled during all phases of the core process. The activities in testing focus on virtual and physical analyses of the product and process performance. These activities are necessary to assure the functionality and quality of the product and processes.

For the phase "product development" (top left, Figure 1) necessary activities can be summarized in five notions. These notions have a sensible sequence, but should not be understood as a process because iterations and jumps between activities under different notions are frequently necessary. The notion "requirements" summarizes activities which aim to translate customer wishes and expectations into appropriate requirements as well as to manage these requirements. Activities which deal with the abstract logic of the product on a functional level are subsumed under the notion "functions". Such functions can be realized by means of a combination of physical phenomena. The notion "phenomena" summarizes a number of activities aimed at clarifying and modifying those chains of physical phenomena. Activities which focus on realizing functional and physical structures of the product and process in the form of geometrical objects are subsumed under the notion "geometry …" also indicating the material properties, which are on the same abstraction level. The notion "modules" summarizes activities with the objective to develop smaller subsystems of the product commonly referred to as modules.

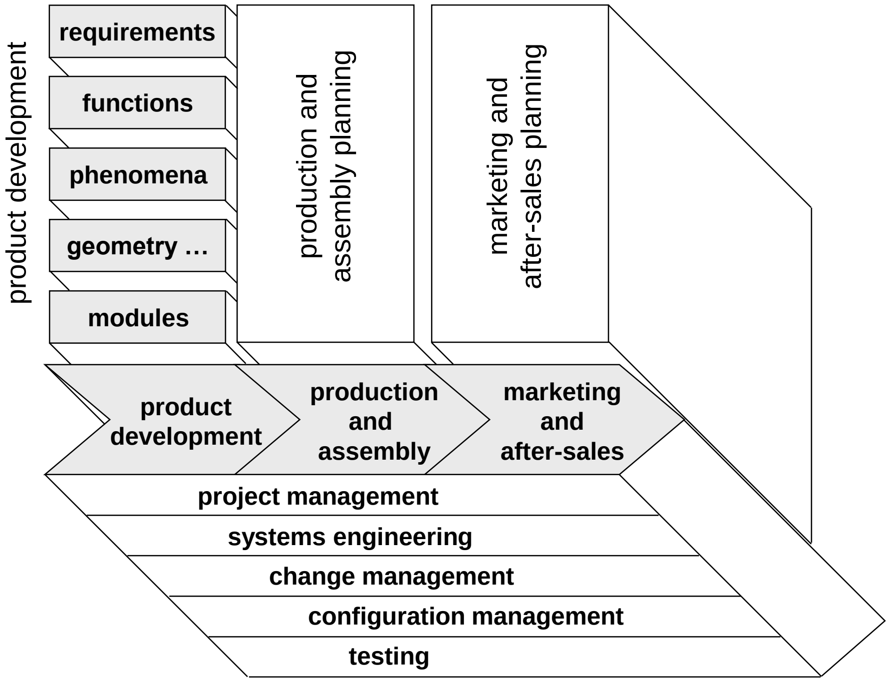


Figure 1. Model of product development processes

The phases "production and assembly" as well as "marketing and after-sales" are not analysed in this paper in detail. Consequently no groups of activities are defined and displayed in this model. This is not meant to indicate that such groups of activities are not sensible in these phases of the core process. These phases are not the focus of this paper, a definition of groups of activities is left to further research, though they are probably similar.

3 CONTROL AND DESIGN FOR CONTROL

The notion "control" includes certain activities with the aim to manage, command, direct or regulate the behaviour of devices or systems and has been the focus of extensive research for many decades. In the last six decades, the techniques of adaptive control have found rising attention. Early research was aimed at realising autopilots for airplanes. Adaptive control usually relies on an aggregation of a conventional control methodology with some form of recursive system identification (Sastry and Bodson (2011)). An adaptive controller can be formed by combining an on-line parameter estimator, which provides estimates of unknown parameters at each instant, with a control law that is motivated from the known parameter case (Ioannou and Sun 1996). Current research focuses on fault-tolerant control (FTC). Such systems allow preserving performance and stability of complex products despite the presence of faults (malfunctions in systems in contrast to failures which indicate catastrophes). Fault-tolerant control is essentially a combination of control and fault diagnosis algorithms as well as systems. Early detection and accommodation of faults can help avoid system shutdown, breakdowns and even catastrophes involving human fatalities and material damage (Witczak 2014). Witczak presents an abstract depiction of a modern control system (Figure 2).

FTC systems can be classified into two distinct classes: the passive and the active FTC systems. In the case of the passive systems, controllers are designed to be robust against a set of predefined faults. Therefore, there is no need for fault diagnosis. This design of the controller allows the system to cope with the fault presence, but usually degrades the overall performance (Witczak 2014). On the other hand, in the case of an active FTC system, this system relies on information given by a Fault Detection and Isolation (FDI) system, so that through some accommodation technique (compare Blanke et al. 2015), the fault is tolerated with minimum performance degradation.

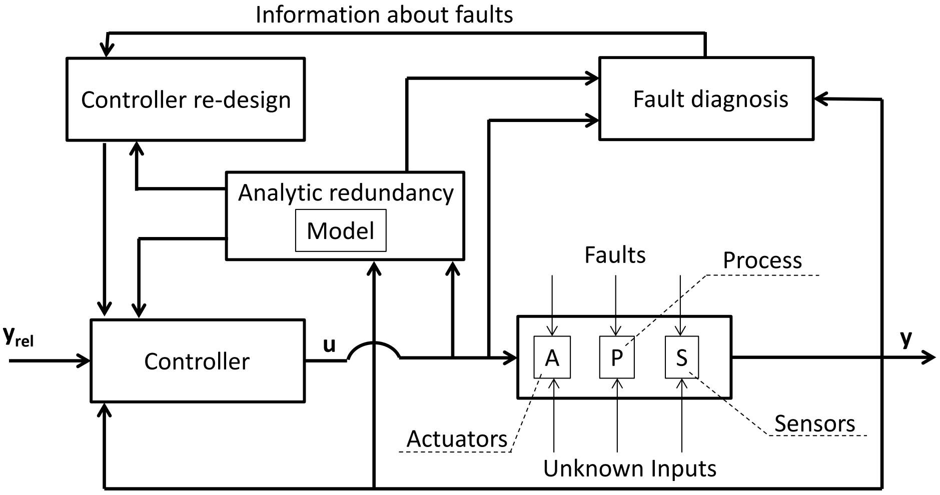


Figure 2. Modern control system (Witczak 2014)

As mentioned before, only a rather small amount of research concerning Design for Control (DfC) has been published so far. One approach for DfC was presented by Li et al. 2001; however, the main focus was limited to obtaining simple dynamic models of the mechanical structures and controller design. Related work is described by Li and Lu (2015). They describe an integrated design and control methodology (Figure 3).

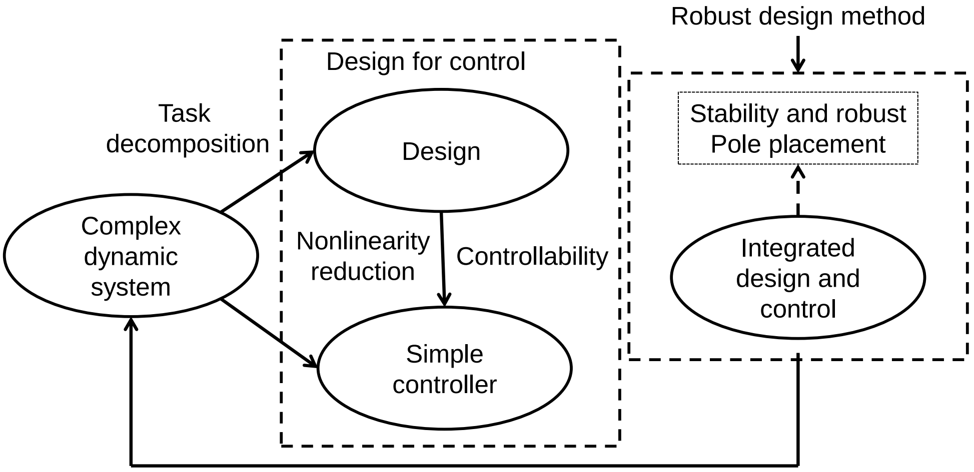


Figure 3. Integrated design and control methodology (Li and Lu 2015)

However, the focus is again on the controller design of existing mechanical structures and little emphasis is placed on the task of design engineers to design products which enable and ease control. Research in the area of production economics (Bordoloi and Guerrero 2008) has led to a so-called perspective "design for control" (DFC). However, in this research the focus was limited to the control of manufacturing and assembly looking only at cost and time. Notable are the investigations concerning Design for Diagnosis (DfD) which share some common elements with DfC (Stetter and Phleps 2011; Stetter and Kleinmann 2011).

4 SAMPLE PRODUCT: DEVELOPMENT OF AN AGV

This section describes the product development of an AGV for outdoor used (compare also Stetter and Simundsson (2015)). The AGV makes use of a unique steering system based on torque differences and is suited for rough terrain because of four independent legs with wheels (Figure 4).

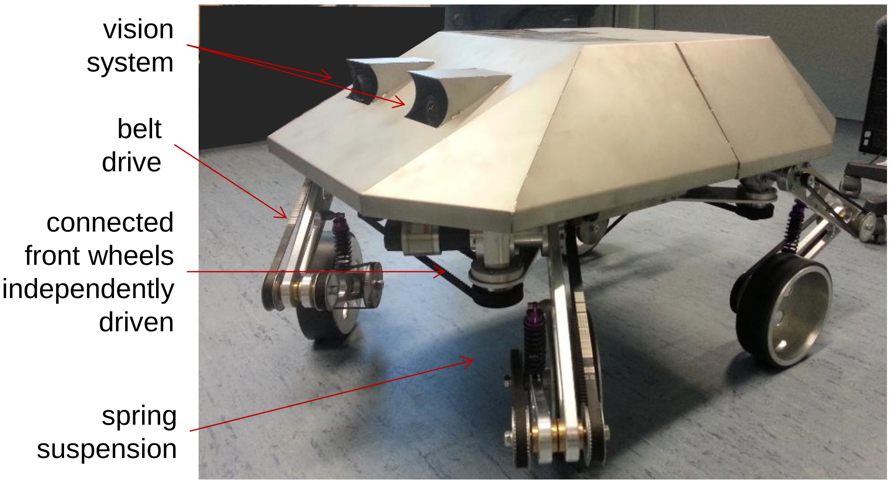


Figure 4. Example product: AGV

The main objective of the development project was to develop a Semi-Autonomous Outdoor Vehicle designed to explore and work in open areas. The steering is based on torque differences. The distinctive quality of the steering system used is its dynamic behaviour. This innovative steering system is based on the concept of using the torque of drive motors (more exactly, the torque differences between wheels) to steer four independent axles of a vehicle. The principal steering system is shown in Figure 5.

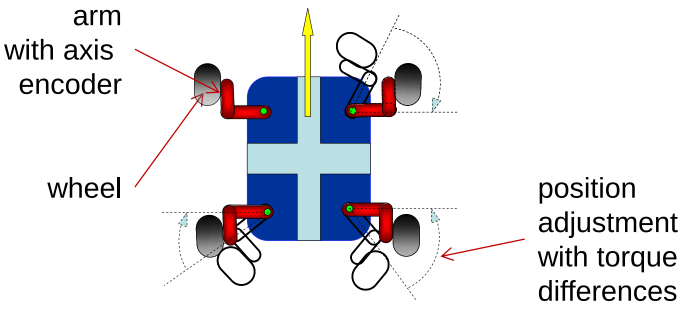


Figure 5. Steering principle

In this example, a vehicle consists of four drive motors which are fastened on arms that may freely rotate. These arms have no drive or brake- only an angle encoder which is attached at the end of each axle. These angle encoders measure the angle of the motor and the wheel with regard to the vehicle platform. The distinct characteristic of the innovative drive system is the absence of dedicated steering motors. By means of angle encoders applied at the four steering axles and highly dynamic control algorithms, it is possible to steer such vehicles only by means of the four drive motors (compare Figure 5).

Each of the wheels on the short axle can be directed into the desired position by means of the torque applied on the wheel. This could take place sequentially for each individual wheel but also simultaneously, if the control allows different torque on all wheels. This characteristic allows simpler and simultaneously more robust vehicle concepts. It is also a main advantage of this concept that the resulting vehicle is able to drive directly in any direction without time- and space-consuming turning manoeuvres. Furthermore, a vehicle based on the dynamic drive system is able to turn around its own centre. This characteristic is very important if cameras or other equipment are mounted on such vehicles which can only be used in a certain orientation. The innovative steering system shares these advantages with Omni drive systems (Ashmore and Barnes 2002), but has reduced friction as well as easier controllability. It also offers the possibility to determine an exact position and orientation from an analysis of the angles of the steering axes and the angles of the drive wheels (odometry).

The control of the vehicle occurs on different levels. A central computer receives a movement desire either directly from the user (manual driving) or improved by a superordinate intelligence (semi-autonomous driving mode) or only from a superordinate intelligence (autonomous driving mode). Based on a mathematical model of the AGV, this movement desire is than translated into a speed command to the drive motors as well as desired angles for the wheels (one angle for both front wheels and one angle for both back wheels).

5 HYPOTHESES

This section explains the developed hypotheses regarding how designers may design their products in order to enable and ease control. The section is organised according to the product development part of the model presented in Section 2.

5.1 Hypotheses concerning requirements

A systematic consideration of requirements naturally leads to the need to manage requirements throughout the product development process. This concerns activities such as "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 an early consideration of requirements was highlighted frequently in literature (e. g, Lindemann and Stetter 1998). Sometimes control activities are not considered as essential for the main function of a product. However, the example of the steering system of the AGV (compare Section 4) shows that the basic functionality would not be possible without a control system. Also, many other products, such as cars, require control for an economic and ecological performance. Consequently, it can be assumed that control functionalities should also be treated as immediate requirements and not only as means which help to fulfil other requirements.

When focusing on the AGV from Section 2, one can notice that some control functions can initially appear without requirements from the end-user. In essence, users were not expecting this functionality, but if it is available, they may like it. For instance, in recent years it became possible to use rather cheap gyro-sensors in order to survey the inclination of an AGV. Here, a technology push can create additional requirements which have first to be presented to the later user as possible functions. Demands for control or a high economic or ecologic potential through control can be identified using the well-known method Quality Function Deployment. Amongst others, QFD allows for linkage of product characteristics, such as control functionalities, to the wishes and needs of the user, thus allowing the assessment of the specific end user merit of a certain control functionality. Additionally, elements of a product benchmark are contained in QFD and allow assessment of the desirable performance level of a control functionality.

To conclude: the main hypotheses concerning requirements are that **early phases** are extremely **important**, that the consideration of **control as immediate requirement** and a conscious **application** of **Quality function deployment** QFD can be helpful and that **new requirements** may appear as a consequence of a technology push in control and diagnosis.

5.2 Hypotheses concerning functions

Certain requirements describe necessary functions of future products. By means of function analysis (and synthesis), it can be described how these functions can be realized on an abstract level. 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 systematic product development of control functionalities, is the function structure as proposed by Ehrlenspiel and Meerkamm (2013). The main advantage of this form of function analysis is the inclusion of states (input and output states of functions) and the description of different types of linking possibilities of secondary flows to primary flows (types: condition state, process state, additional state). In the flow-oriented function structure, the direct functions and a connecting diagnostic function can be described in a consistent representation. The link type "process state“ especially allows one to assign a diagnostic function to a flow of matter, energy or information undergoing some kind of operation. Through this type of function structure, it is therefore possible to show exactly which entities are being diagnosed and to localize 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 exist and could evaluate process conditions of the function carrier.

This kind of function analysis was also applied in clarifying the control functionalities of the AGV. Here, the distinct functions of the steering angle control were analysed and depicted. The connection types "process state" (P) and "condition state" (C) were used to connect auxiliary flows to the main flow which describes the transformation from an arbitrary angular position of the wheel to the descried angular position of the wheel. This depiction has the advantage of clarifying complex function combinations within the products and by this, to assist the product development engineer in their endeavour. Figure 6 shows the flow-oriented function model of the control of the angular position of a wheel of the AGV.

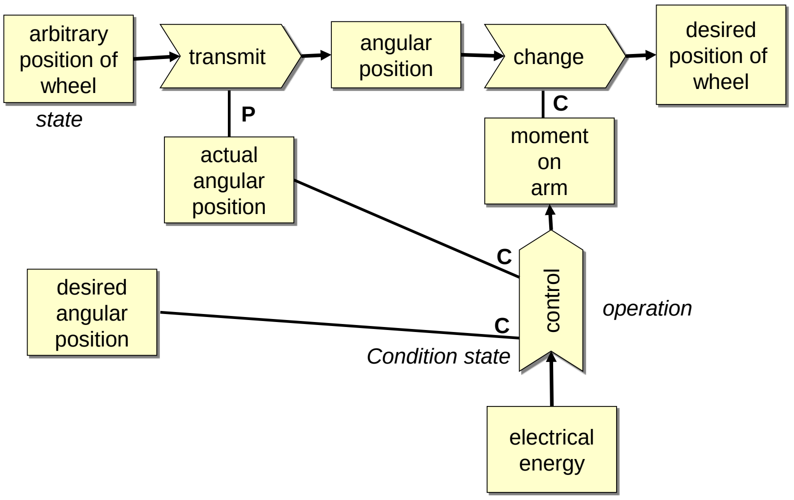


Figure 6. Flow-oriented function model: control of the angular position of a wheel

Another well-known approach to analyses functions is based on the work of Altshuller and used in connection with the tools of TRIZ/TIPS (compare e. g. Herb (2000)). This kind of function structure concentrates not on the flows, but on the relations in a product. Figure 7 shows one notation example (other notation conventions exist) and a control example of the AGV.

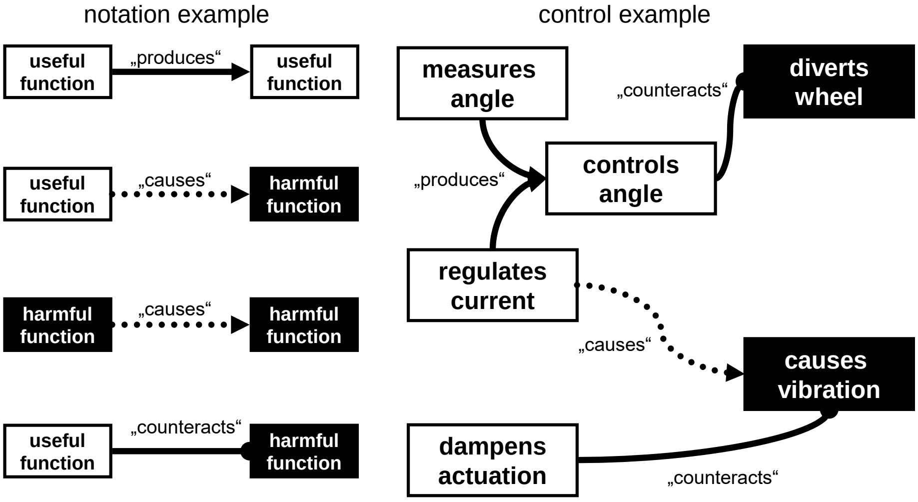


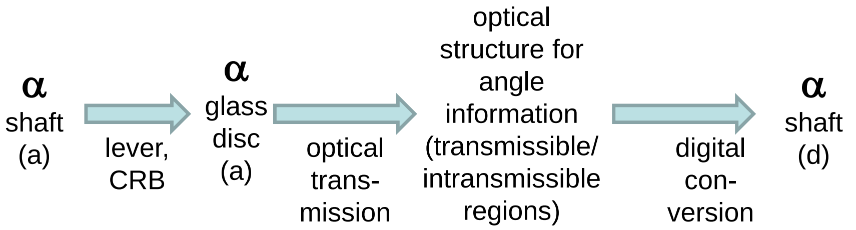
Figure 7. Relation-oriented function structure; right side: AGV example

As the results at the right side show, a relational function structure can ease the understanding of control functions and thus support systematic product development. The special merit of this kind of function model is the identification of contradictions. The methodology TRIZ offers certain guidelines on how to deal with the identified contradictions. The functional domain and the different models used in this domain offer several possibilities to develop and explore control functionality.

To conclude, the main hypotheses concerning functions are that a **flow oriented function structure** may help to **explore flows for control purposes** and that a **relation oriented function structure** may help to explore **contradictions**.

5.3 Hypotheses concerning physical phenomena

In general, the physical domain describes how functions of a product are realized in the most abstract physical sense. A number of authors (e. g. Ehrlenspiel and Meerkamm, 2013) propose to describe the physical domain by means of elementary physical effects. These physical effects are listed in the form of a catalogue, which also contains 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 realization can be described by means of effect chains. In Figure 8, a physical effect chain for an axis encoder of the AGV (compare Section 4) is shown.



(a): analog; (d): digital; CRB: cohesion of rigid bodies

Figure 8. Physical effect chain “axis encoder of the AGV”

The current angle of the wheel alpha is present at the shaft. By means of the physical effects “lever” and “cohesion of rigid bodies”, the machine element “parallel key” transmits the angle to a glass disc. On this glass disc are certain structures of transmissible and intransmissible regions, which allow for identification of the absolute angular position by means of the physical effect “optical transmission”. This information is then converted in digital angular information in regards to the angle of the wheel. Obviously, this kind of effect chain allows analysis and depiction of the physics acting in a product, thus fostering a deeper understanding and enabling communication between engineers. When describing the realization 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. To conclude, the main hypothesis concerning **physical phenomena** is that their investigation helps to **foster understanding** and can **ease communication**.

5.4 Hypotheses concerning geometry and material

The design of the final geometry and the choice of material of systems with control functionality may seem to be not much different from conventional systems. However, some aspects on this rather concrete level of engineering design can be identified, which may ease the control of technical systems.

One aspect is the integration of over-actuation capabilities. Currently, over-actuated design is understood as the usage of more actuators than necessary for controlling the rigid-body modes of motion systems (Schneiders et al. 2004). Ryll et al. (2013) describe the successful application of over-actuation on the example of an unmanned aerial vehicle (UAV - see Figure 9, left side).

This UAV is a quadrocopter which also possesses actuators to tilt the propellers. Here, the concept of over-actuation is also realized by means of MORE actuators than necessary. When looking at the AGV described in Section 4, another possibility for over-actuation becomes apparent: the use of STRONGER actuators than necessary. For a suitable dynamic behaviour of the steering system (which works by means of torque differences), it is necessary to apply drive motors with considerably more torque and power than necessary just for driving the AGV. Over-actuated designs usually have the advantage of a better controllability. Additionally, over-actuated designs can allow for expanded possibilities for fault-tolerant control, because the over-actuation potential can be used to compensate for faults.


Over-actuated UAV
quadrotor with tilting propellers
(Ryll et al. 2013)

High-redundancy actuation
inspired by musculature
(Davies et al. 2014)

Figure 9. Over-actuation and high-redundancy actuation

Another connected aspect is the application of high-redundancy actuation. The high-redundancy actuator (HRA) concept uses a high number of small actuation elements, assembled in series and parallel in order to form a single actuator (Davies et al. 2014 - see Figure 9, right side). Davies et al. (2014) report that such structures afford resilience under passive control methods alone, but active control approaches are likely to provide higher levels of performance. Consequently, high-redundancy actuation can also be understood as a means to foster fault-tolerant control.

Generally, the use of systems which exhibit non-continuous behaviour is not desirable for control applications. This kind of non-linear dynamic friction can be the cause of significant control errors (Ruderman 2012). For instance, the unavoidable stick-slip effects in friction clutches for cars complicate the control of start-up processes. Also, in the AGV described in Section 4, certain non-linear adhesion effects of the tooth belt which connects the front wheels may be a cause for the difficulty in controlling the torque steering.

A final aspect is that self-reinforcing behaviour should be avoided in order to ease control. One example is early automatic transmission for cars. In these systems, a band brake was used for the locking of gear rings in epicyclic gearing. The physical principle of a band brake allows self-reinforcing, but complicates control (Naunheimer et al. 2007). Consequently, in modern automatic transmissions, this task has been taken over by multiple-plate brakes.

To conclude, the main hypotheses concerning geometry and material are that a **potential** for **over-actuation** or **high-redundancy actuation** may have a positive effect and that it is generally sensible to **avoid non-continuous** and **self-reinforcing behaviour**.

5.5 Hypotheses concerning modules

The main problem concerning the modular structure is that a system containing control functionality must be structured in different dimensions. The structures have to cover the abstract functional structure, the structure of modules, the mechanical structure (geometry), the electronic structure (“systems”) in the meaning of a network, as well as the software structure (software functions) (Stetter and Pulm 2009). It is one main hypothesis of the presented research that these **structures** should be as **congruent** as possible in order to decrease complexity and to increase flexibility. Modular products allow a large number of product variants with a relatively small number of modules. Furthermore, modules allow a reduction of complexity, which is likely a necessity for the product development of mechatronic systems by functional disentanglement. The main challenge concerning modules is to define binding and stable interfaces, which often go beyond the borders of disciplines. It can ease interdisciplinary work, if interfaces are discussed and defined early and can remain stable during the design process. Based on experience in several product development projects, the hypothesis was developed that it is favourable if **modules contain local intelligence** on their own for a local control, and couple matter, energy and information flows in a small scale network and create some kind of subsystem isolation.

6 SUMMARY AND OUTLOOK

The initial step presented in this paper was a structured formulation of hypotheses concerning sensible procedures on different levels of abstraction. These hypotheses were explained on the basis of a sample product - an AGV with an innovative torque-based steering system. On all levels of a model of product development, certain aspects could be identified which may enable and ease control. Future research will test and expand these hypotheses.

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