INTEGRATING PRODUCT DEVELOPMENT MODELS AND "IN-PRODUCT MODELS"

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Abstract

Current complex products such as transportation systems usually dispose of an elaborate monitoring, control and diagnosis system. Very often such intelligent systems rely on models of the product (e.g. mathematical models). Such models are stored in the control units, in diagnosis and/or safety systems of the product and can therefore be referred to as "in-product models". It is important to note that several models of the product are generated during the product development of this system. One example for an in-product model might be a monitoring system for condition based service. Such systems rely on sensory information such as from vibration sensors and need to determine when service is necessary. Similarly, in product development engineers investigate vibrations of the product and need to determine how much vibration is admissible. Today, the generation of the two kinds of models is frequently done in separate departments and is usually not connected in a systematic manner. This paper discusses possibilities to integrate the generation of product development models and "in-product models" using the product example oil free compressor for braking systems of trains.

Keywords: Product modelling / models, Mechatronics, Design practice

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1 INTRODUCTION

Current complex products such as transportation systems usually dispose of an elaborate monitoring, control and diagnosis system. Very often such intelligent systems rely on models of the product (e.g. mathematical models). Such models are stored in the control units, in diagnosis and/or safety systems of the product and can therefore be referred to as "in-product models". It is important to note that several models of the product are generated during the product development of this system. One example for an in-product model might be a monitoring system for condition based service. Such systems rely on sensory information such as from vibration sensors and need to determine from these sensory information (amongst other information) when service is necessary. Similarly, in product development engineers investigate vibrations of the product and need to determine how much vibration is admissible. Today, the generation of the two kinds of models (product development models and "in-product models") is frequently done in separate departments and is usually not connected in a systematic manner. Very often important relationships are modelled twice or even many times, causing inefficient processes and increased error possibilities. This paper discusses possibilities to integrate the generation of product development models and "in-product models" using the product example oil free compressor for braking systems of trains. The structure of the paper is as follows. Firstly, the example product and some major challenges are presented. Subsequently, the different kinds of product development models and "in-product models" are explained. Finally, the integration possibilities of the generation of both kinds of models are discussed and elucidated on the example of a complex system.

2 SAMPLE PRODUCT - OIL FREE COMPRESSOR

The Knorr-Bremse Group is the world's leading manufacturer of braking systems for rail and commercial vehicles. For more than 110 years now the company has pioneered the development, production, marketing and servicing of state-of-the-art braking systems. In the rail vehicle systems sector, the product portfolio also includes intelligent entrance systems, HVAC systems, power conversion systems, control components, and windscreen wiper systems, as well as platform screen doors, friction material, driver assistance systems and control technology. Knorr-Bremse also offers driving simulators and e-learning systems for optimum train crew training. In the commercial vehicle systems sector, the product range includes complete braking systems with driver assistance systems, as well as torsional vibration dampers, powertrain-related solutions and transmission control systems for enhanced energy efficiency and fuel economy.

Since Gorge Westinghouse developed in 1869 the pneumatic brake air is used to brake trains (exceptions are e.g. light rail vehicles which use hydraulic energy or vacuum brakes). Compressed air is used in railway industry to provide the energy for braking and to transmit the braking signals throughout a train or secure the air suspension to ensure the same heights of a train at platforms if passengers are entering or leaving the vehicle (e.g. in Metros or High Speed Trains). It is as well an environmental friendly source of energy for braking, considering that there is no pollution in case of leakages – imagine a freight train of a length of 740 m (typical length in Germany, the world record is 7353 m of an Australian Iron Ore Train) with more than 20 cars coupled daily under harsh environmental conditions.

Knorr-Bremse introduced in 2005 a new technology for compressors in railway application, the oil free technology for piston compressors. Oil is no longer used as lubricant or cooling fluid. Target of this development was to further reduce the pollution of the environment as no oil is any longer used in the braking system. In terms of position evaluation it is important to note that this compressor is much closer to an ideal product as the main flow can be kept constant and one auxiliary flow is reduced to zero (compare section 3.3). It is a further main target to reduce the life cycle costs. Train operators do not have to check the oil-level of the compressors continuously, nor do the oil has to be pre-heated when the train is started at very low temperatures. The compressor is operating from -55°C up to 50°C ambient temperature. The portfolio of oil free piston compressors is available from auxiliary compressors with a delivery of 64 l/min up to 6000 l/min for compressors for North American Freight Locomotives (Figure 1). Up to now 22.000 compressors were sold in over 60 countries.

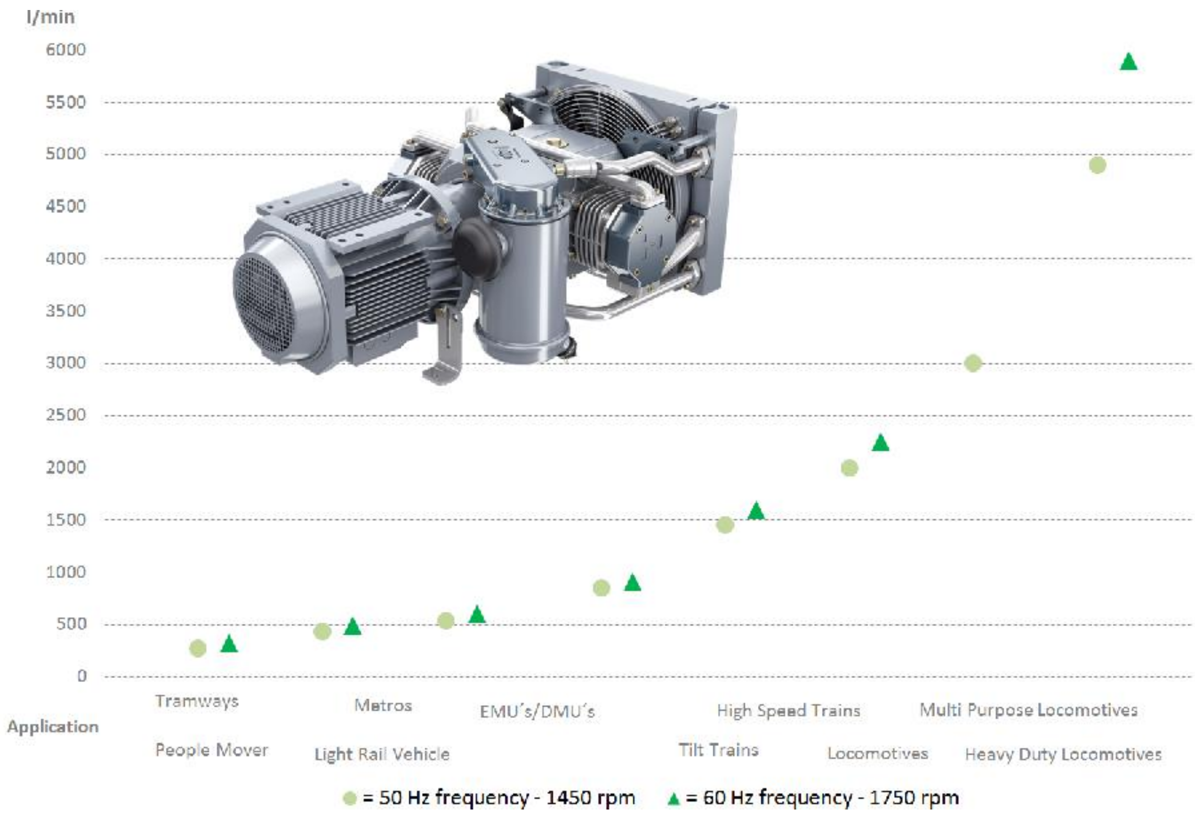

Figure 1. Product Portfolio of the oil free compressor range (Aßmann et al. 2017)

One of the challenges for air supply in railway operation is that pneumatic energy is needed discontinuously. After a braking process or entry and exit of passengers at regularly scheduled stops the compressor is activated. This application is a major challenge compared to industrial application when compressors are mainly in continuous operation, as in railway there are up to 30 starts an hour with very short running times of e. g. 10 secs. Due to the fact of changing requirements within operation and between different operators, the differences in application through the world wide ambient and operational requirements, high safety regulations systems are needed to identify the actual situation and behaviour of the product. The challenges in product development and operation are reflected in the applied models. It is important to note that some models in both areas were altered from the applied systems in order to protect intellectual property.

3 MODELS IN PRODUCT DEVELOPMENT

Models in general are material or immaterial artefacts which are created in order to represent an original in order to achieve some goal (Roth 1988). In mechanical design, models are primarily used for representing the product to be designed. The abstraction level of these representations stretches from nearly solution neutral requirement models to product similar prototypes. Models in mechanical design can be classified considering the function, i.e., the objective pursued by the use of the model and the form, i.e., the type of representation of the models (Lindemann et al. 1999). Models in mechanical design serve to verify geometric, functional, production or cost aspects of a product. Furthermore, they can be used for supporting designers (Stetter & Pache 1998). They are an aid in discussions about the future product, as they make it possible to explain certain aspects or to direct the attention of discussion partners. Furthermore, they assist designers by relieving, e.g., their short-term memory. Based on this and other effects such as intuitive playing with models, they foster the creation of new ideas. Models also enable the transfer and storage of information as they carry their geometric construction plan with them. Models can also be used for data integration, i. e., to represent the logic of a product. In product development, models are used for documenting (left side in Figure 2) and for analysis purposes (right side in Figure 2).

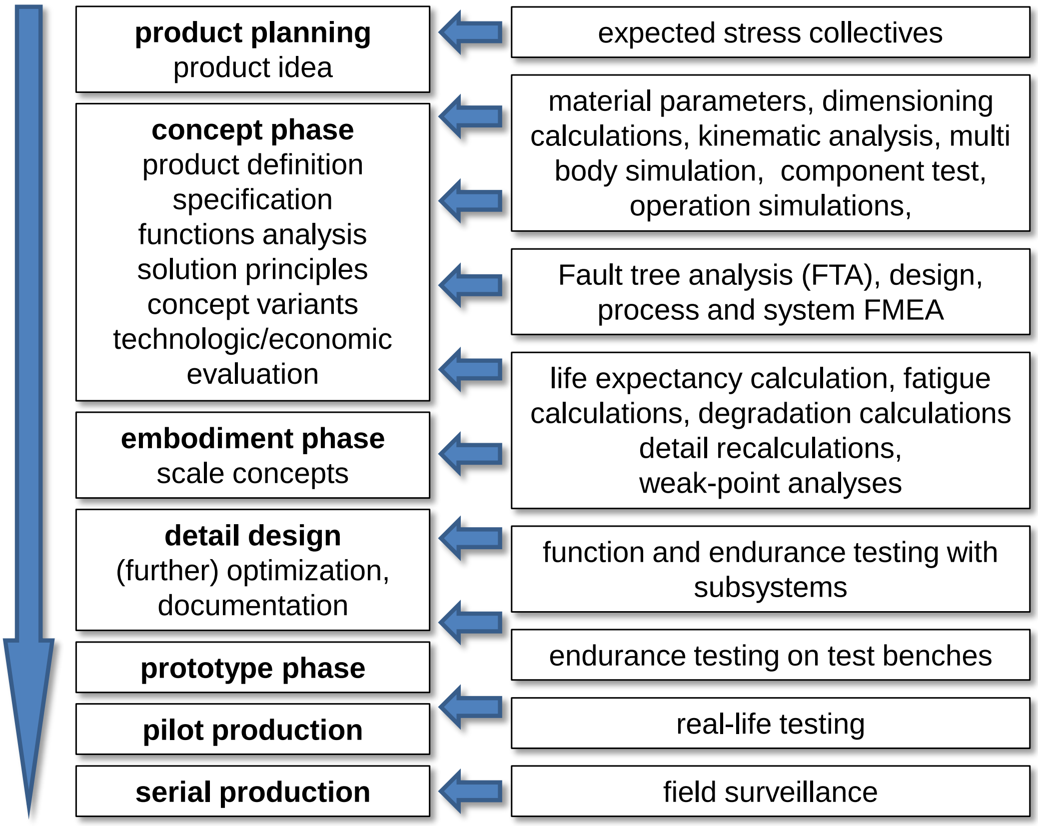

Figure 2. Synthesis and analysis in product development (adapted from Lindemann 2004)

Generally, it is advisable in the sense of an early evaluation of product properties (DTM) to start analyses very early in a product development process. Already in a very early stage expected stress collectives can be prepared, as they mainly depend on the operation scenarios, but not on the product itself. In the concept phase dimensioning calculations play a major role, but also kinematic investigations and many other calculations are carried out. In order to enhance safety, reliability and product quality the methods fault tree analysis (FTA) and Failure Mode and Effects Analysis (FMEA) are performed. In the embodiment phases a main emphasis is given to methods which can predict the life-time behaviour of a product such as fatigue calculations. These methods are usually supported by extensive testing. Finally, also certain analyses such as field surveillance even accompany the serial production and use of the products. Needless to say, in numerous analysis steps models of the product are generated in order to allow the performance of this analysis.

In this context, the current research activities concerning modelling cyber-physical systems and modelling in the scope of Industry 4.0 have to be considered. This research has already led to modelling languages which can synchronize system architecture, logical and physical modelling; frequently the notion "digital twin" is used for this integration endeavour (compare Shi et al. 2011, Lee et al. 2015, Zheng et al. 2016, Grieves & Vickers 2016). This integration also includes elements of control and diagnosis (such as collaborative diagnostics). The actual integration of the product development models and the models for control and diagnosis on an operational level was not the point of main emphasis of the research activities.

Another stream of research concerns the creation of models on the basis of observation, e. g. by means of statistical methods (compare e. g. Clarke & Zuliani 2011). The application of methods such as neuronal networks or fuzzy logic can also pursue similar objectives (compare e. g. Patan 2008). These streams of research have led to enormous achievements. However, in industrial application models are frequently used which are based on physical phenomena as well as engineer's knowledge and experience. Possible causes for the conscious application of such models are:

- a high level of trust in this proven models of the product;
- the extrapolation possibilities due to an orientation on and an understanding of describable physical phenomena;
- an easier transfer to changed product configurations or parameters.

This paper focuses on the actual integration of product developments models, which are often based on knowledge concerning physical relationships and experience, and in-product models for monitoring, control and diagnosis on an operational level. Such models and their functionality are presented in the next section and the potential to use product development models as a basis for in-product models is discussed in section 5.

4 IN-PRODUCT MODELS

In-product models are stored in the control units, in diagnosis and/or safety systems of the product and allow certain tasks. On a very general level such models can be distinguished concerning their main objective: monitoring, control or diagnosis.

The notion "monitoring" summarizes all kinds of systematic observation, surveillance or recording of an activity or a process by any technical means. In complex products such as transportation systems today usually a large share of the operation data of the product are being monitored for the three main reasons safety, efficiency and plannability:

- The safety of a product 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 a product can be enhanced because any kind of waste (usually energy) will be detected and can subsequently be prevented or reduced.
- The planning possibilities and planning quality e. g. for service operations can be enhanced if accurate data from a continuous monitoring system are available as realistic prognosis is enabled by such data.

Monitoring activities have a merit on their own, as they are usually necessary for safety and for planning activities. Additionally they are the first step for control and diagnosis.

The notion "control" names certain activities with the aim to manage, command, direct or regulate the behaviour 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 (Sastry&Bodson 2011).

On a very general level the notion "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 survey works of Blanke et al. (2016), Isermann (2005), Witczak (2007) and Korbicz et al. (2004). 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 dysfunctions. Figure 3 shows a summary of the notions diagnosis, monitoring and control.

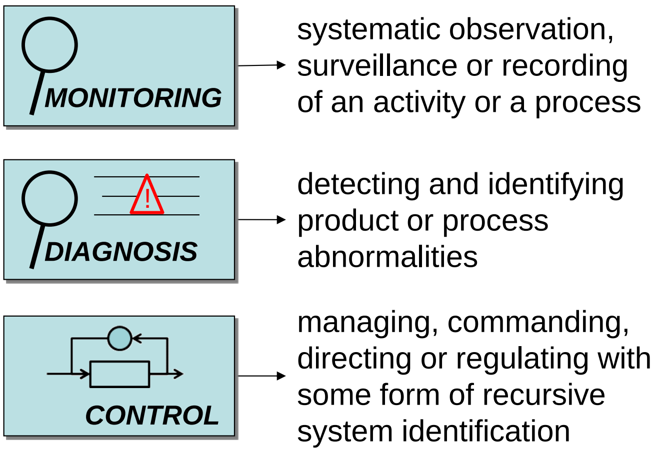

Figure 3. Monitoring, Diagnosis and Control

4.1 In-product models for monitoring

Essentially, the objective "monitoring" would not require a model, if it would be satisfactory only to gather certain data from sensor and to send them to a superordinate intelligence. However, very often the available sensor data requires refinement due to noise, suboptimal sensor placement and a lack of sensor. Additionally, it is very often sensible to reduce the amount of data already within the monitoring system, for instance in order to reduce bus load. Sometimes sensory data can also be filtered by means of model based filters such as kalman filters (compare e. g. Dabrowska 2012). Finally, frequently the mathematical combination of the information of many sensors can lead to additional important information (sensor fusion) which cannot be generated by any other means. Figure 4 shows an example of an in-product model for the monitoring of the compressor.

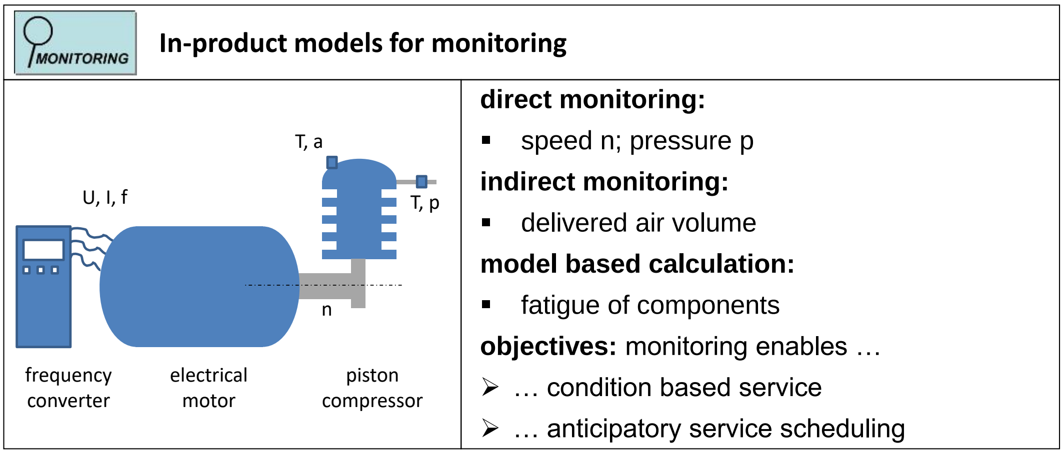

Figure 4. In-product model for monitoring: example

It is today desirable to allow condition based service. Until now, the service intervals for compressor were only depending on time (e. g. one service per year) or operation hours (of the train; seldom of the compressor itself). However, the fatigue of the compressor is largely depending on the amount and pressure of the air delivered. With the sensors available, this cannot be directly measured, but an empirical model in the monitoring system allows a reliable calculation taking into account available sensor data and information form the frequency converter which supplies the motor which drives the compressor. Through this in-product model the availability can be greatly enhanced.

4.2 In-product models for control

For simple control algorithms such as PID-controllers no explicit model of the product is necessary. However, in recent years several developments in the direction of model based control have led to enormous successes (Naus 2010). Some years ago, the control of a compressor was realised only by a pressure-release valve. Very often the compressor was delivering a higher air volume than necessary and the air, which was not needed, was just released. The efficiency of the solution was sub-optimum. Current developments allow a regulation of the electrical motors by a frequency converter. It is possible only to generate the amount of air really needed. However, mathematical models of the electrical motor as well as the compressor are needed in order to allow this kind of control and can be developed from the product development models.

Current research in the area of control is focusing on fault tolerant control (FTC). Such systems allow preserving performance and stability of complex products despite the presence of faults. 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). An air compressor for supplying brakes in a train has an important role in the safe operation of this train. It is therefore desirable that a fault in this system or a surrounding system is not leading to a malfunction but can be accommodated by the control system of the compressor. The detection and identification of faults is a part of diagnosis and is therefore discussed in section 4.3. By means of fault tolerant control, a controller can accommodate certain identified faults (e. g. higher compressor speed if a small leak is detected) and can contribute to the reliability and safety of the train (Figure 5).

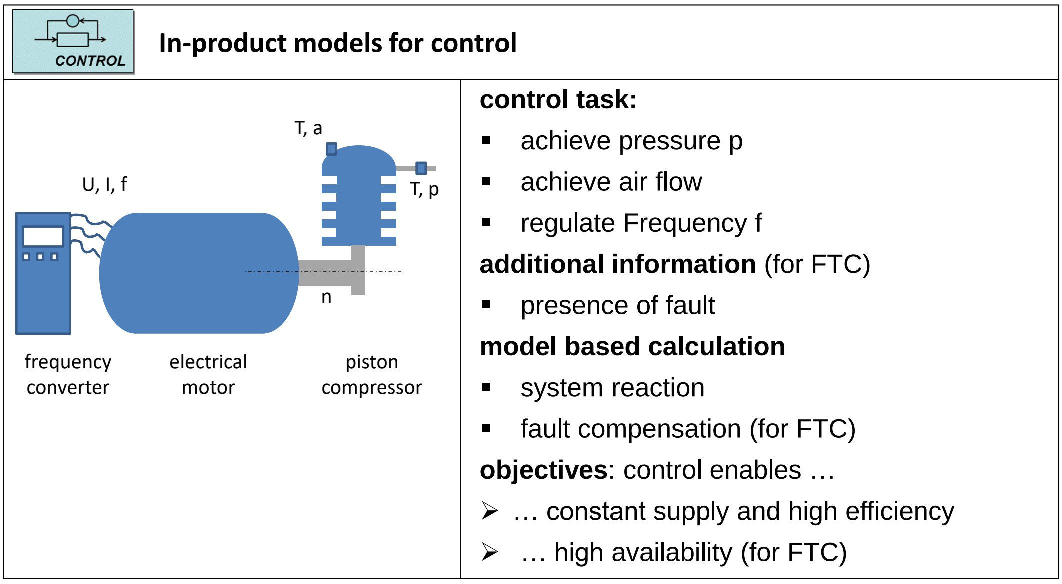

Figure 5. In-product model for control: example

4.3 In-product models for diagnosis

The core element of diagnosis is the detection and identification of faults. This is usually based on residuals which essentially described possible differences between the real state of the system and some expected state of the system. Such differences can indicate faults. The calculation of an expected state of a system requires a mathematical model of this system, i.e. of the product. For the compressor example, based on an in-product model an expected air pressure may be calculated based on the current and voltage in the frequency converter and additional information such as air temperature etc. This expected air pressure and be compared with the actual sensor information from the pressure sensor. A difference can then indicated a fault e.g. an air leak (Figure 6).

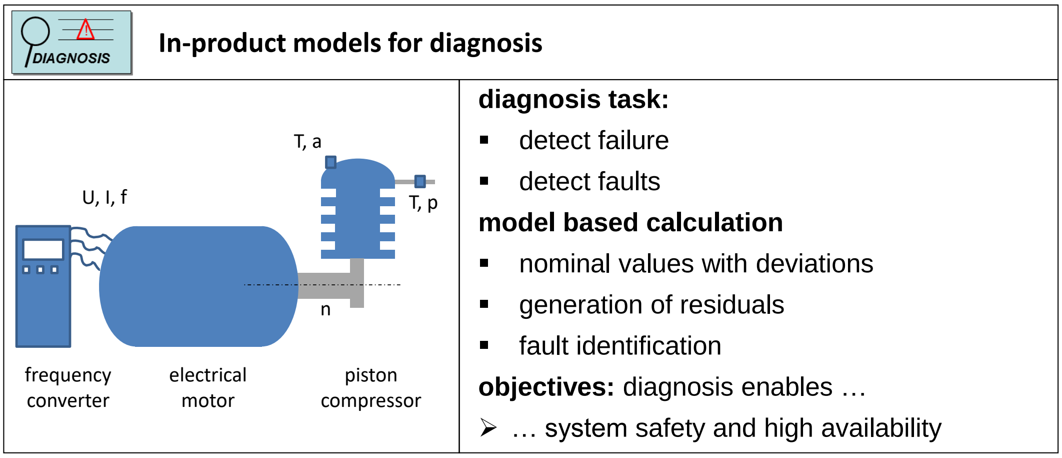

Figure 6. In-product models for diagnosis. example

5 INTEGRATION OF BOTH KINDS OF MODELS

The combination of product development models and in-product models has until now not been the in the centre of research. Naus (2010) lists two first steps in a control design approach:

- Study the system to be controlled and obtain initial information about the control objectives and
- Model the system and simplify the model, if necessary.

He does not even ask the question, if models may already be available from product development. There is no consideration if the system to be controlled is already developed or if some changes may still occur. It can be hypothesized that control engineers frequently wait until a product is fully developed, before they start to develop the models which they need for monitoring, control and diagnosis. If we compare this situation with simultaneous engineering, i. e. the parallelization of product design and production planning activities, which is today wide-spread practice in many industries, we might come to the hypothesis that not only crucial time is lost by a sequential procedure, but also that certain synergies cannot be activated. Stetter&Phleps (2011) were able to show that it may be advantageous to design a product so that it can enable or ease diagnosis tasks; similar research is currently also carried out looking at control tasks (Stetter&Simundsson 2017). One essential first step for an integration of product development models and in-product models may be the initiation of communication between product development and control engineers in spite of different mind-sets (compare Figure 7).

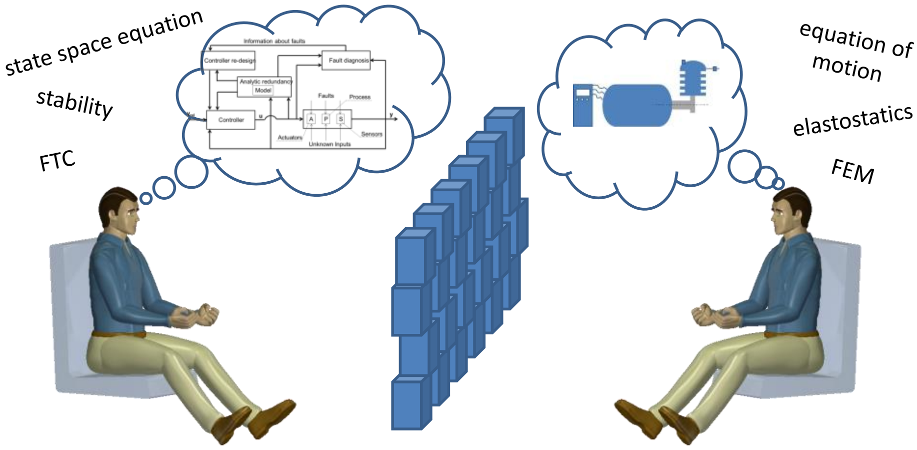

Figure 7. Different mind-set of control and product development engineers

Both sides need to understand that both parties rely on models of products and that both parties contribute to the overall functionality, quality, reliability and safety of the product. It may be the case, that the results of the application of models may look very different and that these concrete results may block the insight that the modelled behaviour is very similar.

A good starting point for integration are the numerous fatigue or degradation analyses which product development engineers perform in order to assure the life-expectancy of a product. The results of these analyses can be used for monitoring purposes, for instance if condition based service is aimed at. An in-product model may use a simplified fatigue equation in order to estimate the state of fatigue on the basis of certain sensor signals (left two puzzle blocks in Figure 8).

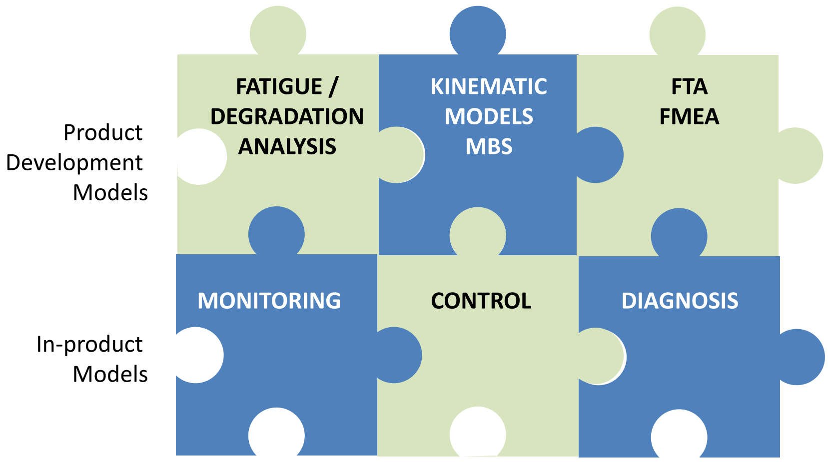

Figure 8. Integration of product development models and in-product models

In product development, the behaviour of systems is very often investigated using kinematic models and multi-body-systems (MBS). For model based control a description of the behaviour of systems is usually a main cornerstone for success (middle to puzzle blocks in Figure 10). Obviously, some simplifications of models and a transformation into a state space form are usually necessary. Still it is reasonable to hypothesize that intensive knowledge of the product development models may ease the development of the in-product models largely and may improve them.

Fault tree analysis (FTA) and Failure Mode and Effect Analysis (FMEA) are well-known tools in product development. They intend to support the identification of potential faults and failures in the

product under development. The identification of faults is also a main element in diagnosis. It is only logical to conclude that FTA and FMEA contain just the main information for the development of efficient and effective diagnosis systems.
An integration of both kinds of models in a complex system was possible during the transformation from a component based to a system based approach in air supply (Figure 9).

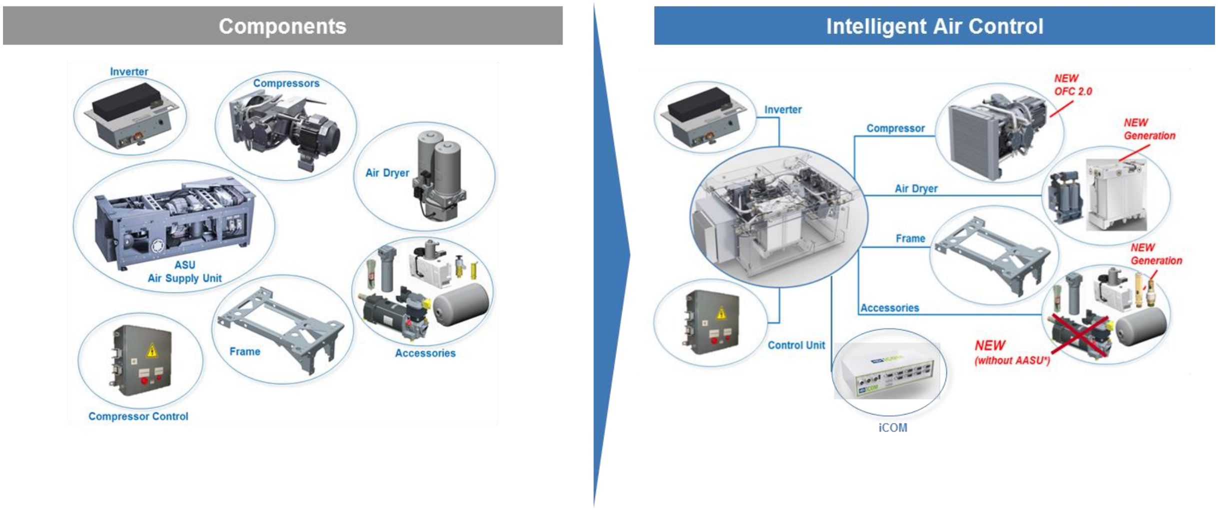

Figure 9. Complex model: Intelligent Air Control

The main step is the realization of an integrated controlled air supply system - Intelligent Air Control. This step requires a system approach and holistic simulation but helps competing with the main competitors. In this case the concept models from the product development department, which were based on the general physical relationships, could successfully be used as models for the integrated control. The parameters of the models had to be tuned using systematic observation, but the general structure could be sustained. The integrated, model-based control and diagnosis system of a complex system can lead to the following advantages:

- avoidance of inrush current,
- omission of an auxiliary air supply unit,
- realization of a short time boost function and
- a significant reduction of the sound power level.
- functions for conditions based maintenance, e.g. in replacement of wear parts according actual wear

These advantages show the potential of a control system which uses "in-products" models which were developed from the models developed and used by the product development engineers.

6 SUMMARY AND OUTLOOK

A new vision for the development of innovative products which dispose of complex control systems is the simultaneous synthesis of product development models and in-product models. The notion "product development models" summarizes all kinds of product models (geometrical, textual, mathematical, …) which are used as means for solution generation, solution analysis, solution evaluation and documentation, but which are NOT used in the control system during the operation of the product. On the contrary, in-product model are used in the control system - however, usually they may differ to an astonishing amount from the product development models. Today, the generation of the two kinds of models is frequently done in separate departments and is usually not connected in a systematic manner. The presented research seeks for possibilities to integrate the generation of product development models and “in-product models”. The research was based on a complex product example which disposes of a control system - an oil free compressor for braking systems of trains. Main exploration areas concern the integration possibilities of the generation of both kinds of models. Crucial points are the different mind-sets of product development and control engineers and the common belief that a control engineer can only start when the product development engineer "has done its job". It was possible to elaborate integration possibilities for different focus points of in-products models such as monitoring, control and diagnosis.

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