Systematic Product Development of Control and Diagnosis Functionalities

R Stetter¹, A Simundsson²

¹ Hochschule Ravensburg-Weingarten, Weingarten, Germany
² University of Manitoba, Winnipeg, Manitoba, Canada

E-mail: stetter@hs-weingarten.de

Abstract. In the scientific field of systematic product development a wide range of helpful methods, guidelines and tools were generated and published in recent years. Until now little special attention was given to design guidelines aiming at supporting product development engineers to design products that allow and support control or diagnosis functions. The general trend to ubiquitous computing and the first development steps towards cognitive systems as well as a general trend toward higher product safety, reliability and reduced total cost of ownership (TCO) in many engineering fields lead to a higher importance of control and diagnosis. In this paper a first attempt is made to formulate general valid guidelines how products can be developed in order to allow and to achieve effective and efficient control and diagnosis. The guidelines are elucidated on the example of an automated guided vehicle. One main concern of this paper is the integration of control and diagnosis functionalities into the development of complete systems which include mechanical, electrical and electronic subsystems. For the development of such systems the strategies, methods and tools of systematic product development have attracted significant attention during the last decades. Today, the functionality and safety of most products is to a large degree dependent on control and diagnosis functionalities. Still, there is comparatively little research concentrating on the integration of the development of these functionalities into the overall product development processes. The paper starts with a background describing Systematic Product Development. The second section deals with the product development of the sample product. The third part clarifies the notions monitoring, control and diagnosis. The following parts summarize some insights and formulate first hypotheses concerning control and diagnosis in Systematic Product Development.

1. Systematic product development

Systematic product development can be traced back to the inventor Reuleaux, who presented a procedure for kinematic synthesis close the end of the 19th century. Especially after the world war two many researchers were investigating and formulating product development strategies, methods, guidelines and tools. The German engineering design methodology “Konstruktionsmethodik” played a central role, but in many other countries elaborate research efforts were carried out, as well. Central researchers in this endeavor were Rodenacker [1], Pahl&Beitz [2], Koller [3], Roth [4], Ehrlemspiel [5] and Lindemann [6]. An important milestone was the formulation of the VDI (German society of engineers) guideline 2221. This guideline was based on the earlier VDI 2222. The goal of this guideline is to propose a general methodology for designing technical systems and products and to
support a methodical and systematic designing, in order to produce a more efficient working style [7]. The main process which is described in this guideline is shown in Figure 1.

![Systematic Product Development according to VDI 2221](image)

Figure 1. Systematic Product Development according to VDI 2221 [8].

There is little doubt concerning the merit of this guideline. Recent investigations, however, have shown that design processes are much more iterative and frequently display evolutionary characteristics [9], [10]. It was therefore 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 [11]. This model, which is shown in Figure 2, 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 core of the model is the core process of producing companies consisting of 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 concern 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 [12]. 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 [13]. In order to allow this traceability often a version management is 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 fulfill 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 producing 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 side in Figure 2) necessary activities can be summarized using 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 “function”. Such functions can be realized by means of a combination of physical phenomena. The notion “physical effects” summarizes a number of activities aiming 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 “structure”. The notion “modules” summarizes activities with the objective to develop smaller subsystems of the product commonly referred to as modules.

The phases “production and assembly” as well as “marketing and after-sales” are not analyzed 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.

2. Sample Product Development of an Automated Guided Vehicle AGV

This section describes the product development of an AGV for outdoor used (compare also Stetter & Simundsson [14]). 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 3).

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 used steering system is the dynamic behavior. This innovative steering system is based on the concept to use 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 4.

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 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 4).

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 maneuvers.
Furthermore, a vehicle based on the dynamic drive system is able to turn around its own center. 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&Barnes [15]), but has reduced friction as well as easier controllability and 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 happens on different levels. A central computer receives a movement wish 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 wish 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).

Based on this sample product development several aspects of systematic product development are explored. In the next section first the notions are clarified.

3. Monitoring, Control and Diagnosis
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 plannability:

- 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.

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 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 (Sastry&Bodson [16]).

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; recent additions also concern the distributed diagnosis of mechatronic systems; see for example survey works of Blanke et al.[17], Isermann [18], Witczak [19] and Korbicz et al. [20]. 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 5 shows a summary of the notions diagnosis, monitoring and control.

In the following sections hypotheses concerning systematic product development are discussed. The structure follows the model of systematic product development shown in Figure 2.

4. Systematic product development of requirements
A systematic consideration of requirements naturally leads to the need to manage requirements throughout the product development process. This concerns 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.

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 2) 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 fulfill other requirements.

Especially diagnostic functions are frequently linked to the direct functionality of the product. For an example, a diagnostic function “detect low battery status” of the AGV is strongly linked to the direct function “supply energy”. 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.

When focusing on the AGV from Section 2 one can notice that some control and diagnostic functions can initially appear without requirements from the end-user. 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.

It is important to note that especially the Failure-Mode-and Effects-Analysis (FMEA) offers a straight-forward possibility to identify demand for diagnosis (compare Stetter&Phleps [21]). 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 to link product characteristics such as control functionalities to the wishes and needs of the user thus allowing assessing the specific end user merit of a certain control functionality. Additionally, elements of a product benchmark are contained in QFD and allow assessing the desirable performance level of a control functionality.

Figure 6 summarizes the hypotheses concerning requirements.

![Figure 6. Hypotheses concerning requirements.](image)

5. Systematic product development of functions

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 realized. Many different approaches and models have been proposed for function analysis. The first one, which will be analyzed with regards for its potential to support systematic product development of control and diagnosis functionalities is the function structure as proposed by Ehrlenspiel [5]. 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 – compare [22]). Figure 7 shows the notation and an example of the flow orientated function structure. In the example of the AGV (lower right of Figure 7) the moment of an electrical drive motor driving the AGV is connected as a so-called “condition flow (C)” – depicting a necessary condition for the realization of a function.

In this function structure the direct functions and a connecting 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 [21]. By 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 are existing and could evaluate process conditions of the function carrier.

![Flow oriented function analysis diagram](image)

**Figure 7.** Flow oriented function analysis.

This kind of function analysis was also applied for clarifying the control functionalities of the AGV. Here the distinct functions of the steering angle control were analyzed 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 described 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 endeavor. Figure 8 shows the flow oriented function model of the control of the angular position of a wheel of the AGV.

![Flow oriented function model of the wheel angle control](image)

**Figure 8.** Flow oriented function model of the wheel angle control.
Another well-known approach to analyzing 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 is concentrating not on the flows but on the relations in a product. Figure 9 shows one notation example (other notation conventions exist) and a control example of the AGV.

As the results at the right side show, a relational function structure can ease the understanding of and overview over control functions and thus support systematic product development. In summary, the functional domain and the different models used in this domain offer several possibilities to develop and explore diagnostic functionality. Figure 10 summarizes the hypotheses concerning requirements.

6. Systematic product development of physical effects
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. Ehrleinspiel [5] propose to describe the physical domain by means of elementary physical effects. These physical effects are listed in 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 11 a physical effect chain for an axis encoder of the AGV (compare section 2) is shown.

![Figure 11. 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 identifying the absolute angular position by means of the physical effect “optical transmission”. This information is then converted in digital angular information about the angle of the wheel. Obviously, this kind of effect chain allows analyzing and depicting the physics acting in a product thus fostering a deeper understanding and enabling communication between engineers. Generally, sensory physical effects which have electrical outputs are desirable for diagnosis purposes [21]. Additionally, 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. Figure 12 summarizes the hypotheses concerning physical effects.

![Figure 12. Hypotheses concerning physical effects.

7. Systematic product development of structures and modules
The main problem concerning structure is that a system containing control and diagnosis functionality has to 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) [11]. 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.

Current mechatronic products are usually realized by means of a combination of modules. This strategy allows a large number of product variants with a relatively small number of modules which can be combined in different ways. Furthermore, modules allow a reduction of complexity which probably is a necessity for the product development of any mechatronic system [11]. The main challenges concerning modules are to define binding and stable interfaces, which often go beyond the borders of disciplines, and the fact that a modular design (due to variants, production etc.) is suboptimal compared to an integrated design. Based on experience in several product development projects the hypothesis was developed that it is favorable if modules contain an intelligence on their own and couple matter, energy and information flows in a small scale network.

Figure 13 summarizes the hypotheses concerning structure and modules.

8. Summary
This paper was aiming at developing an initial basis for further research in order to enable a systematic product development of control and diagnosis functions. The ultimate vision is the development of design guidelines aiming at supporting product development engineers to design products that allow and support control or diagnosis functions. The product example of an automated guided vehicle was used for explaining a series of hypotheses which were structured according to a model of systematic development. Until now not all aspects of the model could be covered and further research is necessary to test and further elaborate the presented hypotheses.

9. Acknowledgments
Parts of the research were carried out in the scope of the project „digital product life-cycle (ZaFH)“ (information under: https://dip.reutlingen-university.de/) which is supported by a grant from the European Regional Development Fund and the Ministry of Science, Research and the Arts of Baden-Württemberg, Germany (information under: www.rwb-efre.baden-wuerttemberg.de).

References
[1] Rodenacker, W.: Methodisches Konstruieren: Grundlagen, Methodik, praktische Beispiele. Springer, 1991.
[2] Feldhusen, J.; Grote, K.-H. (Eds.): Pahl/Beitz Konstruktionslehre: Methoden und Anwendung
erfolgreicher Produktentwicklung. Springer, 2013.

[3] Koller, R.: Konstruktionslehre für den Maschinenbau: Grundlagen zur Neu- und Weiterentwicklung technischer Produkte mit Beispielen. Springer, 2011.

[4] Roth, K.: Konstruieren mit Konstruktionskatalogen: Band 1: Konstruktionslehre. Springer, 2000.

[5] Ehrleinspiel, K.; Meerkamm, H.: Integrierte Produktentwicklung: Denkabläufe, Methodeneinsatz, Zusammenarbeit. Hanser, 2013.

[6] Lindemann, U.: Methodische Entwicklung technischer Produkte: Methoden flexibel und situationsgerecht anwenden. Springer, 2009.

[7] Jänsch, J.; Birkhofer, H.: The Development of the Guideline VDI 2221 - the Change Of Direction. In: Proceedings of the International Design Conference - DESIGN 2006. Cavtat: 2006.

[8] Verein Deutscher Ingenieure (VDI): Richtlinie VDI 2221 "Methodik zum Entwickeln und Konstruieren technischer Systeme und Produkte". VDI-Verlag: 1993.

[9] Stetter, R., Möhringer, S., Pulm, U.: A Comparison of Evolutionary and Revolutionary Approaches in Mechatronic Design. In: Proceedings of the 18th International Conference on Engineering Design (ICED 11) Vol. 1, 2011, pp. 221-232.

[10] Stetter, R., Möhringer, S., Günther, J.; Pulm, U.: Investigation and Support of Evolutionary Design. In: Weber, C.; Husung, S.; Cascini, G.; Cantamesa, M.; Marjanovic, D.; Bordegoni, M. (Eds.): Proceedings of the 20th International Conference on Engineering Design (ICED 15) Vol 8: Innovation and Creativity, Milan, Italy, 27-30.07.2015, pp. 183-192.

[11] Stetter, R.; Pulm, U.: Problems and Chances in Industrial Mechatronic Product Development. In: Norell Bergendahl, M.; Grimheden, M.; Leifer, L.; Skogstad, P.; Lindemann, U. (Eds.): Proceedings of the 17th International Conference on Engineering Design (ICED'09), Vol. 5., 2009, pp 97 – 108.

[12] Daenzer, W.F.; Huber, F.: „Systems Engineering – Methodik und Praxis“. Verlag industrielle Organisation, 2002.

[13] Crnkovic I., Asklund, U. & Persson-Dahlqvist, A.: “Implementing and Integrating Product Data Management and Software Configuration Management”. London: Artech House, 2003.

[14] Stetter, R.; Simundsson, A.: Control and Diagnosis in Integrated Product Development - Observations during the Development of an AGV. Journal of Physics; Conference Series 659 012056 (2015).

[15] Ashmore, M., Barnes, N.: “Omni-drive robot motion on curved paths: The fastest path between two points is not a straight line”, Proceedings of the Australian Joint Conference on Artificial Intelligence, Dec., 2002, pp. 225-236.

[16] Sastry, S. and Bodson, M. Adaptive Control: Stability, Convergence, and Robustness. Sastry & Bodson: 1994.

[17] Blanke, M., Kinnaert, M., Lunze, J., and Staroswiecki, M. Diagnosis and Fault–Tolerant Control. Berlin: Springer, 2016.

[18] Isermann, R. Fault–Diagnosis Systems: An Introduction from Fault Detection to Fault Tolerance. Berlin: Springer 2005.

[19] Witzczak, M. Modelling and Estimation Strategies for Fault Diagnosis of Non–Linear Systems: From Analytical to Soft Computing Approaches. Lecture Notes in Control & Information Sciences. Berlin: Springer 2007.

[20] Korbiez, J., Kościenly J.M., Kowalczuk Z. and Cholewa W. Fault Diagnosis: Models, artificial intelligence methods, applications. Springer: Berlin, 2004.

[21] Stetter, R., Phleps, U.: Design for Diagnosis. In: Proceedings of the 18th International Conference on Engineering Design (ICED 11) Vol. 5, 2011, pp. 91-102.

[22] Stetter, R., Kleinmann, S.: Design Guidelines for Diagnosis on the Example of Pump Systems. In: Bokor, J. (Ed.): Proceedings of the 9th Workshop on Advanced Control and Diagnosis, ACD'2011, 17. and 18. November 2011, Budapest, Ungarn.