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DRIVERS FOR ADAPTIVE SYSTEM DESIGN USING SMART MATERIALS

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Keywords: adaptability, goal-conflicts, spreading requirements, adaptronics

1. Introduction

The behaviour of a system is defined by a sequence of states [Hubka 1984]. Each state is characterised by a set of properties. In order to realize the expected system behaviour, during the design process a solution with the properties required has to be worked out. The required properties are derived from the user demands as well as foreseen operating conditions and environments and are realized by a proper structure [Gero 1990]. However, the actual properties during systems operation are affected by the context and the environment the system is used in. Roozenburg emphasizes „a product having the requested properties, therefore, functions in the intended manner only if it is used in the environment and in the way that the designer has thought up and prescribed" [Roozenburg 2002]. In design practice fulfilment of all required properties is hindered by the following challenges:

- Operating conditions and user demands of modern products are frequently changing during use and thus require different properties [Chmarra et al. 2008], [Bischof 2010].
- System properties of mechanical systems are indirectly determined by characteristics [Roth 2000], [Weber 2005]. Interactions between characteristics and different properties often hamper simultaneous fulfilment of all properties, resulting in goal conflicts during the design task.
- Often there is a difference between the properties provided by a solution element and the properties needed [Birkhofer 1980], [Roth 2000]. This difference affects the systems behaviour in a negative way.

In order to address these challenges, different strategies are applied resulting in robust or adaptive systems. Robust systems aim for minimizing the effect of changing operating conditions and user demands on systems performance without changing systems properties, whereas adaptive systems are able to react on changing environments by adapting system properties [Olewnik et al. 2004].

This contribution focusses on the development of adaptive systems using smart materials, called adaptronic solutions. Since the development of these systems often results in an increasing effort, drivers for adaptive system design are introduced supporting the evaluation of the needed adaptability during early design phases. In order to point out the focus of research, the following sections introduce the understanding of adaptability and adaptronics. In section three drivers for adaptive system design are derived from a literature review comprising different development approaches in fields of adaptable and adaptive system design. The identified drivers are divided into two types and related to different design stages in order to highlight the product models needed to detect them.

2. Background and focus of research

The following sections introduce the understanding of adaptability as well as adaptronics needed to formulate two questions motivating the research presented.

2.1 Adaptability of technical systems

Literature presents a divers understanding concerning a systems ability to cope with changing operating conditions and user demands. Terms like flexibility [Sethi and Sethi 1990], [Bischoff et al. 2008], reconfiguration [Krefft et al. 2006], [Ferguson et al. 2007], changeability [Fricke and Schulz 2005] and adaptability [Chung and Subramanian 2004], [Hashemian 2005] are used to describe this ability. The underlying understanding of terms differ concerning the way changes are carried out, for instance, by the user or the system itself and the phase of the product life cycle the change is addressed e.g. during design or during use. Based on the definition of Olwenik et al. [2004], for this research, adaptability is defined as "passive (offline, system is out of operation) or active (online, system is running) change of systems properties within a given range with the goal to enhance systems performance in predictable changes in the operating environment". The distinction between passive and active adaptability results in different design approaches and system structures (see Figure 1).

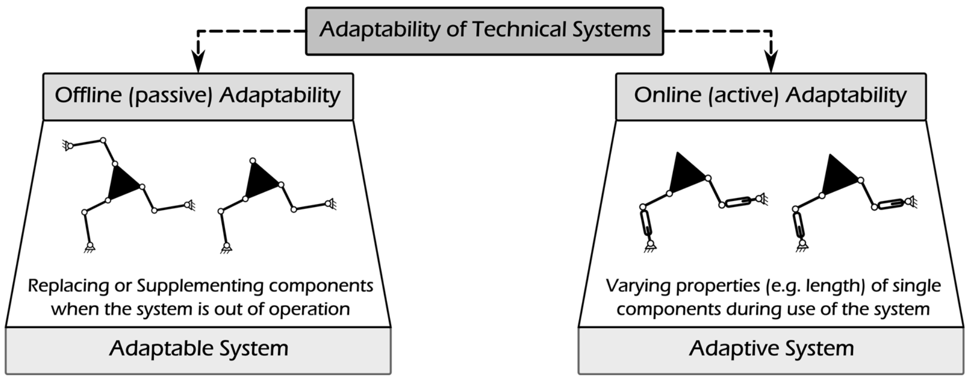

Figure 1. Passive and active adaptability of systems and their underlying design approaches

Passive adaptability is realized by replacing or supplementing single modules. For instance, replacing links with different length in a parallel kinematic robot can be understood as passive adaptability and results in an enlargement of the workspace dimension [Schmitt et al. 2009]. A replacement of the modules should be possible without affecting other module, e.g. drives or their interfaces, e.g. drives. Therefore, modules as well as interfaces have to be determined during design [Ulrich and Eppinger 1995]. Active adaptability is realized by changing the properties of several system elements during systems operation (online). For instance, the application of additional drives to vary the link length of a parallel kinematic robot results in active adaptability of the workspace dimension [Krefft et al. 2006]. However, this adaptability requires active elements (actuators) to influence system properties. Furthermore, sensors and control functions are necessary to allow for goal-oriented adaption. Thus, the required system structure for adaptive systems is similar to this of mechatronic systems [VDI 2004].

This paper focusses on the active adaptability of a system where changes are carried out while the system is performing a task. In the following section, the concept of adaptronic solutions as a means to realize active adaptability is introduced.

2.2 Adaptronics and smart materials

According to Pahl et al. [2007] objectives of adaptronic solutions are to adapt structures to changed load conditions, reduce the effect of disturbances and cope with changed functional requirements. The adaption is carried out using sensors providing information about the system and its environment, a control algorithm working on the gathered information and deriving adequate adaption of several system properties by actuators. All or some of these functions within this control loop are realized by smart materials such as piezoelectric ceramics or shape memory alloys. These smart materials realize load bearing functions and functions of energy transformation (electrical into mechanical) and signal generation at the same time [Cao 2007]. Compared to mechatronic systems the application of smart materials results in a higher level of spatial and functional integration [Welp and Jansen 2004] of elements and thus reduced installation space and system weight (cf. Figure 2). With regard to the functions that can be realized by smart materials three classes can be defined [Neumann 1995]. Smart materials of the first class are able to realize all functions of the control loop (actuator, sensor, and control function) like shape memory alloys or photochromic materials do. Materials of the second class combine two functions of the control loop in one element. For instance, piezoelectric ceramics with limitations concerning frequency of loads and movement can be used simultaneously as actuator and sensor. Materials of the third class only fulfil one function of the control loop e.g. magnetostrictive fluids. The number of functions integrated into one element essentially affects the level of spatial integration that can be achieved. Furthermore, the effort for (multidisciplinary) design is affected since secondary functions, for instance, to provide auxiliary energy or modelling the control path, have to be fulfilled. In order to evaluate this effort against the use and advantages of smart materials for adaptive system design, criteria have to be identified addressing both, systems properties and the development process.

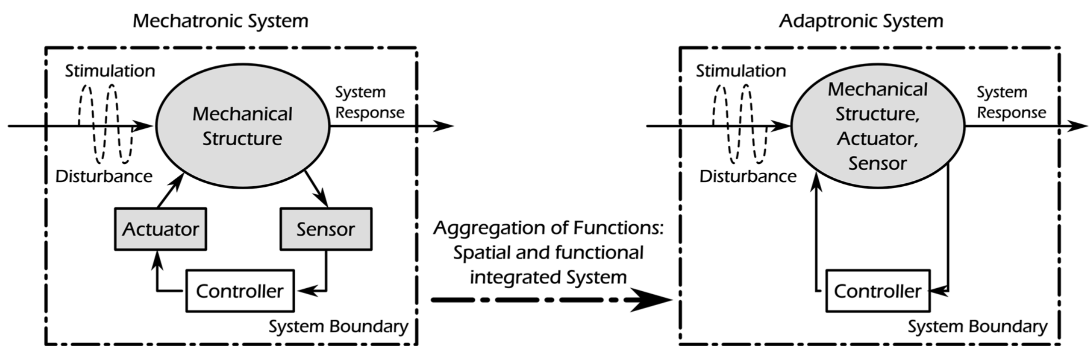

Figure 2. Distinguishing between mechatronic and adaptronic systems with regard to functional und spatial integration cf. [Drossel 2006]

2.3 Research focus and approach

Although, there are different research works dealing with the application of smart materials for adaptive system design [Janocha 2007], [Hesselbach 2012], industrial applications are rare. Beside technological drawbacks, e.g. limited performance and high costs of the actuators, the design is rarely supported especially for non-experts, for instance, from the domain of mechanical engineering. The overall aim of the author's research is to provide a systematic approach supporting non experts in using adaptronic solutions for adaptive system design. In order to develop suitable support, two research questions have to be answered:

- What are reasonable starting points to apply smart materials for adaptive system design?
- Which design knowledge is required to support engineers in realizing adaptive solutions based on smart materials and how can it be provided?

To answer the second question existing applications of smart materials in different fields of application were analysed in past works of the authors. Based on this analysis adaptronic solutions principles were formulated, describing the possible adaptions of properties of working bodies, working surfaces and pairs of working surfaces during use of a system [Inkermann et al. 2013], [Inkermann 2016]. The research presented in this contribution aims to identify drivers for adaptive system design as starting points to evaluate the appropriate use of the formulated solution principles. In order to identify potential drivers, a literature review is conducted, analysing motivations for adaptive system design. Furthermore, preconditions are defined to detect these drivers within the design process. Based on these findings a framework is introduced supporting identification and evaluation of the drivers and thus appropriate application of smart materials.

3. Drivers for adaptive system design

Adaptive system design often results in a higher effort during the design process. In addition to extra costs caused by specific components such as actuators, development of adaptive systems as compared to purely mechanical systems often result in extra effort for integration processes and tests as well as additional costs due to new manufacturing and verification technologies [Braun and Lindemann 2007]. Furthermore, involving different disciplines leads to an increased effort to coordinate development activities [Tomiyama et al. 2007]. Increased development effort and costs during product use (e.g. due to energy consumption) have to be justified by added value for suppliers or product users. According to Hansen [2000], the additional value of mechatronics and therefore adaptronic solutions as compared to purely mechanical solutions should contribute to the following three aspects:

- Increased user attractiveness due to better fulfilment of the properties required by the users
- Increased profitability through lower (total) costs for the company and product users
- Possibility to transfer solution concepts in limited time and with limited resources in a physically realizable solution

With regard to this superior criteria, in the following drivers for the development of adaptable systems are identified by a literature review. These drivers can be used for decision making about different adaptability strategies and the application of smart materials.

3.1 Literature review

In order to identify drivers for adaptive system design, approaches for the development of adaptable (offline adaptability) and adaptive systems (online adaptability) were analysed. Similar to drivers for the modularization of systems described in literature [Ericsson and Erixon 1999], [Stake 2000], [Vietor and Stechert 2013] the drivers should support the decision making for or against the development of adaptive systems during product development. Considering approaches of both fields enables to transfer support for decision making for the development of adaptable systems to the development of adaptive systems. For the analysis methodologies and methods were considered that provide assistance for the development of adaptive and adaptable systems at different stages of the development process.

The approaches analyzed are limited to the mechanical domain since decision making for or against the development of adaptive systems have to be based on the mechanical structure which is influenced by the smart materials used for adapting several properties. Table 1 provides an overview of the approaches and the criteria used for the analysis. In addition to the drivers described in the following section, the focus and the design knowledge as well as tools applied for the development were analysed. For instance some of the approaches provide guidelines or principles for the design of adaptive systems. As a second part, it was analysed if smart materials are explicitly considered for adaptive system design and which product models are used to identify the drivers. Relating this product models to different design stages (see section 2.3.) allows to give insights about the design phase each of the drivers can be identified and used to derive adaption strategies. Furthermore, the used product models bring up requirements for the objects and its relations to model (see section 4).

Table 1 outlines that in several approaches only objectives of developing adaptive systems are given without providing support for the identification of the drivers (e.g. [Buur 1990], [Neumann 1995]). In these approaches general advices to overcome goal-conflicts for instance in the field of automotive [Braess 1992] are given, examples of adaptronic solutions [Neumann 1995] are provided or procedures for the development of mechatronic systems [VDI 2004] are described. These works provide insights for the application of smart materials for adaptive design but do not support the decision making during design process. However, this decision is needed as a starting point for development work.

From the analysis four drivers for adaptive system design were derived namely goal-conflicts, undesired effects, spreading requirements and extended system functionality. These drivers and their classification into two groups are explained in the following section.

3.2 Description and classification of drivers for adaptive system design

The drivers derived from literature review are explained and classified using the CPM/PDD-model introduced by Weber [2005]. Like mentioned before, the aim of adaptive systems is to minimize the difference (ΔP_n) between the properties (behaviour) of the system (P_n) and the required properties (PR_n) (see Figure 3). With regard to their impact the drivers can be divided into solution-related and use-related drivers (see Figure 3). While goal-conflicts and undesired effects are related to the characteristics (C_m), relations (R_n) and internal dependencies (D_x), spreading requirements and changes of the number of properties are related the value and number of the properties required (PR_n). In the following sections the drivers are explained in detail.

Table 1. Overview of approaches, drivers for adaptive system design and models proposed for detection of drivers (excerpt from complete literature review presented in [Inkermann 2016], for detailed information about literature please contact the author)

Approach/ Authors	Drivers metioned for adaptive system design				Type of Model used for detection				Consideration of smart Materials?	Tools and Support provided
	Spreading Requirements	Extended System Functionality	Goal-Conflicts	Undesired Effects	Requirements	Functions	Working Principle	Embodiment		
Buur [1990]	x	x	-	-	○	○	○	○	No	Principles and secondary functions for mechatronic system design
Neumann [1995]	x	-	-	x	○	○	○	○	Yes	Examples of application, Collection/ classification of smart materials
Chakrabarti et al. (CJ99), (CRSS11)	-	-	-	x	○	●	○	○	Yes	Effect and component database
Bruch [2004]	-	-	-	x	○	●	●	○	No	Functions to compensate undesired effects
VDI 2206 [VDI 2004]	-	x	-	x	○	○	○	○	Yes	Procedure (V-Model)
Pahl & Beitz [Pahl et al. 2007]	x	x	-	x	○	○	○	○	Yes	Examples of applications
Lommatzsch et al. [2011]	-	x	-	-	○	○	●	●	No	non
Ziebart [2012]	-	-	x	x	●	●	○	○	Yes	Function-State-Matrix, Solution elements with potential undesired effects
Ognajanovic et al. [2013]	-	-	x	-	○	●	●	○	No	Conflicting function carriers and principles to overcome
Ericcson and Erixon [1999]	x	-	-	-	●	○	○	○	No	Modul Identification Matrix (MIM)
Hashemian [2005]	-	x	-	-	●	●	○	○	No	Guidlines for adaptable and adaptive system design
Renner [2007]	x	-	-	-	●	●	○	○	No	Advices for handling of spreading requirements
Blees [2011]	x	-	-	-	●	●	●	○	No	Module-Interface-Graph
Altschuller [1984]	-	-	x	-	●	●	○	○	No	Principles of separation, Conflict matrix, Innovation principles
Braess [1992]	-	-	x	-	○	○	○	○	Yes	Principles to overcome automotive goal-conflicts
Franke and Firchau [2001]	-	-	-	x	●	●	●	○	No	Strategies for controlling undesired effects
Bischof [2010]	x	x	-	-	○	○	○	●	Yes	Guidelines for the development of adaptable and adaptive Systems

Legend: x = Driver considered; - = Driver not considered
● = model used for detection; ○ = model not used for detection

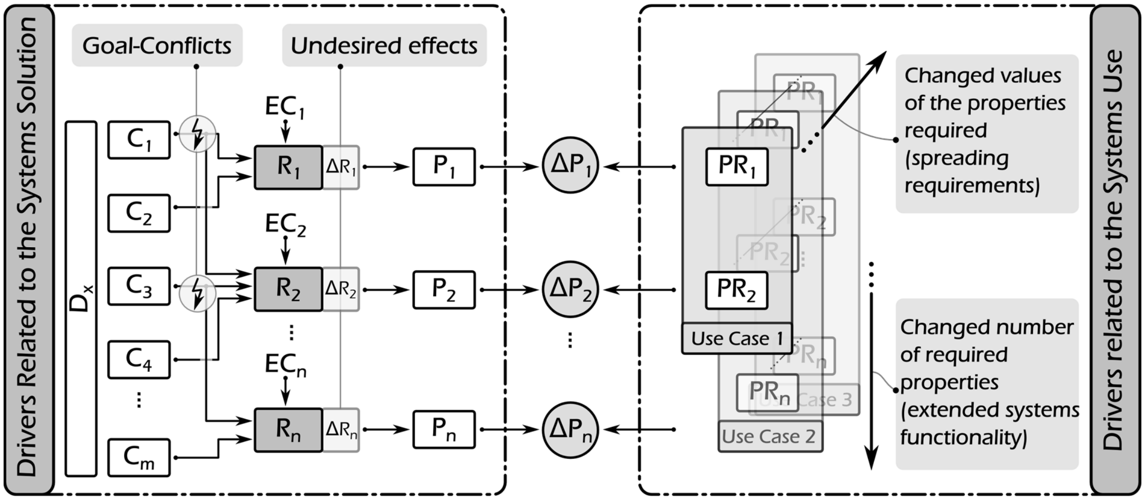

Figure 3. Classification of drivers for adaptive system design using the CPM/PDD-model

3.2.1 Drivers related to systems use

Drivers related to systems use result from changes of the properties required (PR_n), which are caused, for instance, by changing use cases the system is used in. They specify changes of the required system behaviour resulting in changing requirements (spreading requirements) on the system to be developed. In addition, the realization of additional functions during a systems use (increased user attractiveness) is classified as a use-related driver. While in case of temporal changing requirements, the number of desired properties (PR_n) stay the same, realization of additional system functions results in decreased or extended number of desired properties, see Figure 3. The use-related drivers are defined as follows:

- Spreading requirements are temporal changes of the properties required during the use of a system. These changes are caused by changing environments or user demands [Schmitt 2009]. For instance, the application of a robotics system for different use cases like pick-and-place or handling and assembly tasks results in differing requirements with regard to workspace dimension, pay load and positioning accuracy.
- Extended system functionality is realized by a higher number of properties provided by the system than required by use case. Furthermore, enhancing the number of freedoms to determine several system properties can be understood as an extension of systems functionality. For instance, applying adaptive revolute joints in a parallel robotic system able to change their kinematic degree of freedom offer new calibration concepts [Last 2008] and can be used for workspace enlargement during systems use [Schmitt 2010].

Drivers related to systems use change the properties to be realized during the design process. While spreading requirements can be identified during task clarification, see section 3.3, and therefore, provide a basis to evaluate the adaptability needed, the extension of systems functionality can be seen as additional advantage of adaptive solutions, but not as a criterion to evaluate the adaptability needed.

3.2.2 Drivers related to the systems solution

Drivers related to the systems solution pertain to the relations (R_j) between the characteristics (C_m) and actual properties (P_n) of the system to be developed. These drivers result from restrictions to (independently) determine the characteristics or deviations of relations (R_j). Sources of these restrictions and deviations are physical and logical (part of the relations R_j) and, for instance, technological constraints (considered by constraints EC_j) hampering the development of a solution fulfilling all properties required. Drivers of this group are goal-conflicts caused by conflicting optimization directions of several characteristics or combinations of characteristics. Furthermore, undesired effects resulting in deviations of the required properties are among the solution-related drivers. Through adaptable or adaptive solutions, the actual properties (P_n), e.g. by temporal changes, are enhanced to minimize the difference ΔP_n. Solution-related drivers are defined as follows:

- Goal-conflicts arise when improvement of one required property results in a degradation of another property [Lindemann 2007]. Goal-conflicts prohibit to fulfil all required properties by a solution. For instance, there is a global goal-conflict concerning stiffness and weight of a mechanical structure caused by hooks law. In order to overcome physical conflicts there are four separation principles are introduced by Altschuller [1984], implying the temporal change of system properties and therefor application of adaptable solutions.
- Undesired effects are effects that cause deviations of the required input/output relations or structural changes of a system [Franke and Firchau 2001]. They can be divided into internal and external effects. Internal effects result from the chosen working principle or varying material characteristics. External effects are caused by changed operating conditions, for instance, loads [Pahl et al. 2007]. The reduction or compensation of undesired effects is mentioned in large number of the works analysed mostly related to the design stage of embodiment.

The drivers goal-conflicts and undesired effects are related to the solution of a system and therefore arise during the synthesis. In order to decide on the development of an adaptive solution based on smart materials these drivers have to be identified early during the design process.

3.3 Product models and preconditions to identify the drivers

The presented literature review outlines that different product models are used to detect and evaluate the drivers. Based on the models found in the analysis the drivers can be allocated to design stages highlighting a logical sequence of their detection during the design process. The model required for detection of the drivers is determined by the type and quantity of information (e.g. physical laws of a working principle) needed. Because of the increasing concretisation during design, it becomes obvious that the number of spreading requirements, goal-conflicts and undesired effects grows.

In the following sections preconditions are defined to detect each of the drivers. Based on this definition requirements on a framework for the goal-oriented application of smart materials for adaptive system design can be formulated (see Section 4).

3.3.1 Identification of spreading requirements

Basis for the detection of spreading requirements are qualitative or quantitative definitions of single requirements (required properties), for instance, for different use cases. Qualitative definitions e.g. related to the kinematic degree of freedom of a robotic system are made at the beginning of the design process. Further properties are added as well as their single values defined when preceding the process. Within the design process qualitative and first quantitative spreads of requirements can be detected during task definition. Preconditions for detecting requirement spreads are assumption about different use cases of the system or analysis of existing system variants [Renner 2007].

3.3.2 Identification of goal-conflicts

Logical, formal and physical goal-conflicts can be detected within task clarification using e.g. consistency matrix [Lindemann 2007]. Therefore, interrelations between single requirements (required properties) are evaluated differing, for instance, between supporting, indifferent and opposing relations [Daenzer and Huber 2002]. Deimel states that in order to ensure physical goal-conflicts and identify technical conflicts, a first solution concept including its main characteristics like dimensions or materials is required [Deimel 2007]. Detection of physical goal-conflicts, therefore, depends on known physics (e.g. effects and working principles) of the system to be developed.

The number of goal-conflicts increases during the design process, since more and more characteristics and relations are determined [Franke 2006]. Furthermore, technological, economic and material related conflicts can be detected based on principle solutions and first preliminary designs. In order to identify goal-conflicts certainly, relations between requirements or properties on the level of effects, working principles, components and subsystems have to be represented.

3.3.3 Identification of potential undesired effects

Undesired effects can be detected based on first definitions of the required system behaviour, first physical effects (working principles) and the foreseen system environment. In a first step internal and external effects on functions defined for the system can be evaluated based on experiences of past solutions. By detailling working structures internal effects can be quantified, for instance, based on mechanical properties like stiffness or mass. Undesired effects based on varying material properties and deviations resulting from manufacturing or assembling processes can be evaluated using preliminary designs [Pahl et al. 2007].

3.3.4 Evaluation of extended systems functionality

In order to evaluate possible extensions of systems functionality, the required system behaviour including the required properties has to be determined and first working principles have to be chosen. Comparing the properties required and the properties provided by a working principle, potential functional extensions can be evaluated. In context of adaptive systems, especially the temporal relevance of the single properties have to be analysed in order to identify, for instance, approaches for integrating functions into a limited number of elements [Ziebart 2012].

The drivers introduced in this section serve as a basis for decision- making on the development of adaptive systems using smart materials. Like highlighted in section 3.3. different product models have to be analysed in order to detect the drivers.

4. Conclusion and further research

Aim of the research presented was to support decision-making for the development of adaptive systems based on smart materials. In order to drive the focus of research different types of adaptability were introduced, highlighting adaptronics. Based on a literature review four drivers were identified that justify the increased effort of adaptive system design, namely spreading requirements, undesired effects, goal-conflicts and extended system functionality. These drivers serve as starting points for goal-oriented application of smart materials since they support evaluation of the adaptability needed. Hence, an answer to the first research question formulated in section 2.3 is given. Relating the identified drivers to the solution principles formulated in past works of the authors, they help to choose appropriate solutions for the design task at hand and increased the quality of a solution (solution-related drivers) and usability of the system (use-related drivers). In order to highlight the product models needed to identify and evaluate the drivers during the design process specific preconditions for each driver were defined.

Since motivation of the presented research was to identify potential drivers and preconditions for their detection and evaluations it does not generate any testable result. However, the proposed drivers serve as a basis to derive further requirements on methodical support of the appropriate application of smart materials. In the end this research has to be seen as a descriptive study according to the DRM-framework [Blessing and Chakrabarti 2009].

In order to define a consistent framework for the identification and evaluation of the proposed drivers for adaptive system design different approaches to model the required system behaviour and the system structure have be analysed by the authors [Inkermann 2016]. Based on this analysis nine modelling objects were derived, namely: use cases, processes, operands, operators, states, system properties, working elements and undesired effects and their relations. These objects and their interactions are used to model three views onto the system under development:

- Systems behaviour view represented by use cases, processes, system properties, operands and operators,
- System structure view represented by operands, operators, working elements and properties of working elements and
- Disturbance view represented by potential undesired effects.

The system behaviour view represents the required behaviour including changes of required system properties during use caused by different use cases and processes. The system structure view is used to picture relations between different working elements as well as the effect of the element properties on the system properties. Within the disturbance view, deviations of system properties caused by potential undesired effects during use are highlighted. With reference to the integrated function modelling approach of Eisenbart [2014], matrices are used to model the relations between the single objects and views. A first evaluation of the framework has been made working on an adaptive solution of a revolute joint for parallel robotics systems [Inkermann 2016]. In this case study based on the goal-conflict between low friction and high stiffness of different bearings, suitable adaptions strategies are developed using piezo electrical actuators for quasi statical normal force variation [Inkermann et al. 2013]. This case study highlights the general applicability and validity of the framework as well as the proposed drivers. Future research of the authors will focus on the use of object based modelling approaches like e.g. SysML to model the objects and their relations within the framework and therefore support detection and evaluation of the drivers for adaptive system design based on smart materials proposed in this contribution.

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