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DESIGN FOR DEPENDABILITY – IDENTIFYING POTENTIAL WEAKNESSES IN PRODUCT CONCEPTS

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ABSTRACT

The increasing competitiveness and the need to create innovative products force manufacturers to replace conventional technologies in their products by new technologies, thus injecting uncertainty in the design process. In this paper an existing design process of a smart memory alloy-actuator, representing the new technology, is analysed with regard to uncertainty and impacts on dependability. In order to systematically reduce the inherent uncertainty and to enable a dependability-oriented design process, a combination of a heterogeneous modelling approach and an “Inverse Functional Modelling” (IFM) method is presented. While the heterogeneous modelling approach enables a successive problem solving and helps the designer to intuitively model a product concept, the IFM method assists to identify non-intended functions and potential failures as well as disturbances at an early stage.

Keywords: dependability, new technology, heterogeneous modelling, inverse functional modelling

1 INTRODUCTION

Nowadays, successful design processes are characterized by the ability to quickly generate innovative products with a high degree of maturity. While the time to develop ideas for innovative concepts is very restricted, more and more customer demands have to be fulfilled and the development costs as a whole also have to be reduced for economic success. Furthermore, the dependability of a product plays a major role for the outcome of the design process, since only the dependable product, which meets customer requirements and has “no failures”, will result in satisfied customers [1].

Designing innovative products often requires the use of new technologies, which also increases the level of uncertainty and therefore interferes with the design premise of a dependable product. Nevertheless, many companies are investigating new technologies and the interconnected technology jumps in order to secure possible advantages in their competition [2]. Especially small and medium sized enterprises with limited resources regarding employees, existing experience and development time are confronted with diverse problems when replacing conventional technologies with new technologies. Applying new technologies injects uncertainty into a design process, since only limited experience exists, therefore making it difficult to fulfill the design premise of dependability.

In order to further investigate this conflict, an existing design process of a shape memory actuator is analysed with regard to uncertainty and to the impact on dependability. Based on this, a heterogeneous modelling approach is presented to enhance the support for the designer and to better mimic the “real world” design process. To ensure a dependability oriented design process in the early phases, a method called “Inverse Functional Modelling” is then interconnected with the heterogeneous modelling approach.

2 ANALYSIS OF A DESIGN PROCESS WITH NEW TECHNOLOGIES

In the following paragraph, a completed design process which included the appliance of a new technology is analysed regarding uncertainty and dependability. Since uncertainty is a term that is used in various fields with different meanings, the following definition by Hastings and McManus [3] is considered adequate in the context of this paper: “Uncertainties are things that are not known, or known only imprecisely. They may be characteristics of the universe (e.g. statistical processes) or characteristics of the design process (e.g. information not yet collected); in either case they are factual

[..]". According to Laprie, the term dependability can be understood as a "global concept that subsumes the usual attributes of reliability, availability, safety, integrity, maintainability, etc." [4].

Increasing demands for comfort lead to a high level of automation in the automotive industry. Modern, especially luxurious vehicles offer numerous opportunities to employ actuators, e.g. with regard to unlocking functions or the opening/closing of windows. These tasks are usually fulfilled by the use of electric or electromechanical actuators. Due to the wide spread usage of these conventional actuators, the need for optimization and improvement, e.g. regarding weight, costs, sounds or efficiency, is rising. A promising new technology is shape memory alloy (SMA), which can be characterized by a high power density, simple design and silent actuation. Therefore, an actuator based on this SMA-technology has been developed in order to replace a conventional electric motor with the task of unlocking a glove compartment in the vehicle interior. The final actuator also had to be integrated in the latch of the existing glove compartment [5].

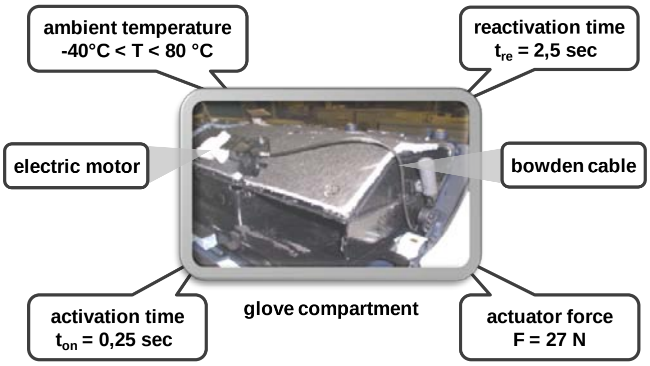

Figure 1. Excerpt of identified requirements for the SMA-actuator

The design process was divided into the classic four stages: planning phase, conceptual design, embodiment design and component design. During the design process, models with different levels of abstraction were created, e.g. functional models, active principle models and component based models. Due to several design problems during the process caused by high levels of uncertainty and the interconnected dependability issues, the models had to undergo various iterations. In addition, some product concepts had to be completely discarded due to design flaws and unmatched requirements.

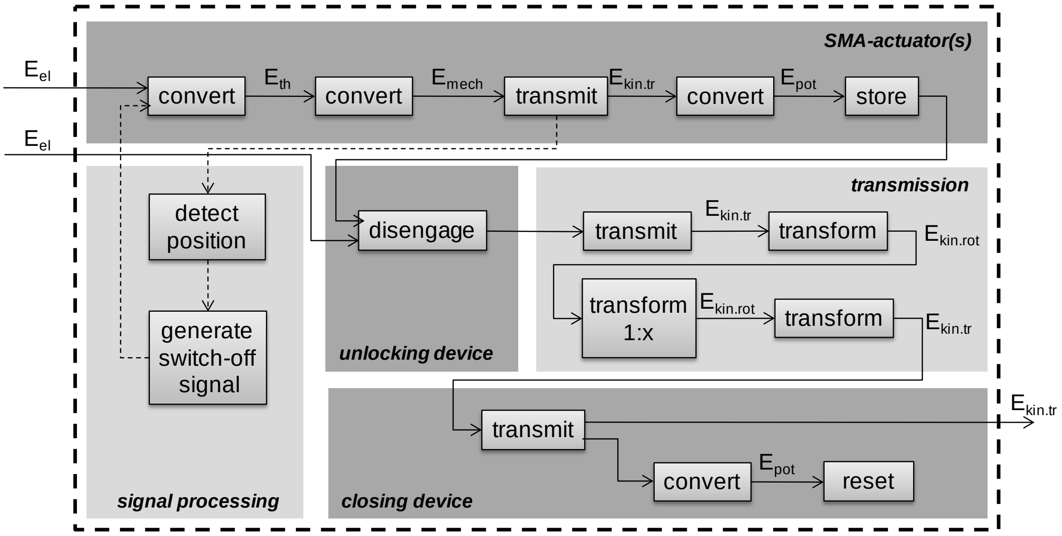

Figure 2. Functional structure of the unlocking actuator

As a starting point in the design process, the conventional solution of an electric motor and a bowden cable were analysed, resulting in the specification of requirements. Ambient temperatures between -40°C up to +80°C and a reactivation time of 2,5s were identified as important requirements which could be critical to the dependability of the actuator (see Figure 1). The calculated wire diameter, which is needed to achieve the operating force, influences the time of the wire to cool down after its activation. Experiments revealed that it takes approx. 10 seconds for such a wire to cool down, so the main problem was how to fulfill the requirement for the reactivation time while generating enough force. An obvious solution to get around this challenge included multiple actuator wires, which would be activated sequently. The final idea envisioned an energy accumulator, which could be charged via a primary SMA-wire and then discharged at the specified frequency. This discharging of the energy accumulator could be triggered by further unlocking SMA-wires. Based on this idea, the functional model of the actuator was adapted, now describing the most essential, abstract functions as well as the idea of the energy accumulator (see Figure 2). Analyzing this example, it becomes clear that the reactivation frequency – as a major dependability requirement – is responsible for several process iterations and model adaptations.

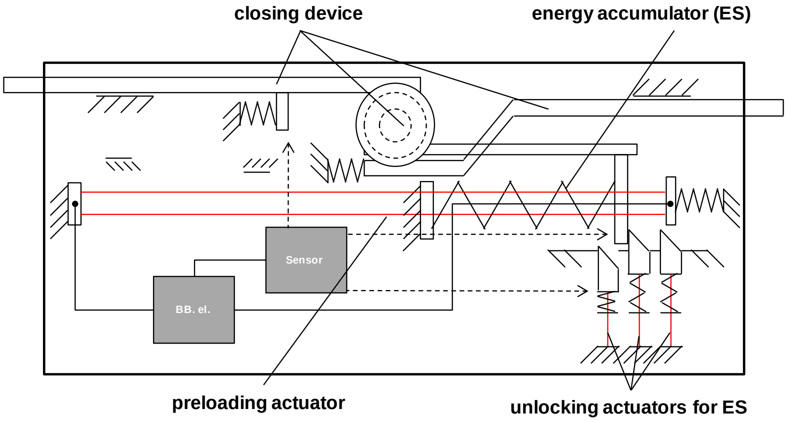

Figure 3. Principle model describing the first idea for the unlocking actuator

To further concretize the product concept, active principles were selected for each function and a principle model was derived (see Figure 3), which was then concretized in the embodiment design phase. Unfortunately at that stage it was discovered that this concept promotes jamming and is highly unlikely to function properly due to a high number of degrees of freedom at the mechanical level. Predictably, this would result in a non-dependable product, so an adapted concept had to be realized in another iteration. The final design draft with all necessary adaptations can be seen in Figure 4.

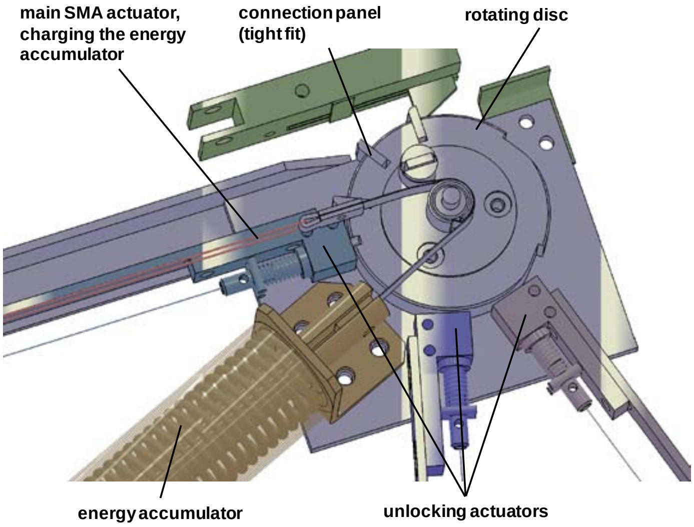

Figure 4. Final design draft

By comparing Figure 3 and 4, it can be seen that the final design draft is very different from the principle model, which was generated beforehand. Therefore, this iteration caused a further update of the functional and active principle model to the current concept state. Even though the design process was basically divided into the classic four phases according to the Directive 2221 of the Association of

German Engineers (VDI 2221 – [6]), the “real world” process proved to be of a non-linear type with numerous iterations. Concurrent to each iteration, multiple changes in the models were required, including updates to previous models with higher levels of abstraction.

It can be concluded from the analysis of the presented design process of the SMA-actuator, that..

- the inherent uncertainty in the appliance of new technology induces a lot of iterations and changes, especially in the early phases,
- main drivers for the iterations in the concepts were dependability issues,
- applying new technology and fulfilling dependability requirements forced the problem solution to become quite complex (functional wise, principle wise and geometrical wise),
- inherent high uncertainty caused even very promising product concepts to be discarded.

Based on these findings, it can be stated that there is a need for a better support of the “real world” design process when applying new technologies. It could be shown that the designers often criss-cross between different levels of abstraction to solve problems during the development process. This behavior is currently not supported by traditional modelling approaches like described by VDI 2221 [6] or Pahl/Beitz [7]. A methodology that would allow such a successive problem solving and would not force the designer to stay at a certain level of abstraction could improve this situation and enhance the design process. During the early stages of product development, it is also necessary to systematically reduce the uncertainty caused by the appliance of new technologies. Potential failures and possible design flaws need to be identified much earlier on and prior to the embodiment design phase in order to ensure more flawless products. This would require a dependability oriented design process, centered around the conceptual phase.

3 HETEROGENEOUS MODELLING APPROACH

As stated before, it becomes clear that there is a strong need to support the intuitive human way of problem solving, which includes criss-crossing at different levels of abstractions during the design process. Such a heterogeneous modelling approach is presented in this paper. Its basic idea was first proposed by Jansen [8] and used for domain allocation in mechatronic systems [9]. The modelling approach of Jansen has been extended by Sadek [10] to broaden its applicability to product-service systems. Several experimental studies have been carried out in order to optimize this approach with regard to its applicability and teachability [11, 12]. Furthermore, the modelling approach has been implemented as a software tool.

The fundamental idea of the approach is to model different types of elements with different levels of abstraction using only one heterogeneous modelling plane. In contrast, conventional approaches like Pahl/Beitz [7] use several separated modelling planes with fixed levels of abstraction for each plane. Regarding the heterogeneous modelling approach, a technical system can be described by coupling model elements with different levels of abstraction, detailing and formalization on a single modelling plane. This allows the designer to intuitively model his ideas with his current level of abstraction in mind and to get a consistent comprehension of the system concept at a glance. Up to now, two basic types of model elements are implemented: system elements and context elements.

3.1 Model elements and relations

System elements are used to model functions, active principles or physical components of the concept (see Figure 5). While functions describe the product on a very high level of abstraction using verbal and functional descriptions, like “accumulate energy”, active principles describe the basic physical behavior of a connected function. Referring to the example, energy could be accumulated by using a mechanical spring. Moving to the lowest level of abstraction, concrete components can be specified, like a “helical spring”. This component can be represented on the modelling plane by using a draft, a picture or a technical drawing with further detail regarding e.g. a specified modulus of resilience or geometrical data. Each type of system element (functions, active principles, components) can be connected to each other and allows further annotation for quantitatively and qualitatively description of their properties.

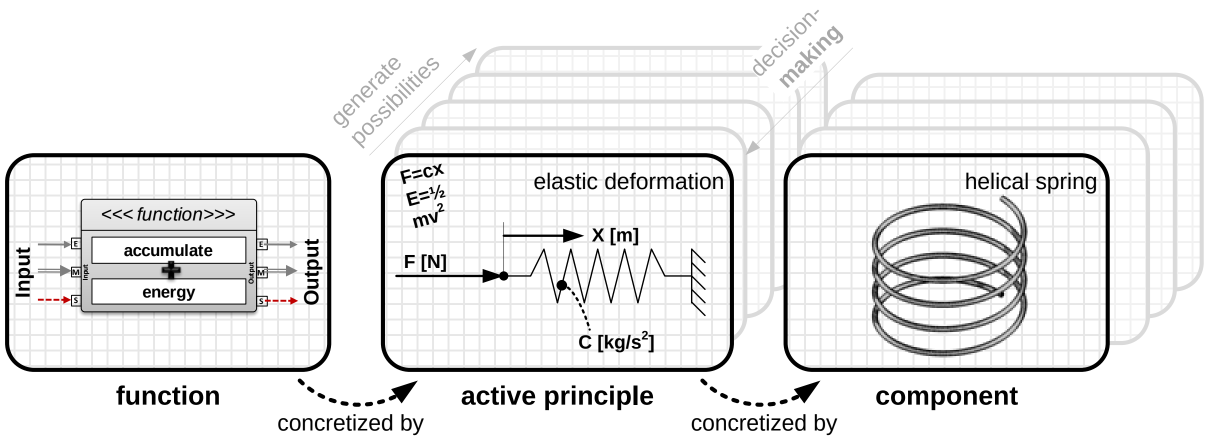

Figure 5. Exemplary system elements for heterogeneous concept modelling

In order to incorporate system requirements into the heterogeneous concept model, context elements can be used. They can resemble requirements or display additional information for the user in order to be able to better understand the currently modelled concept. Context elements can be regarded as "digital Post-Its", which can increase the traceability of decision making during the engineering process. Although these context elements are not a necessary part of the concept model itself, they offer the designer valuable information, e.g. by additional text or drafts. In contrast to system elements, they do not embody a functional aspect or physical behavior.

The original heterogeneous concept modelling approach by Jansen [8] defines different types of relations, but they proved to be too complex for operative use. With regard to the analysis of the design process in Chapter 2 and the conducted preliminary studies [9, 10], it became clear that a reduced set of relation types could effectively improve the usability of the approach and still make use of the potential of heterogeneous modelling. On the highest level of abstraction, functions can be connected to each other by the three conventional relations representing different flows: material flow, energy flow or signal flow. To interconnect system elements with different levels of abstraction, various relations are implemented, e.g. "is concretized by", "is a part of" or "belongs to". These rudimental relations are owed to the fact that removing the conventional modelling planes at first increases the complexity of the model. By supporting the designer with a limited, but concise set of relations, this seemingly disadvantage is impaired and the advantage of heterogeneous modelling, intuitive and successive problem solving, is still made use of.

3.2 Model representation

Applying the heterogeneous modelling approach to the previously mentioned design process of the SMA-actuator might lead to a conceptual model as shown in Figure 6. All system elements are located inside a system boundary (dashed line) and represent the current development stage as a kind of snapshot. The most important requirements are modelled by the use of context elements and are connected to system elements across the system boundary. As it can be seen, the functional model of the actuator seems almost complete, while active principles are still missing for some functions and no components have been assigned yet. This is owed to the fact that the shown model belongs to the conceptual phase. Nevertheless, this heterogeneous concept model allows the comprehension of the technical system at a glance and can be completed where and whenever necessary by further intuitive modelling.

According to the fundamental idea of the approach, a designer can model his concept with functions, active principles or components, without being restricted to a single level of abstraction. It is not required to complete a specific modelling plane to carry on with the modelling process as a whole. Therefore, this approach allows a successive problem solving and resembles the "real world" design process as discussed in Chapter 2 in a much better way. Furthermore, whenever iterations occur during the process – e.g. caused by uncertainty – and specific model elements have to be updated or changed, the quick overview of the single modelling plane assures that no elements will be ignored or forgotten.

In addition to that, it is much easier to analyse the model with regard to the interdependencies between model elements on different levels of abstraction.

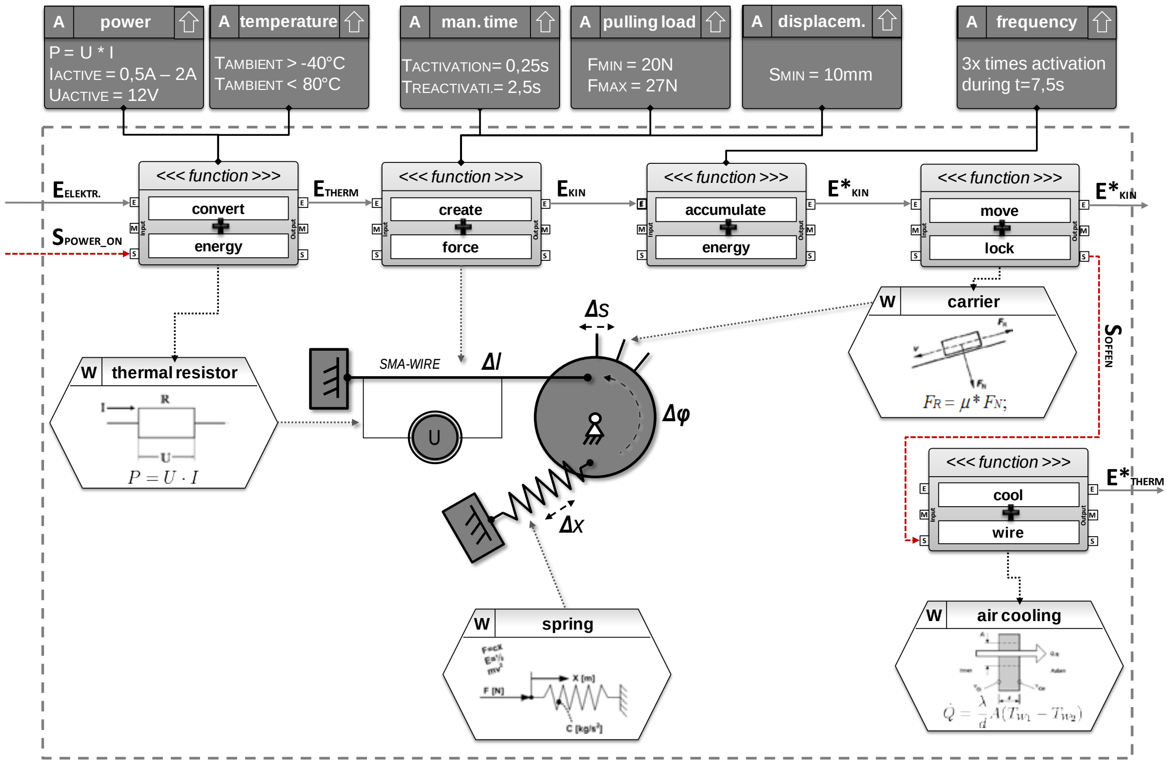

Figure 6. Heterogeneous concept model of the SMA actuator

4 INVERSE FUNCTIONAL MODELLING (IFM)

Now that it is possible to enhance the support for the designer during the conceptual development and to display the current state of the concept on a single modelling plane, it is still necessary to reduce the uncertainty which is injected by the appliance of new technology. This would ensure a dependability oriented design process and a more flawless product. Therefore, as a starting point for the method, it is necessary to identify those functions in the concept, which are most crucial for the functionality and which emerge due to the appliance of the new technology. In the example of the SMA-actuator from Chapter 2, such an intended function could be “accumulate energy”.

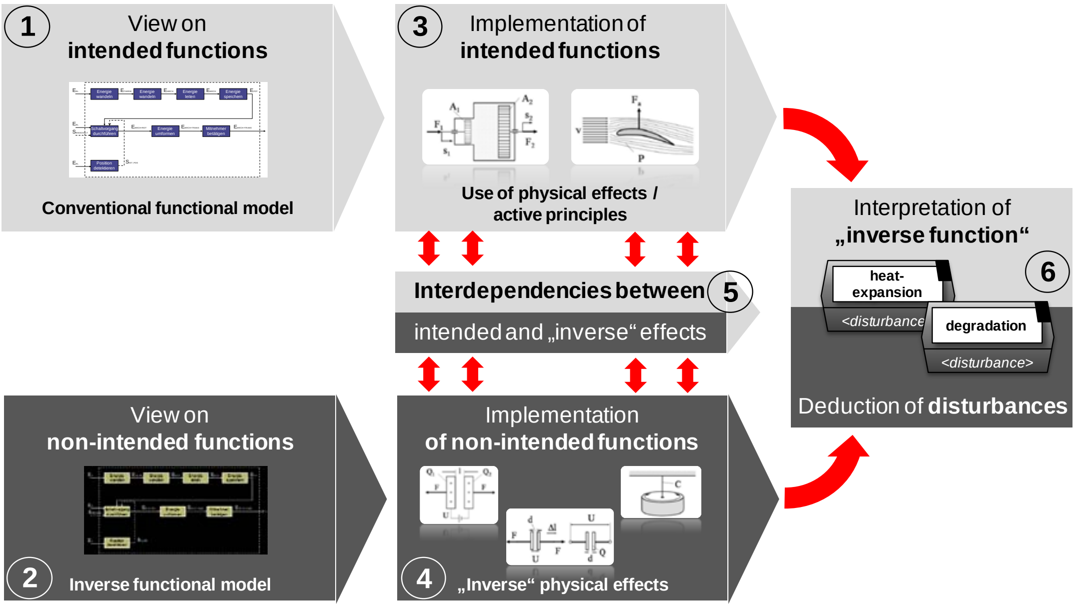

Figure 7. Basic approach of Inverse Functional Modelling (IFM)

The first two steps of Inverse Functional Modelling focus on the intended functions as well as on building the non-intended, “inverse” functions (see Figure 7, step 1 & 2). Each function can be represented by an operand (noun) and an operator (verb). To build the inverted function, it is only necessary to invert the operator. This approach transforms the function “accumulate energy” into “discharge energy”. The basic idea of inverting functions is wide-spread and can e.g. be found in the methodology of TRIZ/TIPS [13,14] (“Theory of Inventive Problem Solving” by Genrich S. Altschuller) within the method “Antizipierende Fehlererkennung” [15] (engl.“Anticipatory Failure Detection”). One possibility to support this step of inverting the verb could be to create a catalog for inverted verb pairs, which could be based on conventional function classes.

The third and fourth step aim at identifying the physical effects for the intended/non-intended functions. Regarding the intended function “accumulate energy”, the active principle could be realized as a “mechanical spring”, based on the physical effect “elastic deformation” (see Figure 8, left side). On the inverted view, physical effects that could realize the non-intended function are of primary interest. In case of the non-intended function “discharge energy”, possible effects that would support such a function could include “plastic deformation”, “heat radiation” and “friction” (see Figure 8, right side). The subsequent fifth step is to analyse the interdependencies between the intended and the non-intended physical effects. This step is best summarized for the current concept by the question “how do the inverted physical effects interact with the intended active principle of a mechanical spring?”.

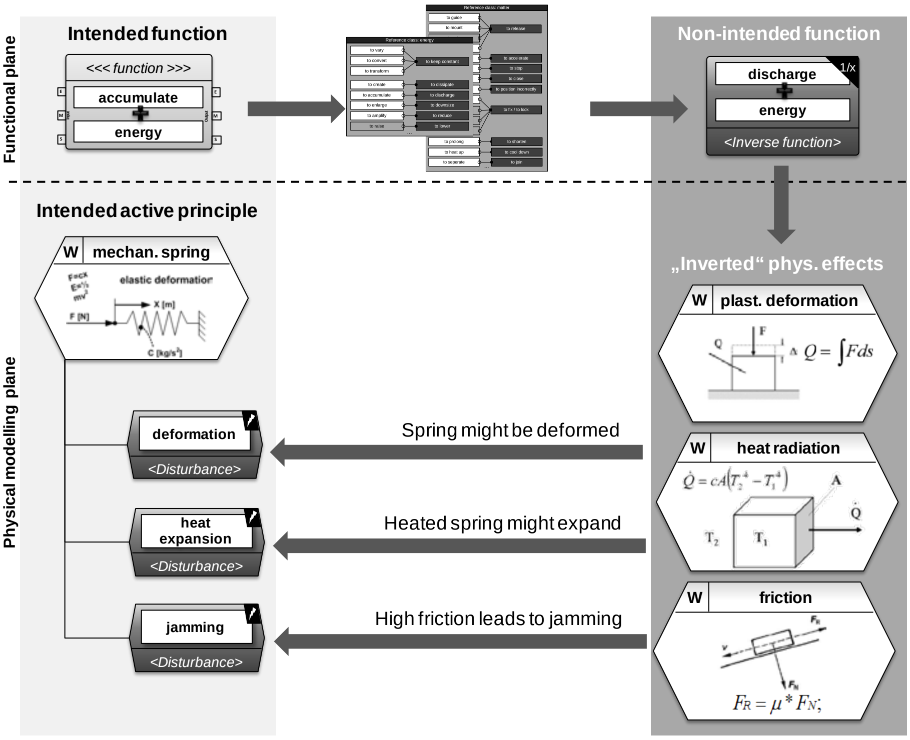

Figure 8. Interpretation of non-intended functions on the physical modelling plane

Answering this question is the main responsibility of the designer, but this approach helps to systematically find those interdependencies. The heterogeneity of the developed concept model allows an intuitive way of interpreting these interdependencies by looking at the context of each function. Since various elements on different levels of abstraction might be connected to the intended function, these could be possible sources for physical effects as well and should be investigated. In case of the intended function “accumulate energy” with the corresponding active principle “mechanical spring”, the three inverted physical effects could be interpreted in step 6 as follows (see Figure 8):

1. Plastic **deformation** could mean that the spring might be deformed due to a high load.
2. Heat radiation might cause the spring to severely heat up, causing **heat expansion**.
3. Friction could imply a possible **jamming** of the spring in its housing.

These identified disturbances and potential failures can be used as further input to narrow the interpretation range for the non-intended function “discharge energy”. Yet another advantage of this methodical approach is that it can be used to reduce the uncertainty of specific functions, introduced by the appliance of new technology. In addition to that, it is now possible to display the derived potential disturbances in the heterogeneous concept model. This offers the advantage of adding valuable dependability information to the model, so the next user of this model can benefit from the previous analysis. A final result of an “inverse concept” of the SMA-actuator (see Figure 6) with incorporated findings from the Inverse Functional Modelling is shown in Figure 10.

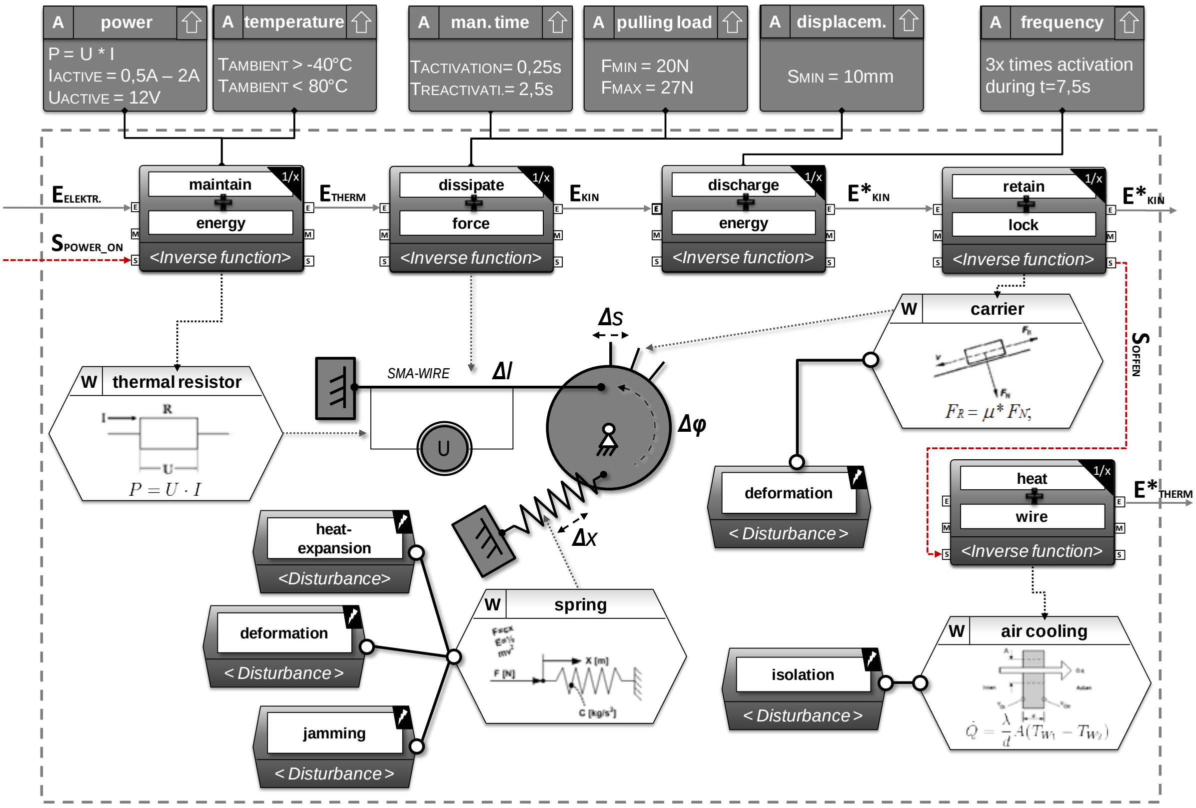

Figure 10: “Inverse” concept model with non-intended functions and disturbances

Based on this “inverse” model, it is possible to integrate further dependability methods in the design process, like the FMEA (Failure Modes and Effects Analysis). The goal of this method is to identify potential failure modes, to investigate causes and effects, to assign risks and to formulate actions to eliminate potential failures [16]. The identified potential failures and disturbances by the IFM method can now be used to partly fill out the FMEA-form for the SMA actuator. A well known problem when using the established FMEA method is that, especially at early design phases, there is not always enough information available, preventing the designated use of this method. Therefore, the results from the IFM method can be seen as another starting point for the FMEA, aiding in identifying possible weak spots in the concept and reducing the uncertainty. This might also save time for small and medium sized enterprises, which do not have their dedicated FMEA experts or tons of experience regarding dependability. Furthermore, the IFM method could give less experienced designers a starting point for their analysis or act as a thought-provoking impulse.

Based on the results from the IFM method, a FMEA has been conducted for the SMA-actuator from Chapter 2. Two possible options for interpreting the results can be deduced. As a first option, the inverse, non-intended functions can be seen as potential failure modes for the system. From here on, possible failure causes and effects can be examined for the concept (Figure 11, upper half). As a second option, and towards a more concrete interpretation, the identified disturbances of the IFM method can be seen as causes of failures (Figure 11, lower half). Combining both options leads to an extensive view at the dependability of the modelled concept and can help to reduce the information deficit in the early phases.

	Failure Mode	Effect(s) of Failure	Failure Cause	Recommended Action(s)	Sev	Occ	Det	RPN
Inverse Functions as Failure Modes	maintain energy	carrier does not moved, unlocking is prevented	SMA wire did burn out due to high current feed	limitation of the current feed	4	7	5	140
	dissipate force	carrier will not unlock under some circumstances	high friction within the moving parts	add lubricant	6	4	3	72
	discharge energy	system could be deformed or heated up (causing fire)	short circuit , fatigue break	control and limit energy sources	8	2	6	96
	retain lock	unlocking is prevented	mechanical jamming	optimization of mechanical friction	7	7	9	441
	heat wire	reactivation time is rising drastically	isolation within the latch	active cooling	8	6	7	336
...								
Disturbances as Failure Causes	deformation of the helical spring	breakage of the spring, unlocking is prevented	PLASTIC DEFORMATION due to improper high activation force	limit activation force	5	8	3	120
	expansion of the helical spring	changed modulus of resilience causes deviating displacement	HEAT RADIATION of SMA-wire heats up the helical spring	integrate heat protection	4	5	8	160
	jamming of the helical spring	unlocking cannot be completed	FRICTION in the housing of the spring causes tensioning	decrease friction	7	6	5	210

Figure 11. FMEA-form for the SMA-actuator based on the results of the IFM method

5 CONCLUDING REMARKS

It has been shown that by combining a heterogeneous modelling approach and the IFM method, the uncertainty due to the appliance of new technologies can be systematically reduced during early design phases. While the heterogeneous modelling approach is able to mimic “real world” design processes and does not inhibit the designer’s creativity by forcing him to think in separate levels of abstraction, the IFM method can be used to enhance the dependability of the created concepts. Applying it specifically to functions with an inherent uncertainty allows the identification of potential weak spots in the concept. Further interpretation of the deduced non-intended functions is supported by an alternation to the physical modelling plane, where potentially harmful effects are examined. Finally, possible disturbances for the selected functions can be identified and give the designer useful hints towards a more dependable design. To further analyse a product concept, the results from the IFM can also be used in existing methods like FMEA, acting as thought-provoking impulses, or as a starting point for a detailed analysis of certain aspects

The current work can be seen as a starting point for further investigations and research activities. As an additional demand from industry, there is a need to aid the designer in identifying and prioritizing “hotspots” related to uncertainty in product concepts. Based on the presented results, a methodology needs to be created, which helps to identify and prioritize those “hotspots”, injected by the appliance of new technologies in a design process. Furthermore, the efficiency of the current approach, consisting of heterogeneous modelling and Inverse Functional Modelling, could be improved by taking the structural aspects of the problem solution into account. A guided search for effects that cause non-intended functions could be carried out based on the heterogeneous model and its structure. In addition to that, failures resulting from interactions between existing model elements, e.g. non-intended functions or disturbances, have to be implemented. It also seems necessary to incorporate the analysis of failures resulting from external interactions, e.g. influences regarding the ambient conditions or use of the product.

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