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A MECHATRONIC CASE STUDY HIGHLIGHTING THE NEED FOR RE-THINKING THE DESIGN APPROACH

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ABSTRACT
Developing mechatronic products is a great challenge for many companies due to the multi-disciplinary nature of the development process. In this article the main objective is an investigation of seven aspects related to the synthesis process of developing mechatronic products. The role and effects of these aspects are illustrated by a case study. A literature study is performed regarding how well the seven aspects have been covered in the literature. It reveals that some suggestions for support can be found in terms of semi-formal modelling suggestions and proposal for procedures, but that the context of the proposed support often originates from a control engineering dominated research area. This circumstance leaves a vast amount of other types of mechatronic products with only sparse development support with the potential of being made operational.

Keywords: Mechatronics, development process, synthesis, literature review, case study, conceptual design

1 INTRODUCTION
Companies involved in developing mechatronic products face the challenge of 'orchestring' the different engineering disciplines involved. Long has it been acknowledged that there is a need for integration and long has it been acknowledged that central areas of mechatronic development lack theory and methods [1], [2], [3]. Without a well covering theory and applicable methods companies cannot exploit the full potential of mechatronics [4].
This article is investigating central aspects, which the engineers must face and must be able to handle in the synthesis of mechatronic products. The investigation is build upon a case study to show the context in which the aspects appear. The investigation of the aspects is then continued in a literature study. The scope of the study is to investigate to which extend the seven aspects are acknowledged in literature and to clarify if methods or tools have been suggested for better handling the aspects. The seven aspects can each be categorized within one of the following three areas: Process related aspects, product related aspects and aspects related to user perceived value. The result of the research presented in this article will be used for directing the search for support for the remaining part of the PhD project.
The investigation is limited to incorporate aspects related to the field of mechanical, electronics and software design. For this article the term 'mechatronics' is used when these engineering fields are combined in the product development. The control engineering field is regarded as a competence in this context similar to many other competences needed for the vast amount of different types of mechatronic products.
The words 'function', 'property' and 'structure' are used in this article. The definitions are adopted from the work done by Mogens Myrup Andreasen [5]. In short, functions and properties describe 'what the product does', whereas the structure describes 'what the product is'. A function has an effect such as the function 'provide power', whereas a property does not have an effect such as 'robustness'.
The article is structured as follows. In section 2 the research steps are explained. In section 3 the selected mechatronic aspects are described. In section 4 the aspects are illustrated in the case study. Section 5 contains the literature review and section 6 concludes on the article.

2 METHOD
Both authors have each nine years or more of hands-on experience with industrial mechatronic projects. This experience has been used to select the seven aspects. The case study is used to illustrate the importance of being able to handle the aspects in the design process. The case study has been built by use of several means: i)Personally recorded experience, since one of the co-authors participated in

the project. ii)Analysis of documents and files from the project and iii)Semi-structured interviews with the project managers. For the literature study, a limited number of eleven references is carefully chosen to reflect the state-of-the-art within providing theory and methods. An overview of the coverage found in the literature is established and is illustrated in Table 1. The case study, the literature review and the overview in Table 1 are used to form the final conclusion.

3 ASPECTS TO BE INVESTIGATED

The aspects chosen as the focus for the case and the literature study are multi-disciplinary of nature. It is not the intention of the authors to create an exhaustive list of relevant aspects when designing mechatronic products. Instead the aspects have carefully been selected within three main areas, which we stipulate have an utmost significant impact for the ability to synthesize successful mechatronic products. The three areas are i) the process of developing a mechatronic product, ii) the product itself and iii) the value created in the meeting between the user and the product. In the following the selected aspects are described and categorized according to the three areas. The identification (A1...A7) is used for tracking each of the aspects in the case study.

Process

- Synchronization between the mechatronic process model and the process models of the separate domains (A1). A mechatronic process model should not conflict with the normally found flow of activities in the domains. Instead it should support the synchronisation of the concurrently performed development within the domains. Without an understanding of the synchronisation aspect in mechatronic development, deliverables between the domains cannot be planned, which will cause the level of integration to decrease.
- Normal iterations occur when we go through the design cycle and improve the solution for each iteration. The iteration aspect to be described in relation to this article is different in nature. When working in e.g. the mechanical domain we must assume the electronics are fixed and does not change in terms of interfaces and functions important to the mechanical domain. Thereby work in one domain must be perceived as evolving in iterations seen from the other domains in between 'integration meetings' (A2). Because the design is constantly evolving in every domain it becomes important to clarify the areas likely to change. The relations can be many and without an overview or a strategy the risk for failure in the project will increase.
- The allocation of functions to the domains can be regarded as a balance between the domains as described by Buur [6]. Relevant balances must be synthesized as alternative concepts to investigate the solution space to reach the ´best fit' solution (A3). The function allocation determines the size of the task assigned to each of the teams representing the domains. Furthermore it will have a direct effect on the physical interfaces needed to connect the technology from each domain. Therefore it has a significant impact on the design process. The allocation can be made, based on various strategies ranging from product related considerations to organisational related considerations.

Product

- Distribution of functions and properties between domains (A4). Functions and properties have to be considered carefully during a development process [5]. Mechatronic projects pose an increased challenge due to the multi-disciplinary nature. The development task has to be decomposed into 'chunks', which can be handled by the different teams thereby risking a separation of closely connected functions or properties. An example could be a property such as "measurement accuracy". Such a property can have contributing factors/elements in each of the three domains. To create and optimise the property several domains have to be considered at the same time, which is a major challenge due to the vast amount of properties and functions found in a product.
- Sharing schemes of the functions and properties in the product to be developed (A5). The design engineers should be well aware of which and how elements contribute to a certain function or property in the product. As an example, the effort of optimizing the property 'accuracy' to the desired extent might be easier achieved in the E domain compared to the M domain in a particular case. The understanding of the sharing schemes gives insight into how the functions or properties should be optimised. For example, the sharing principle in a concrete situation could be 'the weakest link of the chain', or each of the contributions could add to the property in a

multiplicative or additive scheme. Each of the sharing schemes would call for a different optimisation strategy.

- Interface handling (A6). Specifying physical interfaces in development is widely used in the industry to create an architecture by which the various development teams will have fix points for their physical realisation of the product. Decisions in the software domain can affect physical interfaces but interfaces in the physical sense belong to the mechanical and the electronics domain.

User perceived value

- The manipulation of the design to obtain the desired perceived value (A7). Careful attention is needed to simulate, model or by other means try to predict the user-perceived value of the product. The user's interaction with the product during the life phases will generate a perception of value. Typically the value perception is directly influenced by choices we make in the development process, choices that can be of high technical character.

If the members of the development team with multiple engineering discipline backgrounds efficiently can handle the described aspects, a more transparent and rigorous development process can be obtained.

4 CASE STUDY – THE LINDEWERDELIN WATCH SYSTEM

The project chosen for the case study is well suited because the aspects selected for the investigation are well represented in the project and because the case study contains design considerations from each of the M, E and Sw domains.

The case describes the development of a temperature sensing unit, which is a part of a watch system, see Figure 1. The product is targeted the high-end market for outdoor sport watches, and is produced by the company LindeWerdelin. The product idea of the watch system is based on a mechanical watch, on which an instrument with some advanced functions can be attached. An external temperature measuring unit can be positioned away from the watch to measure the actual surrounding temperature. An external heart rate unit can be positioned around the person's chest to measure the heart rate. The external units wirelessly transmit the measured data to the instrument for displaying the information. The system also contains a battery charger for the instrument. It is a part of the product idea to be able to attach the instrument to the thermometer unit, thereby restricting the shape of the temperature unit.

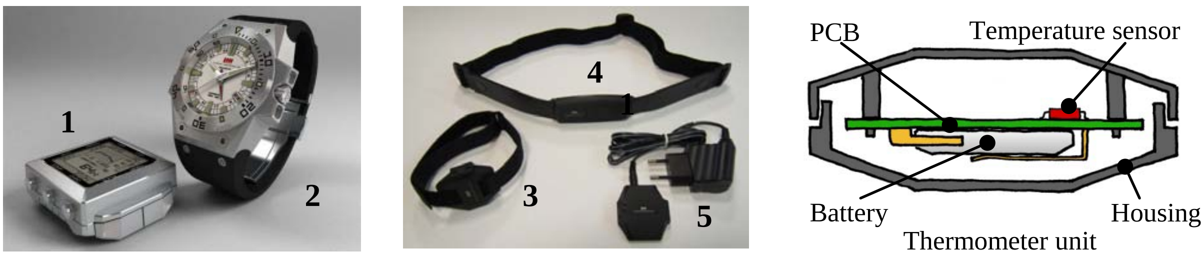

Figure 1. 1: Instrument, 2: Watch, 3: Temperature unit, 4: Heart rate unit, 5: Instrument charger

The project was initiated by the co-founders of the newly, at that point in time and for that purpose, established company. The product idea was developed by the co-founders. The mechanical development was outsourced to one consultancy company and the electronics and software development to another consultancy company. The mechanical watch was to be developed and produced by a Swiss watch company. During the development two mechanical engineers, one electronic engineer and up to four software engineers were working on the project not including the resources for developing the clock mechanism. Figure 2 is a reconstruction of the development phases for the thermometer unit with a short description of the main activities. The description of the case study is sectioned according to these phases.

Task setting	Feasibility study	Conceptual design	Embodiment design	Detailed design	Production preparation
Jan ’03 – Mar ’04	Apr ’04 – Sep ’04	Oct ’04 – Dec ’04	Jan ’05 – Mar ’05	Apr ’05 – Jun ’05	Jul ’05 – Feb ’06
Idea of external unit appears. Main functions and technology is assessed.	Volume of product is assessed. Proof of concept for electronics.	Development of electronics. Functional model is used for integration test (M, E, Sw).	New concept for industrial design and for temperature-sensing is incorporated.	Details are added. Injection moulding forms are ordered.	Minor corrections. A change is made to optimize the temperature sensing.

Figure 2. Development phases of the thermometer unit

4.1 Task setting

In the early stage of the conceptual phase the main focus in the project is to get the concept right for the watch and the instrument. Developing the external units is considered feasible and is therefore not the centre of attention. However, the primary functions for the thermometer unit are considered as being: “to measure temperature” and “to wirelessly transmit the temperature data”. To be able to make a feasibility study of the watch and instrument, communication with the external units has to be taken into consideration. This requires the task setting for the thermometer unit to be defined further. Based on the desired functions of the thermometer unit the following main components are suggested: Housing, battery, print board, antenna.

Within this initial suggestion for means to achieve the functions, an allocation of the functions is being made, which can be seen by the stated means in Figure 3. The figure shows the initial Function/Means Tree. The allocation principle is based on ‘the most obvious choice’. Trying to force a different allocation will make the solution to become obscure. The underlying functions necessary to realise a certain means have to be allocated to one or more domains. A means, which would be described as belonging to one domain, can have supporting functions from the other domains. One example is the PCB, which needs connection support to the housing. The function allocation is occurring throughout the design phases of the project (A3).

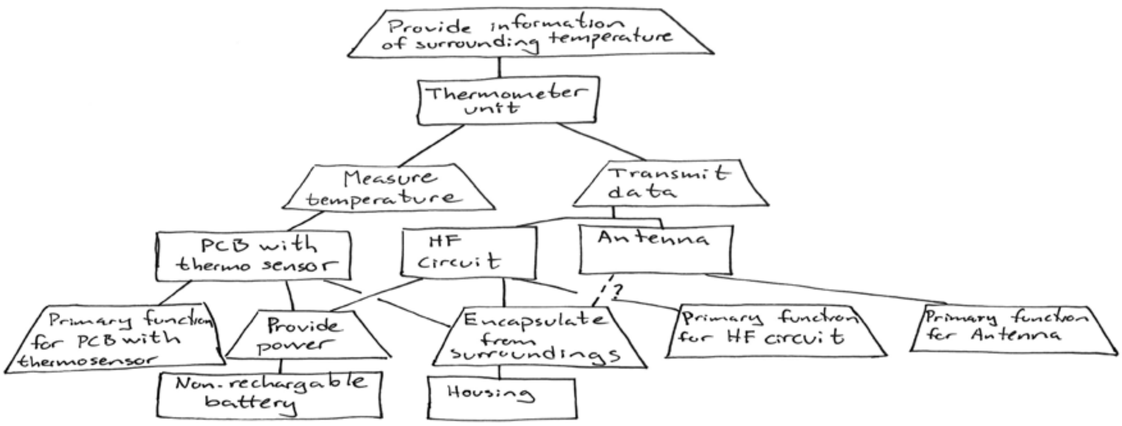

Figure 3. Function/Means Tree

The intention with the watch system is to brand it as being ‘luxurious’ and ‘high-tech’. The product should therefore contain properties leading to this user perception. Two of the needed properties are: ‘Low tolerance on the temperature measurement’ and ‘low power consumption’. The property ‘low power consumption’ is derived from the conclusion that changing battery too often is not leading to the perception of a ‘luxurious’ and ‘high-tech’ product (A4) (A5).

4.2 Feasibility study

The E engineers begin the development of the electronics based on the conceptual idea of the thermometer unit. The two main issues they begin to consider are the power consumption of the electronics and the technology needed to establish the wireless communication. A very rough cad model (undetailed) is made to assess the volume needed and to align it with the industrial design wishes (A1) (A6). Volume requirements are based on the initial guess of needed components. Regarding the power consumption two principally different solutions are considered; namely to preserve energy by different means or to be able to recharge the unit in a charging station by which the problem of power consumption seems reduced. A system where the unit should not be recharged is evaluated to be more user-friendly. Furthermore it is estimated that several means within the E and Sw domain can be utilized to conserve energy, and ultimately a switch can be used to turn off the unit when it is not in use. A switch would have considerable impact on the M domain due to the waterproof requirement. From this it can be seen that there are multiple relations between functions, properties and structure across the three domains when trying to optimize the power consumption (A4) (A5) (A6). The suggested means for the electronics are illustrated in Figure 4.

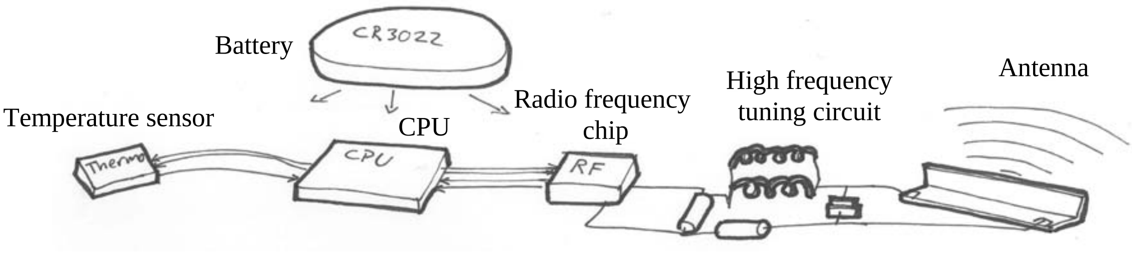

Figure 4. Suggested means for functions, which are allocated to the electronics domain

The feasibility study regarding the instrument and its ability to communicate with the external unit forces the electronics to be developed slightly ahead of the mechanical solution. It means that the electronic diagram and the PCB (Figure 5) are made for initial testing at the time where the structure of the housing is only roughly sketched (A1).

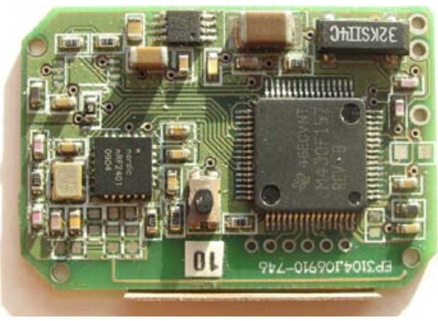

Figure 5. PCB for thermometer unit. Dimensions for PCB: 37 x 25 mm

4.3 Conceptual design

At this stage some of the mechanical development resources are redirected to the thermometer unit. It is assumed that the PCB will remain unchanged with respect to the size, the mounting holes, the shape of the antenna and the position of the antenna. A specific battery is suggested. These components have to be assumed to remain unchanged to admit the mechanical engineers to begin their work based on the industrial designer's suggestion for an outer shape. However, it is known to the design engineers that several components in the electronics design can change including another design of the antenna. The changes might include switching from an on-board antenna to an external antenna, change of the type of the battery and maybe a change due to a requirement to incorporate an on/off switch. This is an illustration that development within one domain has to assume the other two domains as fixed for a certain duration of time. Of course the developers are aware that some and maybe even predefined elements or aspects may change, but the other domains must still be assumed to be fixed until the next iteration of the product (A2).

In the conceptual design phase of the thermometer unit the life phases of the product are considered. Two of the many aspects considered, are the use phase and the service phase in order to optimize the user perceived value (A7). The use phase requires watertight seal of the electronics from the surroundings and the service phase requires easy change of the battery with low risk of harming the electronics by this operation. Several suggestions are made for positioning the battery and designing the battery terminals. Some of those solutions lie within only one domain whereas other solutions require a mix of solutions from several domains. The pool of solutions can be regarded as balances between the domains according to where the functions are allocated. This indicates that extreme balances can be used for generation alternative concepts and for investigating the solution space (A3). In Figure 6 some of the solutions regarding the battery terminals can be seen.

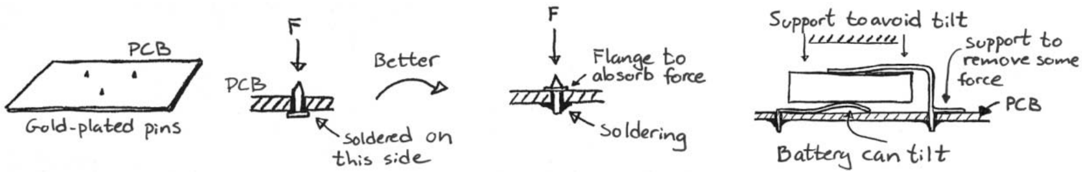

Figure 6. Illustrations of some of the sketched solutions for the battery terminals

The property 'transmitted signal quality' is considered throughout the phases of the project. Many relations between functions and means from all domains influence this property. To illustrate this, the shape of antenna, the chosen electronic components, the position of the battery and other metal objects in the design, the capacity available due to the selected battery and the software code are some of the contributors to this property (A5). The property of 'transmitted signal quality' is different from the property 'robust device', which was also handled in the project. The clear signal can be described as a sequence of instances, which all have to be optimized considering the 'the weakest link of the chain' principle. Robustness can be located many different places in the product. This property can be considered as parallel instances each separately contributing to robustness (A5).

A functional model is made in RPT material incorporating the suggested means (see Figure 7). The functional model of the thermometer is field tested at a ski resort together with the functional models of the instrument and the heart rate monitor.

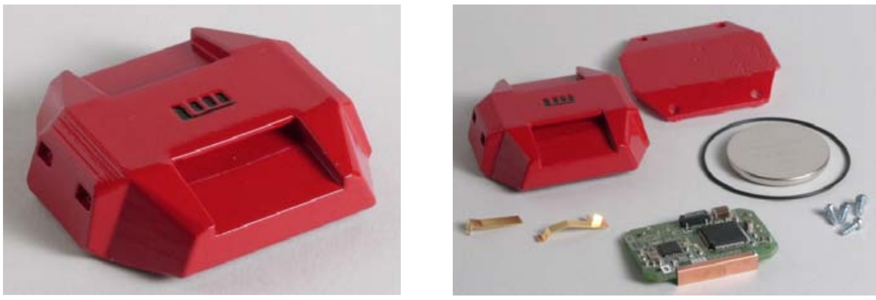

Figure 7. The functional model used for the first field test

4.4 Embodiment design

The integration test shows that the thermometer unit is sufficiently accurate in reading the temperature, but changes in temperature is not detected rapidly enough as anticipated with the temperature sensor located on the PCB. The test also shows that the wireless transmission has to be improved to reach the high standard expected by the users (A7).

At this stage of the development process the E development team is focused on improving the HF transmission by tweaking the discrete components. Furthermore the E development team has to solve issues related to the electromagnetic noise from the transmission, which degrades the performance of the electronics. Concurrently the software engineers are working on controlling of the HF digital chip, which is a more resource intensive task than first anticipated (A1) (A4) (A5).

Based on the appearance of the RPT model the designers suggest a changed shape of the thermometer unit making it appear lighter. The suggested design is shown in Figure 8.

Figure 8. New proposed shape of the thermometer unit

The new shape even though it does not seem significant has consequences. The most important consequence is that the unit has to be re-modelled in the mechanical CAD system (A1). In the new design an aluminium decal on top of the thermometer unit is incorporated to conduct the surrounding temperature to the sensor quickly for the sensor to rapidly detect temperature changes. The idea is to place an aluminium rod between the decal and the sensor mounted on the PCB. In Figure 9 the sketch of the concept is shown as well as a simulation of the heat flux.

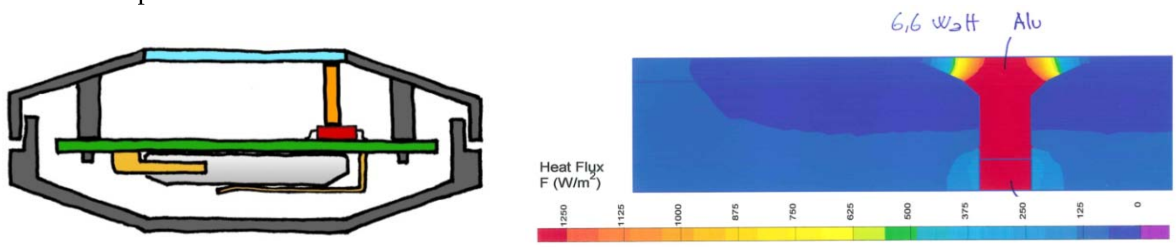

Figure 9. Concept with aluminium rod and the simulation of the heat flux

Power saving schemes are implemented in the software, the electronic components are tweaked by experiments made by external hired specialists to optimize the transmitted signal quality, and the cad model is made so a second field test and laboratory test can be made. Both tests show good results.

4.5 Detailed design

The mechanical design is improved to the stage were injection moulds can be ordered. One of the tasks is to decouple the forces from the battery when the unit is dropped or vibrated so the forces will travel into the housing and not into the PCB or terminals. A vibration test is performed which reveals that the temperature occasionally will not be updated for a short duration of time. After an investigation the cause turns out to be that if the battery is disconnected from the terminal in the range of just microseconds, the µ-processor will re-boot and the instrument and the unit will lose their transmission synchronization. Until reconnected the temperature will not be updated on the instrument. The terminals for the batteries act as springs and should have been able to make a secure connection. However, since the disconnection of just a microsecond can cause re-boot of the µ-processor, eigenfrequencies or similar vibration phenomena could be the cause. Instead of improving the mechanical system surrounding the terminal springs, a capacitor is added to the electric circuit, which will compensate for disconnections (A3). The solution is robust since it is insensitive to the cause for such small disconnections.

4.6 Production preparation

Having the thermometer in the almost finished design more mechanical, electronics and software testing is performed. Due to the wish for high-tech perception the unit should indulge, it is decided to increase the speed at which the unit can detect temperature changes. After some tests and conceptual work, it is evaluated that one particular solution will improve the temperature sensing and only cause minor changes in the mechanical and electronic design. Since the injection moulds have already been manufactured it is important that the change only will require minor changes of the design. Three of the suggested solutions can be seen in Figure 10.

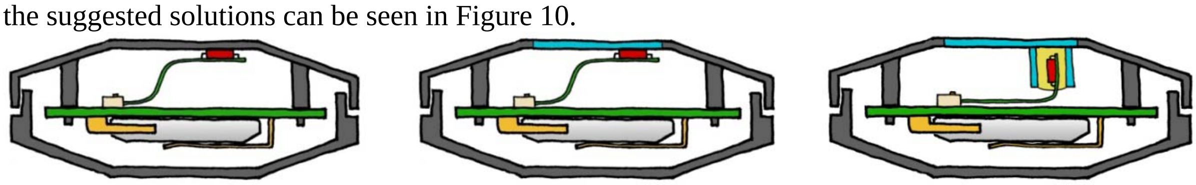

Figure 10. For illustration purpose the position of the terminals has been changed on the illustration

The solution is based on positioning the sensor on a flex print and locating the sensor as close as possible to the aluminium plate as possible considering other requirements. The new version of the PCB can be seen in Figure 11.

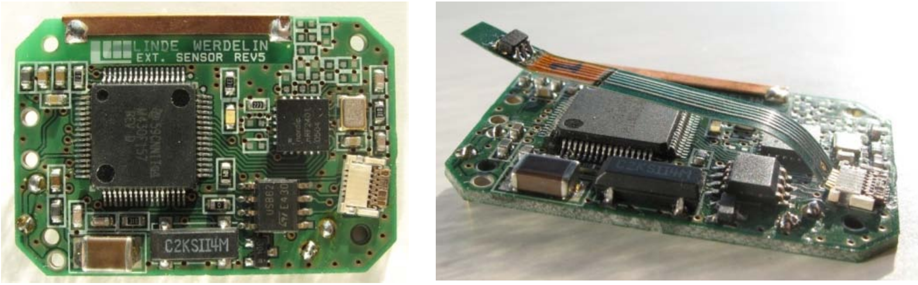

Figure 11. The PCB is shown without and with the flex print inserted in the connection terminal

The case study illustrates the seven aspects related to the design process, the product, and the user-perceived value. The case illustrates that it is essential for the designer to be able to handle the aspects across the engineering disciplines and not just see the issues locally from within a single domain. With the amount of relations to handle, it is hard to imagine that it can be done without applying some sort of systematically approach. Great many relations between functions, properties and structures as well as dependencies between activities in the design process can be observed in the case study. When systems become larger and the number of persons involved in the design process increases so does the potential relations and dependencies. This further underlines that it is important to be in control of the described aspects in the design process.

5 LITERATURE REVIEW

In the following relevant literature is investigated with the intent of revealing the support found in the literature regarding each of the selected mechatronic aspects (A1) to (A7). First an overview is presented in Table 1 showing the rating of how well the literature is covering the particular aspects. Then each of the references is described in a general form to show the context and the intention of the literature to have incorporated mechatronic aspects in the text. To go through every aspect for each of the references would be tedious for the reader, and is therefore omitted. Thereby the reader must rely on the judgement by the authors to have performed the rating systematically and unbiased. The selected literature is investigated in the context of mechatronic synthesis. Therefore, if the a literature is describing for example life phases but not in the context of the synthesis process and without addressing the particular impact on mechatronic development, it will be rated as "not describing" the particular aspect. Types of references include text books, scientific papers and PhD thesis. The legends used for ranking are described in the following.
'0': The aspect is not described.
'1': The aspect is acknowledged and a characterisation may have been performed.
'2': The aspect is treated thoroughly and a method for handling the aspect is suggested.

VDI2206 guideline [7]**.** VDI2206 is a broad introduction to the subject explaining the fundamental challenges of mechatronic engineering. The proposed methodology have great similarities with the methodology for mechanical development suggested by Pahl and Beitz in their book "Engineering Design" in the strong focus on machine design. The V model is used as the process model for illustrating the phases of development of mechatronic products. Besides a general introduction, the guideline describes the phases ranging from the goal setting of the project trough system design over domain specific and validation and verification of the intended product and also including organisational aspects of corporation between team members across disciplines. All these aspects are described in a page wise very compact format, thereby not capable of incorporating descriptions of guidance and methods for performing essential tasks of the synthesis process.

Systems Engineering [8]**,** [9]**.** In Systems Engineering the main idea for handling multi-domain development is to break down the task into subtasks thereby breaking down the product into modules which can be handled. Having performed decomposition, the important relations are modelled in e.g. IDEF and/or via specification management. Multi-disciplinary issues are solved by use of traditional management tools such as project planning, staffing, resources, risk handling, TQM etc. and not by specific mechatronics related methods. It lacks description of the synthesis steps especially for the mechanical area. In this sense it shares more commonalities with development procedures for software such as those found in the book “Software Engineering: A Practitioner’s Approach” by R. S. Pressman [10] than with the procedures for mechanical development such as Pahl and Beitz [11] or Ulrich and Eppinger [12].

Table 1. Overview of how well the aspects are covered by the literature

	VDI 2206	Systems Engineering	V-modell XT	J. Buur	J. Gausemeier	S. Jansen/E.G. Welp	V. Salminen/ A. Verho	R. Isermann	R. H. Bishop	R. H. Bracewell	Pahl and Beitz
Synchronization of M, E and Sw process (A1)	1	1	0	1	1	0	1	2	0	0	1
The domains seen as iterations (A2)	0	0	0	0	0	0	1	0	0	0	0
Function allocation and alternatives (A3)	1	0	0	1	1	2	1	1	1	0	0
Distribution of Fu and Pr (A4)	1	0	1	0	1	1	1	0	0	0	1
Sharing schemes for Fu and Pr (A5)	0	0	0	0	0	0	0	0	0	0	0
Handling of physical interfaces (A6)	1	1	1	1	1	1	1	0	0	0	0
User-perceived value in the life phases (A7)	0	0	1	0	0	0	1	0	0	0	0

The V-model XT [13]**.** The model is based on the ‘V-model’ suggested in 1997, which was solely aimed at software development. The V-model XT is intended for products containing electronics and software, also called embedded systems. The role of the mechanical domain in the development process is not considered even though the embedded systems in most cases will have to interact with the mechanical elements. A framework is suggested for how to configure the V-model XT to fit a particular project. For each configuration of the V-model XT, different entities of the process model will appear. The interesting part of the process model is, however, that the life phases play a central role in the process description, which makes it stand out compared to the other references in the literature study. Even though mechanical development is omitted, the V-model XT is included in the literature study, because the V-model concept is one of the most referenced models in mechatronic literature.

J. Buur [6]**,** [14]**.** The literature comprises a very comprehensive categorisation of differences and similarities between the domains based on the theoretical view of “The Theory of Technical Systems” by Hubka [15] and “The Domain Theory” by Andreasen [16], [5]. Methodologies from before 1990 are discussed and phenomena linked to the development of mechatronic products are described. The theoretical and categorisation approach provides a foundation for understanding the area. However, the limitations of the research lie in trying to stretch a theory originally belonging to the mechanically domain to cover electronics and the software domain. The consequence is that only aspects of the development, which have an equivalent in the mechanical domain, are treated in the research. To illustrate this, issues such as those linked to dealing with ‘real time systems’ cannot be described or made operational by the use of the theories.

J. Gausemeier [17]**,** [3]**.** These two references have been selected among several from Gausemeier. These articles address the early phases in the design process of developing mechatronic products. The focus is on how to specify the principle solution, on how to control the design process and on how to provide an organizational support for the design process. A semi-formal functional model is suggested that should enable designers to specify a mechatronic product in the conceptual phase of a project and thereby overcoming the often mentioned common language gap between domains. The descriptions and models suggested are tangible, but lack the in-depth description of the synthesis process in the domains.

S. Jansen/E.G. Welp [18]**,** [19]**.** Jansen and Welp aim at providing a procedure for development of mechatronic products. The process description is mainly focused on the function allocation aspect, for which he suggests procedural support. It is a suggestion consisting of a process including rules and guidelines for making variations of the function allocation. The suggestions for themes which can be used for creating variants makes it stand out from the other literature contributions within the mechatronic research area. As a part of the process of allocating functions, categorisation and classifications of elements should be done in a written form which then can be modelled in an UML-equivalent model language. The amount of written data needed to make the model operational can prove to be disadvantageous in a synthesis process. The reason is that written information lacks the visual representation needed especially by the mechanical engineers. This disadvantage has also been reported by Bonnema [20]. Furthermore it is the authors experience that large amount of written data tends quickly to be outdated in fast paced projects.

V. Salminen/A. Veho [21]**,** [1]**,** [22]**.** The challenges of developing mechatronic products are thoroughly described and the challenges are categorised according to the development phases they appear in. Aspects needed to be considered in the process of going from user-needs to a functional description while considering strategic issues are highlighted and key questions for support are stated. A vast amount of conclusions are drawn linked to what characterizes the nature of mechatronic development projects. Some guidelines based on best practice are declared and a "metamethodic" is suggested which is a framework for how and when to utilize available methods and tools such as VDI2221, QFD and UML-equivalents in the development process. The integration aspect in terms of the overlapping areas between the domains is only vaguely treated in how it should be handled in a project. The suggestion presented, is to bring designers from each of the domains together to obtain a mutual understanding of the goals and tasks to be performed in the project.

R. Isermann [23]**.** The book has a strong focus on control engineering and control principles. However, a detailed process description is stated by listing activities grouped according to the phases in a development project. Even though description of the process emphasises activities linked to control engineering, the description is unique in the sense of the vast amount of stated activities. The activities are only briefly described and the underlying mechatronic phenomena linked to the activities are thereby not described. A model is illustrated to support the description of the process. However, the model does not show integration activities. In contrary it seems to promote separate tracks for each domain.

R. H. Bishop [24]**.** This book is about mechatronic systems with a strong focus on the control aspect. The chapter of most relevance is called 'Mechatronic Design Approach'. It presents a framework for understanding the elements of a mechatronic system such as actuators, sensors and the information system, various control strategies and a procedure for the design process. Even though a stepwise procedure is stated, the strong focus on control engineering has the effect of suppressing other design activities and needed framework understandings for performing a synthesis of mechatronic products.

R. H. Bracewell [25]**,** [26]**.** This reference is included in the literature study because the program 'Schemebuilder' is claimed by the developers to be 'a highly integrated "design workbench"' capable of assisting the design process in problem analysis and in the conceptual and the detailed phase of designing mechatronic products. Suggesting artificial intelligent computer software for product development should be an object for sound scepticism. However, for this literature study the focus is on the design methodology, which is used as the backbone in the Schemebuilder software. The design methodology is based on French's model of conceptual design, and is as such heavily influenced by traditions of design thinking from the mechanical research area. The suggested procedure is a straight forward functional decomposition procedure, in which the myriad of complex relations between the domains are omitted in sense of phenomena description or tools for handling these challenges. Even though the Schemebuilder is presented as very comprehensive in supporting the mechatronic design process the listed aspects in Table 1 are not covered.

G. Pahl and W. Beitz [11]**.** In the book a short introduction to the phenomenon mechatronics is found followed by a description of three mechatronic products illustrating the benefits of having all three domains working together in a product. The description of mechatronics has been included in a chapter, which also comprises "Mechanical Connections" and "Adaptronics". The topic "Mechatronics" has not been integrated in the chapters regarding product planning, task clarification, conceptual design, embodiment design, underlining that development of mechanical products is the main focus in the book and not mechatronic products. The authors of the text book acknowledge the brief treatment of the topic. Hence, references are made to the VDI2206 and to Rolf Isermann in terms of suggesting a support for a mechatronic design procedure.

Conclusion on the literature review

The following aspects have been rated ‘0‘or ‘1’ in Table 1: Domain iterations (A2), Distribution of functions and properties between domains (A4), Sharing schemes (A5), Handling of physical interfaces (A6), User-perceived value in life phases (A7). This shows that there is a gap between the need for handling the aspects in a mechatronic synthesis and the support found in the literature. The following aspects have been rated ‘2’: Synchronization (A1) and Function allocation (A3). The rating of “2” has, however, only been achieved by one of the eleven literature sources. This also indicates room for improvement. The control engineering field is mechatronic in nature because it has elements from each of the domains. This is reflected in the amount of references originating from control engineering research communities, including those references achieving a top-rating in this article. The logical consequence is that methods and procedures are heavily influenced by activities closely linked to the control issue of the product development. There are many other types of mechatronic products where the control issue is not the essential problem, where we need a support regarding theory, models, methods and procedures. These other types of mechatronic projects, where the control issue is not the main challenge, as in the case study of the thermometer unit, will be the aim of our further research. In our future work there will be a focus on support for creating and handling alternative solutions in the development process and how to model relations to reveal the consequences of our dispositions in one domain to another. We see it of paramount importance to develop a support that will work in highly dynamic development environment, where decisions and changes occur rapidly, paradigm shifts are expected for the concept and simultaneous concepts are developed.

6 CONCLUSION

The case illustrates that generating a mechatronic solution involves a closely coordinated synthesis process between the mechanical, the electronics and the software engineers in the terms of understanding the multiple relations between the domains, which far exceeds what can be specified by defining physical interfaces and communication protocols. The literature review reveals gaps indicating that we do not have sufficient theory or methods for mapping and handling the relations needed to perform a transparent and rigorous synthesis of mechatronic products. If this is not provided, companies can be forced to resort to incremental innovation to lower the complexity of new products or settle for theories for general collaboration between disciplines. The authors of this article, however, believe that the mechatronic aspects should be treated by use of systematic views, understanding patterns and methodologies, which are specifically linked to the mechatronic area and that any support that can aid the designers in handling functions and properties distributed between the different domains will greatly enhance the quality of the design process. Further research should therefore be aimed at finding support for the seven aspects presented in this article.

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