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USE CASE BASED METHODOLOGY FOR CONCEPTUAL DESIGN OF INDUSTRIAL MECHATRONIC PRODUCTS

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Abstract

Mechatronic products play an important role on industry, providing solutions to increase productivity and cost reduction. On the other hand, to develop products for industrial use requires a different set of tools and methods than the ones employed by the design of consumer goods. The existing methods for mechatronic design in general does not focus on industrial product specifically, or provides just an overview of the process for a generic mechatronic product, without focusing on tools and activities. Our proposal integrates the Task Clarification and Conceptual design phases providing an iterative procedure to the design of mechatronic industrial products. The core of this proposal is the use of Use Case Diagrams to provide information necessary to requirements definition, functional modelling and solution principles establishment. To evaluate the proposed method, it was employed on the development of an Automated Vehicle for Railroad Inspection, a maintenance task regularly performed to guarantee the railroad safety. It was observed the viability of the proposal to obtain the desired information from Use Case Diagrams.

Keywords: Mechatronics, Design methodology, Early design phases, Functional modelling

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1 INTRODUCTION

Traditional design methods such as Pahl *et al.* (2007) and Ulrich and Eppinger (2004) usually rely on interviews and surveys to obtain information necessary to clarify the design task. These procedures are welcome for projects involving consumer goods and really new technology based products, with high levels of uncertainty level. On the other hand, in practice, there is a wide range of situations where these tools will provide little benefit. It includes, but not restricted to, a series of mechanical, electromechanical and mechatronic products, designed to perform industrial tasks, usually produced in a very small scale when compared to consumer goods. The observed practice for these situations is to adapt the existing design methods providing a mixture with the activities from Task Clarification and Conceptual Design phases, frequently in an informal way.

Nevertheless, as we observed on our literature review, mechatronic design methodologies do not explicitly provide the design tools needed to clarify the task and develop de product concept, focusing on the methodological overall process. Thus, with only one exception, these methodologies do not deals with the context of design of technology based (industrial) products.

So, it is our main goal to provide a method, including a procedure and design tools, to support the design of mechatronic products for industrial applications. The reason for using mechatronic design instead of traditional design methodologies as basis for the method presented on this paper falls on the complexity of this sort of products, usually based on two or more axes of the mechatronic knowledge.

2 LITERATURE REVIEW

In an overview of the literature review, we observed that the majority of the studied methods focus on the integration among different knowledge and professionals dealing with the development of a mechatronic product. A small portion of the literature evaluates the available methods and points out mechatronics as a solution for developing complex products. In both cases, however, it has been emphasized the need of a proper design team knowledge management. In the next paragraphs are presented the studied design methods.

Salminen and Verho (1992) proposal is based on conception and production procedures of mechatronic products. The authors call attention to the lack of interaction among mechatronics knowledge areas in the late phases of the design process. For the authors the design process evolves form the centre and cooperation occurs on the initial phases, related to idea generation, tasks definition, conceptual design and prototyping. The least interactive phases are the detail design and project review, where each mechatronic knowledge area focuses on its own field.

In this work, the authors provide just an explanation on what occurs during the Conceptual Phase, which is not separated from the task setting activities. This phase includes functional modelling as the only design tool and it has to remain fairly unsystematic to provide a more relaxed environment for ideation. However, latter in their paper, the authors include resources such as Quality Function Deployment (QFD) and Structured Analysis and Structured Design (SA/SD) and knowledge from VDI2221 standard (Systematic approach to the development and design of technical systems and products), providing an amalgam of methods named by the authors as "meta-method".

There are other works providing additional methodological insights. Hehenberger *et al.* (2013) investigated a model structure based on the premises that parameters hierarchy and modularity are analysed with conceptual models. For the authors the modularization step is critical to the conceptual design. Also, parameter hierarchy plays an important role in this proposal as it is related to the product modelling level. So, by this approach, the authors reduce problems on final production stages of a mechatronic product. Problem definition phase, including clarify and define the task, is not detailed on their proposal.

Gausemeier *et al.* (2011) presented a general procedure, to integrate mechatronic and production systems. Their proposal starts with phases similar to traditional design process: planning and clarifying the task and Conceptual design. Major differences appear on the next phases, where the product is divided on modules and, throughout an iterative cycle procedure, each module is detailed and the process is defined concomitantly with the integration of the concept.

In an approach more focused on industrial based products, Heilala *et al.* (1992) presented a method to design grippers and automated industrial systems. The method phase's structure is quite conventional and dived in four phases: clarification of the task, conceptual, embodiment and detail design. The approach for clarification of tasks is particularly interesting. The authors split this phase in Process and Workpiece Analysis, where the process information is accessed in a more technological way, and Preliminary Design of the Gripper, where an initial concept is provided, resulting in specifications for the conceptual design.

Chan and Leung (1996) introduced a spiral development model applied to the development of mechatronic consumer goods that aims to reduce development time and production time. The authors aim to reduce production effort and to allow more flexibility in the initial design phases. It is divided on five phases, starting with the use of new technologies into product conceptualization and finishes with production process, where the authors focus on reducing failures. Each phase corresponds to a cycle of analysis, design, build and test. For the authors, Analysis corresponds to the specification of functional requirements (FRs), transformation of FRs into design parameters (DPs), and use of analytical tools to solve the problems, and Design to creation of sketches, layouts, and detailed drawings of components or sub-systems and selection of sensors, actuators and other purchased items.

The central reference for evaluating methods for designing mechatronic products in recent years is the VDI2206-2004 standard, which works with three central elements. First is the problem-solving cycle as a micro-cycle, where procedural cycles are organized in series. It starts with situation analysis or adoption of a goal, followed by analysis and synthesis micro cycle, analysis and assessment, and finishes with a decision, which can compel a restart of the cycle or the planning for further procedure or learning. No specific tools are provided to aid in this process.

Second, is V model as a macro-cycle, which works as a guide, providing the logical sequence of important sub-steps in the development, which are governed by the already mentioned problem-solving cycle. In a simple way, the V-model can be described as a procedure of breaking down the product information into smaller parts, developed in separated mechatronic knowledge fields (the descending side of the “V”) followed by an integration effort to consolidate the product (the ascending side of the “V”). It is also possible to repeat this procedure, providing different maturity levels of information. Third, there are process modules, which can be described as predefined problem-solving cycle with already known procedures, including process modules for system design, modelling and model analysis, domain-specific design, system integration and assurance of properties.

All observed methods separates task clarification from conceptual phases, except Salminen and Verho (1992), that proposed an integrated and more informal conceptual design, and the VDI2206-2004 standard, which provides more guidance oriented information than a detailed method. However, Heilala *et al.* (1992), introduces a more technological based approach for task clarification phase, which brings concept generation into the task clarification phase. Gausemeier *et al.* (2011) approach also brings some innovation, including iterative cycles of module conceptualization, differently from Chan and Leung (1996) that cycles from the beginning of the design process, demanding more design effort.

So, in our understanding, it is possible to provide a less structured and more relaxed procedure, as aimed by Salminen and Verho (1992), however without losing the systematic support needed to a professional design process. The iterative or cycling procedures are interesting way to provide the maturing of information, so it is another aspect that is incorporated on our approach. In this paper, we will focus only on the initial design phases of the development of industrial (non-consumer) mechatronic products.

3 METHODOLOGY

As Hehenberger *et al.* (2013), the focus of our proposal is also a model based approach. However, the core of our proposal is the use of UML's Use Case Diagrams as a tool guide the product specification associated with functional modelling. Use Case Diagram is a graphical representation that identifies its different types of users and their relationship with a system. Each interaction (or action) is a use case and it is represented by an ellipse in de use case diagrams. Each use case can be detail in to a new use case diagram, providing a more accurate description of an action.

Use cases diagrams have been employed as a tool to obtain design requirements for a long time in software engineering. The results of the study performed by Siau and Lee (2004) show that use case diagrams were interpreted more easily and completely than class diagrams (both UML models for defining requirements), providing a more complete understanding of the model. The authors also point out that use case diagram is easier to teach than class diagrams.

We propose to take use of use case diagrams to guide task definition and clarification concurrently with the functional modelling and idea generation within a morphological matrix, integrating the Conceptual Design into the beginning of the design process. It is a cyclical process, similar to the micro-cycle presented by VDI2206. The use of an iterative approach was already implemented by Gausemeier *et al.* (2011) but focused on the conceptual design and latter stages. Our approach is more related to the one presented by Heilala *et al.* (1992) where Task Clarification were more focused on technical issues, however their approach is presented in a more sequential way. The proposed procedure can be described as follow:

1. Reflect about the main task to be performed by the product. It is usual that, when an industrial product is necessary, some information is already available, including how it is currently performed and what is expected as result. From this information, it is possible to define Task Requirements and Product Requirements.
2. Build a use case diagram focusing on the description of the overall task. Each use case will be deployed into other use case diagrams depicting the lower levels.
3. Now three activities occur in parallel:
    a. Deployment of the use case diagrams.
    b. Functional Modelling
    c. Fill in the morphological matrix.
4. When building this diagram, pay attention to:
    a. Use case "users"; they can generate new possible solutions.
    b. Use cases; they can generate new functions to the functional model.
    c. The need of new product requirements, to provide a more comprehensive list of target specifications to the design team.

After concluded the iterative cycles it is provided two different group of information. First, there is a cluster of information regarding the system logic (software and control), represented by the developed use cases and the software requirements. Second, there is other cluster of information concerning the physical product (electronics and mechanics), grouping functional model, morphological matrix and product target specifications. Figure 1 synthetizes all methodology information.

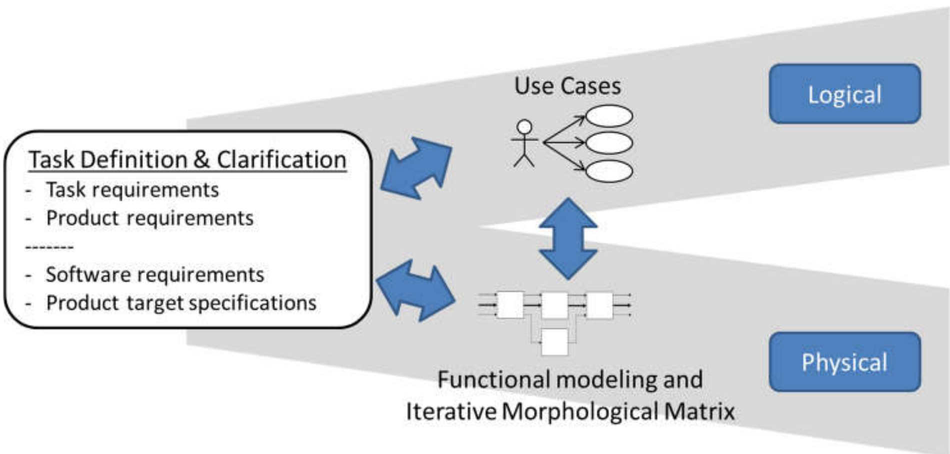


Figure 1. Integrated Task Clarification and Conceptual Design for mechatronic products.

We can make an analogy of our proposal with VDI2206's problem-solving cycle as a micro-cycle, as it can be seen on Figure 2. Task Definition and Clarification on our proposal comprehends the initiation actions from VDI2206, including situation analysis and adoption of goals. It also contains analysis and assessment and decision actions, and it will occur iteratively in a similar way as VDI2206, resulting on the software requirements and product target specifications. The core of this iterative process is provided by the use case diagrams, which provide the guidance needed to synthesize design alternatives. The functional modelling and the morphological matrix provided the basis for creating and selecting design alternatives in a similar iterative way as illustrated on VDI2206.

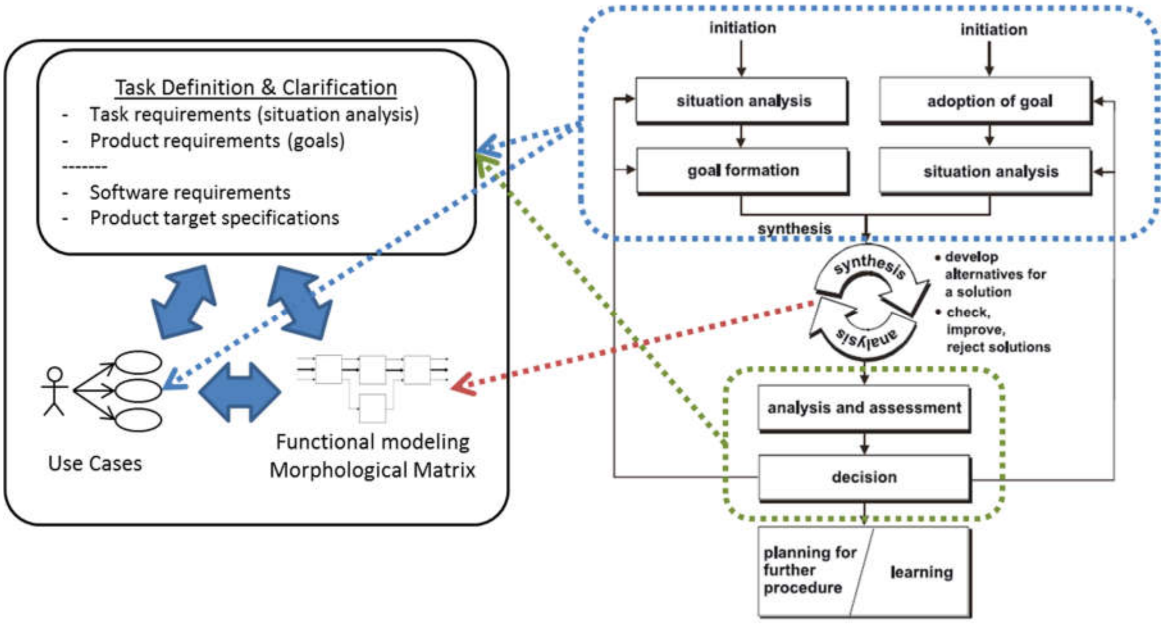


Figure 2. Analogy between the proposed method and VDI 2206 problem-solving cycle as a micro-cycle.

4 METHOD EVALUATION

The proposed method was employed in the design of an autonomous vehicle for railroad inspection (or AVRI). The Task Definition and Clarification starts with the analysis of the current practices. Railroad inspection is regularly performed by rail companies and aims to guarantee the service safety. This procedure is can be performed on all infrastructural elements, including rails and sleepers. For rail inspection, it is executed several tasks such as verifying surface anomalies, wear, geometry deviations and internal cracks. It was performed a gathering of information (patents and industrial websites) regarding the availability of technology to perform rail inspection tasks. The results are:

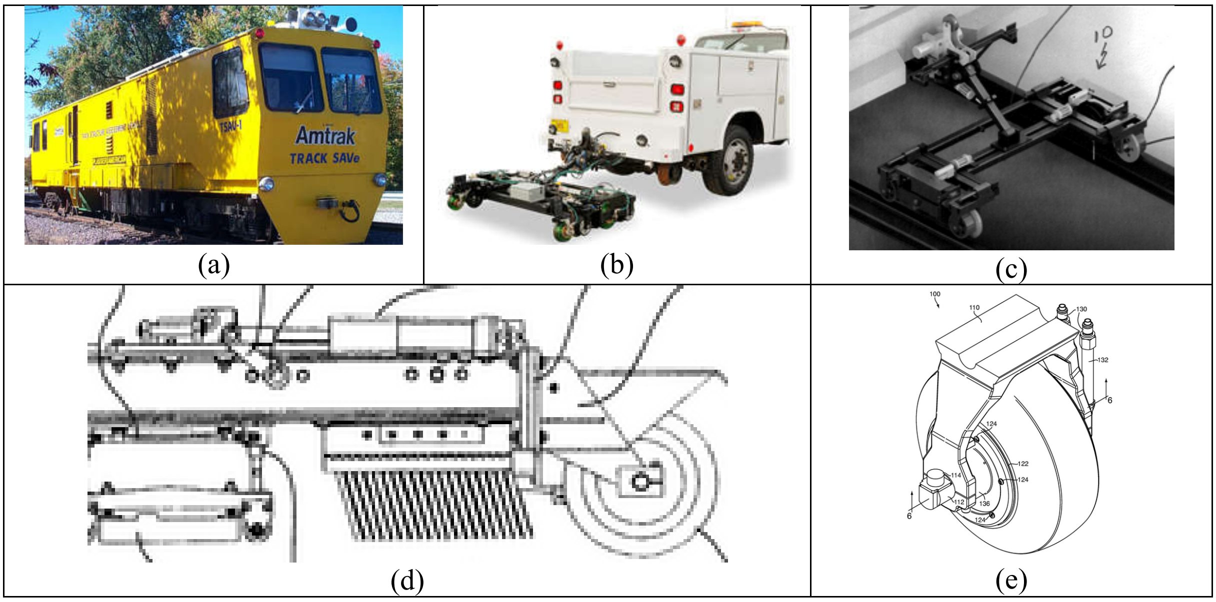
- Ultrasound (internal cracks inspection):
  - Transparency (two transducers)
  - Pulse-echo (one transducer; mono-crystal)
  - Angular transducers
  - Double crystal transducers
  - Phased Array transducers
- Laser measurements:
  - Laser triangulation (rail profiles; there are variants mono-rail, bi-rail, 360°, GPS)
  - Corrugation Rail (wearing, etc.)
  - Associated with cameras (geometry and surface finishing)

Our proposal is to develop an autonomous vehicle to perform, at least initially, two of these tasks: to verify geometry deviations and scan for internal cracks of rails. This product fits well on the problem discussed on our paper, since aesthetics and other marketing features plays small roles in this design problem and technical features for rail inspection are well known. As part of the Task Definition and Clarification, it was performed a search for similar and useful technologies in industry and patents. The result is illustrated on Table 1, and listed as follows:

- (Table 1 -a) vehicle with automated inspection. It has cams that capture images from the track and store it on a database. Not autonomously guided.
- (Table 1-b) hi-rail vehicle based inspection. It has two types of sensor: ultrasound and magnetic induction. Not autonomously guided.
- (Table 1-c) Device with ultrasound and rail size deviation measurements. Has to be coupled to a vehicle (pick-up).
- (Table 1-d) Magnetic sensor. A high-voltage electrical charge pass throughout the rail (via sweeps) creating a strong magnetic field. Interruptions on this field indicate the presence of failures in the rail.

- (Table 1-e) Ultrasound device for rail inspection. The sensor is build inside the wheel, which is full of fluid.

Table 1. Results from technology gathering.



Based on this information (situation analysis), it was developed two types of requirements list. The first list is an overall target specification, as can see as follows:

- Autonomous and programmable.
- Powered by electricity (batteries).
- Batteries must be charged via plug and via energy recovery during braking.
- Communication must be continuous with the Operations Centre (OC). Cellular telephony is the preferred way.
- Communications must provide some extend of remote control.
- Fast (maximum permissible rail speed is 60 km/h).
- Light (carried by the maximum of 4 persons).
- Other legal issues must be obeyed.

The second list, presented in Table 2 is directly derived from the iterations among modelling techniques employed (use cases, functional modelling, and morphological matrix). Information is divided on five columns. First column is to provide identification for each requirement and it is divided in four categories: electrical (ELE), mechanical (MEC), monitoring (MON) and software (SOF). Second column is for actions to be performed by the vehicle; it is usually obtained from the use cases and could be added to de functional model. Third column is the actor, including the user, which will perform the desired task. If the actor is technological (mechanical or electrical) usually is defined side by side with the morphological matrix. The fourth and fifth columns are provided for the control side of the vehicle and describe respectively the desired pre-condition and post-conditions for each action performed. It is important to notice that some information provided on these lists is from later iterations of the proposed procedure and due the cyclical nature of this proposition it is difficult to present them as an evolving list. At the end of the presented procedure, it was listed 47 requirements.

The Use Case modelling started with the establishment of the system overview (Figure 3), which depicts the product integration in its highest level. In our case, it is dived into three parts: software to register and manage the available railways, software to setup and manage inspection missions and the vehicle itself. Each use case from this diagram was remodelled in a new Use Case Diagram and, if considered still too abstract, it was deployed on new Use Case Diagrams. Figure 4 illustrate the Use Case Diagram for use case "Execute Mission" from the previous figure.

Table 2. Product requirements list.

Id	Action	Actor	Pre-condition	Post-condition
ELE_002	Charge battery	Charger	Partially charged	Fully charged
ELE_003	Store energy	Batteries	ELE_A002	Electrical devices powered
MEC_001	Provide movement	Electric engine	ELE_A003	Electric Motor running
MEC_005	Stop vehicle	Brakes	Vehicle in motion	Reduced speed
MON_002	Monitor rail	Cameras	Device working at inspection site Free storage space	Data submitted to storage
MON_003	Monitor cracks	Ultrasound	Device working At inspection site Free storage space	Data submitted to storage
SOF_001	Store data	Databank	Data categorized (SOF_A002)	Data Stored
SOF_002	Process data	Algorithm	Data received without corruption (MON_A002, MON_A003)	Data categorized

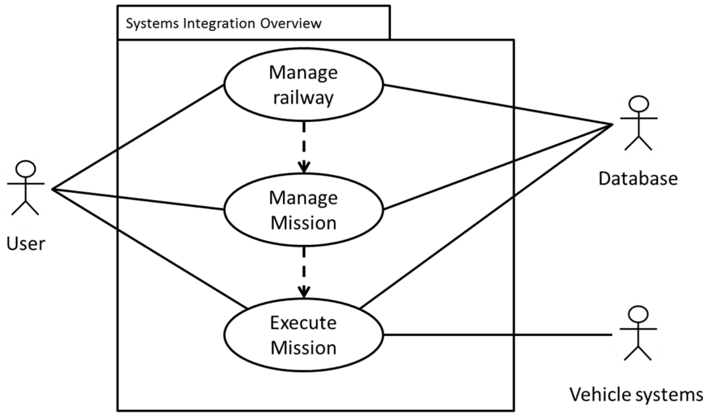


Figure 3. System Overview.

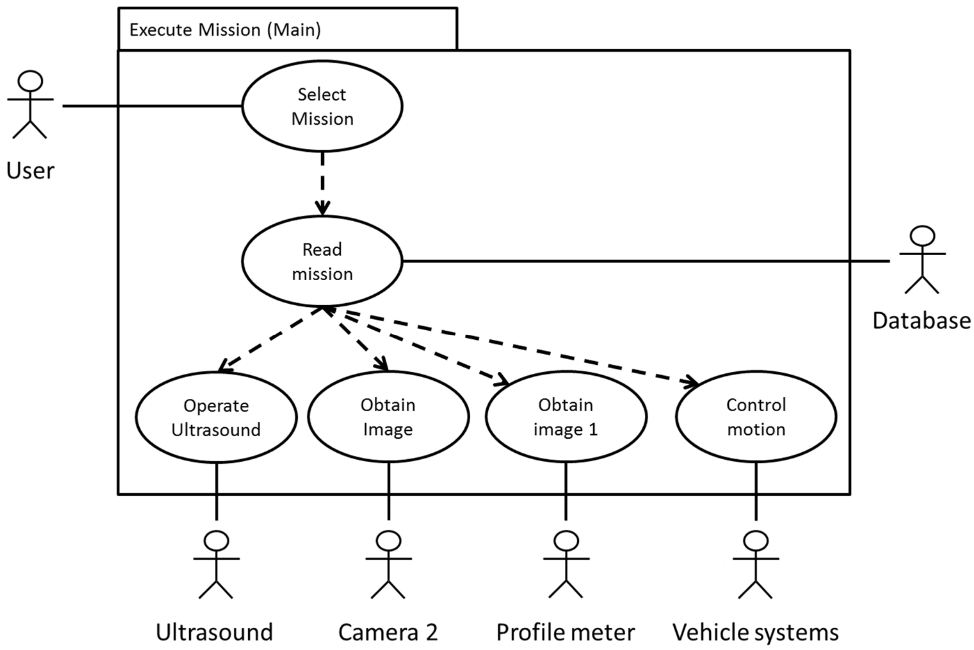


Figure 4. Use Case Diagram for use case "Execute Mission".

For the software and control side of this development, when the abstraction level is considerd adequate, it was stablhised the software requirements. To do so, we adopted expanded use case structure, such as the one presented on Table 3, that details the use case "Operate Ultrasound" from Figure 4. As it can be seen, it registers the use case name specifications for pre-conditions and post-conditions and the main

Table 3. Expanded Use Case "Operate Ultrasound"

Use case name: Operate Ultrasound
Actors: Ultrasound, Database
Pre-conditions: mission must be in the database.
Post-conditions: collected data must be stored and transmitted to Operations Control Centre (OCC).
Main flow: Obtain mission information from the database Activate ultrasound Initiate data gathering Store collected data (repeatable) Transmit data to OCC (repeatable) Deactivate ultrasound

The Functional Modelling occurred concurrently with the Use Case Modelling and, also, with the morphological matrix. Figure 5 shows the final functional model. As it can be seen, the functions where divided in three lanes. First one is for physical parts, usually from mechanical or electrical origin. Second is reserved to devices that interact more directly with the software level (we called it "sensors lane"), providing or receiving larger amounts of information. We observed that the parts lane is usually represented by energy and material flows and the sensors lane by signals flows, but some flow exchange is expected and was observed. Third lane is software. Even though that should be represented by signal flows we decided just to use it to map interactions with the physical elements and choose to continue using UML diagrams to model the software/control side of the vehicle. The controlling side of the software was represented by a function "Control Vehicle".

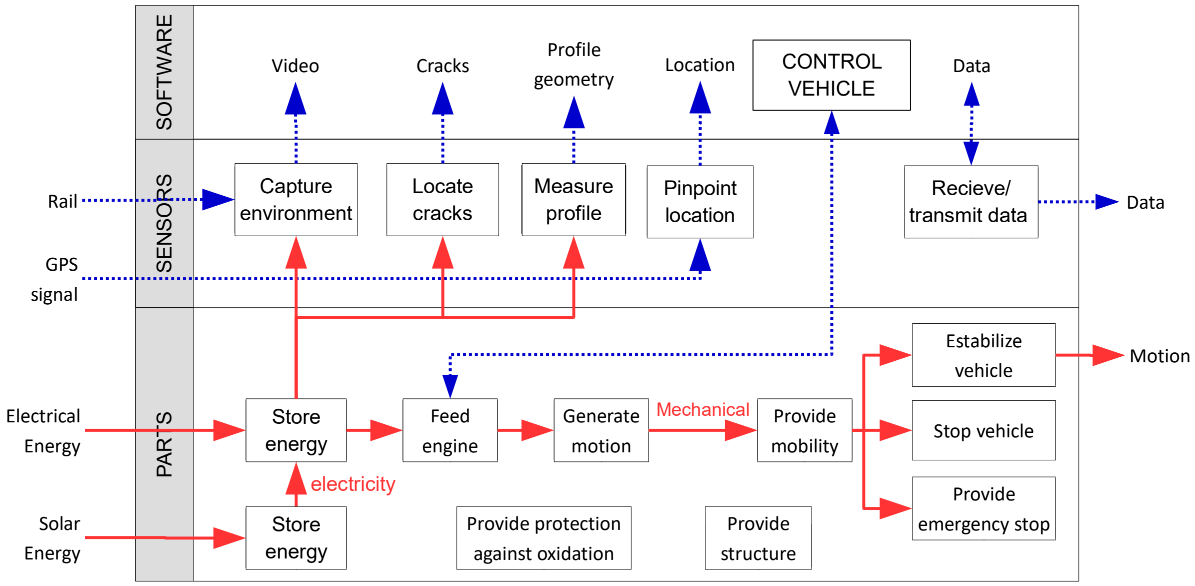


Figure 5. AVRI Functional modelling.

Table 4 illustrates a partial view form the obtained morphological matrix. As could be observed, for some functions just one solution principle was defined. It was done this way since they are related to a previously stated requirement. For other functions, it was performed the usual ideation process expected when using the morphological matrix. However, the usual concept alternatives generation and selection was not performed as a direct result from the smaller amount of possible solutions resulting from the proposed procedure for our particular case. The chosen design alternative is presented in italic letters on this same table.

Table 4. Morphological Matrix for AVRI (partial view).

Functions	Possible solutions		
Generate motion	*Electrical Engine*		
Store energy	*Battery*		
Provide mobility	Standard rail wheels	*Reduced rail wheels*	
Stop vehicle	Rail brakes	*Electrical engine deceleration*	Disc brake
Emergency stop	*Pinch rail*	With magnetism (attract rail)	Same from "stop vehicle"
Provide structure	*Standard aluminium profiles*	Trusses	Single plate (with reinforcements)

5 FINAL REMARKS

In this paper we presented a procedure for the development of mechatronic products with strong technology features, such as several industrial products. This proposal guards some resemblance with the VDI 2206 problem-solving cycle as a micro-cycle since it also initiates with some level of task clarification, pass to a conceptual iterative development followed by decision steps that provides new information to the task clarification or finishes this cycle. The difference is on the detail level of the proposed method. Besides a procedure, we also described the design tools to needed to perform the design task. Our proposal results in a strongly use centred approach, ideal for project involving little impact from consumer needs, as observed on more industrial products. It was possible via integration of use case diagrams with the functional modelling, in an iterative procedure.

To evaluate our proposal, we employed it on the design of an autonomous vehicle for railroad inspection. It is a technological product with no need for aesthetics or other type of value adding except the ones needed to perform the task. The proposed method allowed an easy discussion with the design team and provided the guidance needed to deploy the initial information from task clarification into technical and functional information. In future works we will deal with the next design stages, including directives to the embodiment design and detail design.

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