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DEFINING PLAN METRICS FOR MULTI-AGENT PLANNING WITHIN MECHATRONIC SYSTEMS

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ABSTRACT

The paradigm of self-optimization introduces flexible systems of objectives to the area of mechatronics. From this flexiblity new coordination problems arise. Such a problem is the coordination of function modules in such a way that the overall system of objectives is met as good as possible. Multi-agent planning offers mechanisms to provide this coordination. In this paper we introduce the application of an established method from the area of decision analysis (value tree anaylsis) to define a common and coherent system of plan metrics for the multi-agent based coordination of function modules. The application of this approach is demonstrated on example of function modules within a railway vehicle.

1 INTRODUCTION - SELF-OPTIMIZATION

Advancement in information and communication technology opens fascinating perspectives for mechanical engineering: mechatronic systems with inherent partial intelligence. Typical system characteristics are autonomous reaction to changing situations, self-coordinating by planning in teams and communication. We use the term self-optimization for such systems. Self-optimization enables mechatronic systems to react independently and flexible according to changing operating conditions. A self-optimizing system determines its currently active objectives on the basis of the encountered influences. For example, while a rail system is in normal operation mode the objectives include a high level of comfort and minimal power consumption. Self-optimizing systems are able to adapt their objectives autonomously. This includes modifying the relative weighting of the objectives. Adapting the objectives must result in an adaptation of the system behavior. To determine the suitable adaption of the system behavior, the objectives are used to formulate corresponding optimization problems. The solutions of the optimization problems indicate the suitable behavior adaptation. This is realized by adapting parameters (e.g. changing a control parameter) or the structure of the system (e.g. replacing the current controller). We express self-optimization as a sequence of

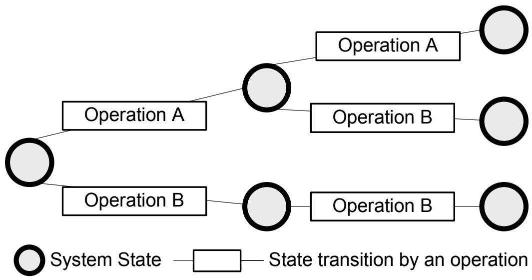

Figure 1. STATE SPACE DIAGRAMM OF A PLANNING PROBLEM

three actions that are generally carried out repeatedly:

1. Situations Analysis: Situations include the state of the system itself and all the observations that have been made about its environment. Such observations may also be made indirectly by communicating with other systems.
2. Determining the system of objectives.
3. Adapting the system behavior according to the new objectives.

This sequence of actions is called a self-optimization process. From a given initial state, the self-optimization process passes, on the basis of specific influences, into a new state, i.e. the system undergoes a state transition.

2 PLANNING IN MECHATRONIC SYSTEMS

We refer to the task of determining a sequence of operations which is able to fulfill a job assigned to a mechatronic system as planning. A job has to be understood as an instance of the overall function of the system, e.g. for a vehicle to transport a good from place A to place B or for a machining center to machine a given material in a specified manner. Self-optimization enables mechatronic systems to implement different sequences of operations to fulfill a job. The system has to chose the sequence depending on the current system of objectives. Since planning determines the sequence in advance, this technique is especially interesting for all applications where the application of certain operations may block the later application of other operations due to its influence on the environment and system state. This is always the case when we introduce limited resources like battery capacity. Here, planning extends the situation analysis in the self-optimization process to future states and influences.

The most intuitive interpretation of the general planning problem is given by a state-space diagram. A state-space diagram visualizes possible sequences of activities - in case of mechatronic systems called operations - and states in form of a tree (fig. 1). A plan metric (a quality function) depending on achieved states and applied operations is used to evaluate the plan. A simple example of a plan metric is the energy consumption of the operations, which depends on the intermediate state in which an operations is performed. The planning procedure tries to find the sequence of operations that fulfills a job with minimal energy consumption. To create a plan an appropriate modeling of the activities and possible states of relevant parts of the system and the environment is required. If such a model is available common planning procedures like state-space search or plan-space search can be applied to generate a feasible plan.

2.1 Multi-agent Planning

Multi-agent systems (MAS) and agent based systems are recognized as a new approach to the control and coordination of mechatronic systems (cf. [1, 2]). MAS are concerned with the coordination of the behavior of several autonomous, partially intelligent systems, called agents [3]. Multi-agent planning is rarely used in mechatronic products today, although it is applied to many other real world applications, like Mars missions [4], production control [5], and logistics [6]. Multi-agent planning is commonly defined as the combination of planning and coordination [7]. There are several approaches to create plans for the multi-agent planning problem. Boutilier and Brafman introduce an extension of classical planning, which is able to consider concurrent, interacting activities [8]. Their approach is centralized and requires a central model of the planning problem, which is not suitable for mechatronic system with buy parts, which have to be treated as black boxes. A more suitable approach is Generalized Partial Global Planning (GPGP) [9]. In GPGP each agent constructs an individual plan in order to achieve its goals. In order to improve the coordination agents can exchange their individual plans. An agent that has knowledge about more than one individual plan generates a so called partial global plan and can use this information to coordinate the individual plans by altering them. The alteration of plan is driven by relations between the planned activities of the agents. An example of such a relation is *facilitate* where the execution of an activity A facilitates the result of an activity B. The coordination tries to maximize positive relationships and minimize negative relationships between the local plans. An extension of GPGP is presented in [4]: Shared Activity Coordination (SHAC). SHAC interleaves the plan coordination and plan execution. Therefore it introduces a so called commit window for every activity. All coordination regarding an activity has to take place before the commit window is expired. Both GPGP and SHAC operate on single activities. This approach implies that the activities are rather independent and the alteration of an activity cannot interfere with the execution of other activities. This assumption cannot hold true for the coordination and planning in function modules.

3 PROBLEM STATEMENT

In [10] we introduced a multi-agent planning concept for the coordination of function modules within a mechatronic system.

The planning and coordination problem encompasses the following elements:

The set of mechatronic function modules M
The set of possible operations of MFM m O_m
The set of possible modes of operation per operation O_{om}
The set of objectives Ω
$weight : \Omega \rightarrow [0,1]$, with $\sum weight(\omega) = 1$, a function denoting the importance of the objectives
$eval : \Omega \rightarrow [0,1]$, a function denoting how good an objective is achieved

Figure 2 illustrates the overall concept of our multi-agent planning approach. It is split up into two separate phases. The first phase is the initial local planning in which each MFM constructs a local plan. The second phase encompasses two interacting processes. The first process improves the coordination between MFM. In a first step, each MFM evaluates the quality of its local plan regarding the plans of the residual systems and estimates the coordination potential. Based on the coordination potential a single MFM is selected to rebuild its local plan in such a way, that the coordination is improved. Afterwards the evaluation has to be updated and the next MFM is selected for rebuilding the plan. In order to limit the computational effort and to be able to interleave the coordination with plan execution, both evaluation and plan rebuilding operate on a limited planning horizon which has to be selected depending on the nature of the interaction between the activities of the MFM.

The second process in the second phase is the plan execution. It starts operations in each time period according to the current plans. To uncouple the plan execution and the plan coordination a so called frozen zone is introduced, in which the coordination is not allowed to make any changes. Thus coordination is limited to the activities in between the frozen zone and the planning horizon. In order to implement a planning approach as sketched, it is necessary to provide the MFM with information about the interaction of activities. This information is provided in a black box manner - each MFM only requires knowledge about which MFM can perform which operations in which mode and how the activities interact according to the possible system objectives. The black box modeling helps to divide the modeling into independent sub processes and increases the flexibility of the overall system. A cooperative behavior is achieved by integrating the knowledge about the interactions in the quality function of the planning procedure. Thus the quality function encompasses two different aspects: the local objective achievement and a social component. Both local goal achievement and the social component are modelled in terms of a plan metric. The social metric of a certain mode of operation within a step t in the plan is determined by:

$$qual(om_t) = \sum_{m \in M} \sum_{om \in OM_m} = weigh(\omega) \cdot eval_{\Delta}^{\omega}(om|om_t)$$

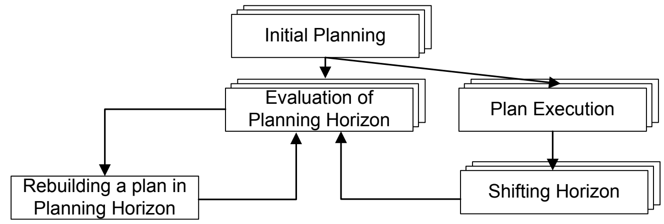

Figure 2. PLANNING PROCESS

Here om_t denotes the application of an operation mode in the t-th step in the plan. The term $eval_{\Delta}^{\omega}(om|om_t)$ denotes the difference in the achivement of objective ω regarding the operation mode om of module m, if om_t and om are executed at the same time. The definition of the social quality of local plans requires the proper definition of a common system of objectives. On the one hand this common system of objective must reflect the possible objectives of the overall system - otherwise the definition of a social quality function in the local planning process is meaningless. On the other hand, the system of objectives must be interpretable on the level of mechatronic function modules. Thus, two main tasks have to be solved: identify possible objectives and identify relations between the objectives. Another prerequisite of the multi-agent planning for mechatronic system is the comparability of the evaluation functions. Without comparability no reasoning about synergies and conflicts between the modules is possible. The modelling of the relation between operations relies on normation of the achievement of objectives to the intervall [0..1].

4 IDENTIFYING OBJECTIVES IN THE EARLY DESIGN PHASES

The design of self-optimizing systems is a challenging task. Established development methodologies in classical mechanical engineering [11] and mechatronics (cf. VDI Guideline 2206 ”Design methodology for mechatronic systems” [12] for instance), are not sufficient in the context of self-optimization. Particularly the early phases ”planning and clarifying the task” and ”conceptual design” are not sufficiently supported. These phases result in the principle solution which specifies the basic structure and the fundamental mode of action of the system. Information obtained in the early design phases may be used to derive elements of MAS planning problem definition. The principle solution is described in a domain-spanning manner by a system of coherent partial models (fig. 3). Thus, the specification of the principle solution forms the basis for communication and cooperation of specialists from the domains mechanical engineering, control engineering, digital electronics and software engineering in the course of the further concretion of the system [13].

The first step in development process is to analyze and describe the system's task. Next, the environment in which the system will work is analyzed and a model of the environment with relevant influences is built up. Simultaneously, the external objectives of the system are identified. These objectives result from the environment, the user or other technical systems and according to this, are introduced from outside the system. For example, this could be the time limit for the execution of a certain system-operation, preset by the user. The objectives are structured hierarchically in a system of external objectives.

Based on the model of the environment, consistent combinations of influences are formed, which are described as situations. By combining typical situations with system states, application scenarios are arising which specify a cut out of the total functionality of the system to be developed. The results of the previous steps will be documented in the list of requirements in the form of requirements and wishes. The functions which have to be accomplished by the systems are extracted from the requirements. To realise the functions, solution elements and respectively solution patterns are searched, which depend on physical effects or on principles of information technology. With the help of consistent combinations of solution elements and solution patterns, the active structure is build up. The active structure contains the linked system elements and represents the basic structure of the systems. Concurrently first approximate models of the shape and the system behaviour occur. Usually, the inherent objectives of the system arise from the active structure. Inherent objectives reflect the design purpose of the system and provide its functionality. For example, this could be a minimum wear of the system. The objectives are also structured hierarchically in a system of inherent objectives.

The set of the partial models represents the principle solution. It is the basis for the domain-specific design processes of the subsequent concretion. The previously identified external and inherent objectives are the basis for internal objectives of the system. Internal objectives represent the actual objectives pursued by the system. They are generated at run-time by dint of selection and weighting of external and inherent objectives and form the system of internal objectives.

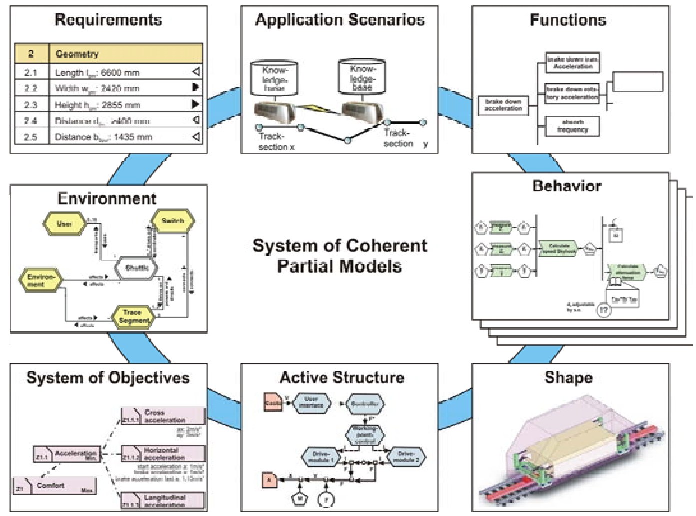

Figure 3. SYSTEM OF COHERENT PARTIAL MODELS FOR DESCRIBING THE PRINCIPLE SOLUTION OF A SELF-OPTIMIZING SYSTEM

5 VALUE TREE ANALYIS

The value tree analysis (VTA) is an integral part of decision analysis. It has a long tradtion in business and management and a solid basis in multiattribute value theory [14]. Although this area of research is clearly focussed on business and management issues, it offers a systematic approach to determine meaningful weighting of objectives and a unified measurement for the achievement of objectives for self-optimizing mechatronic systems.

This section gives a short introduction into the well established area of decision analysis and describes the overall process of value tree analysis. The application of the VTA to a new area of application - distributed decision making in mechatronic systems - is illustrated in the next section.

VTA is about decisions and objectives and defines these and related terms in a detailed fashion. Firstly, objectives are defined as "statements of something that one desires to achieve" [15]. They are divided into two classes: fundamental objectives characterise an essential reason for interest in a decision while mean objectives are only of interest, because they are means to achieving fundamental objectives. The level of achievement regarding an objective is measured in terms of an attribute. An attribute $X(a) = x_i$ indicates to which level the objective O is achieved in decision alternative a. The possible outcome of the attribute are called performance level. A number of attributes $X_1, X_2, ..X_n$ create a mapping from the decision alternatives into an n dimensional consequence space $C = C_1 x C_2 x ... x C_n$. To enable the comparison of decision alternatives the definition of the consequence space is not sufficient. In addition preferences are required. Preferences determine if a decision maker prefers a certain outcome compared to another outcome [16]. To derive preferences without comparing all possible outcome concerning their preference relations, value functions are introduced. A value function v assigns a number $v(x)$ to each consequence $x = (x_i, x_2, \ldots, x_n)$ where x_i is a level of attribute X_i such that the numbers $v(x)$ indicate the relative desirability of the consequence and can be used to derive the preference of alternatives. The definition of preferences strongly relies on the mathematical foundations of utility theory.

Figure 4 shows the process of value tree analysis. The first phase, problem structuring helps to understand the nature of a decision problem. In several subphases the problem structuring provides answers to the following questions:

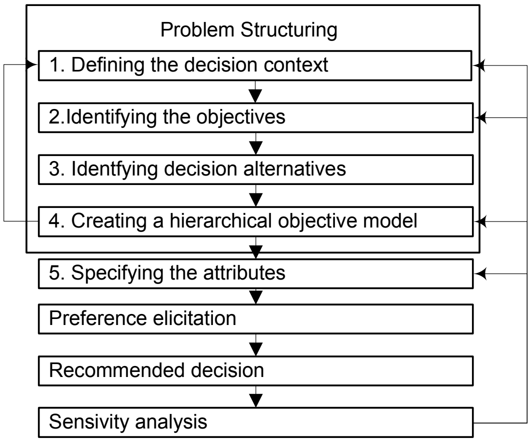

Figure 4. PHASES OF VALUE TREE ANALYSIS

1. What is the setting in which the decision occurs?
2. What are the relevant objectives in the decision problem?
3. What are the relevant decision alternatives?
4. What are the relations between the objectives?
5. How to measure the achievement of an objetive?

The setting of a decision encompasses the enviroment, the people, and systems affected by the decision. The objectives identified in the second steps are divided into fundamental objectives and mean objectives. Decision alternatives describe all possible decisions the decision maker may chose. Relations between the objectives are defined in terms of graph representation. The model is splitted into two parts. The first model, the fundamental objective hierarchy, describes the relation between fundamental objectives. Here, only tree like structures are allowed and every fundamental objective in the hierarchy is exhaustively defined by its child nodes. The second is the mean ends networks. Mean objectives may be connected to more than one parent node and do not necessarely give an exhaustive description of their parent nodes. Figure 5 illustrates the hierarchical model of the relations between objectives. If these questions are adequately answered, decision recommendation requires a unified measure of objective achievment to compare the decision alternatives. This unified measure is provided by utility theory and the aim of preference elicitation is to measure and estimate the prefereneces over a set of objectives.

6 APPLICATION OF THE VALUE TREE ANALYSIS TO DEFINITION OF THE COORDINATION PROBLEM

Value tree analysis offers a process to determine important aspects of the multi-agent planning problem defined in [10]: Determining the objectives, the weighting of the objectives, and the utility functions. Some special features have to be considered. The definition of the decision context should include the user, owner and the environment of the mechatronic system. From their interests and influences the objectives have to be determined. Furthermore, objectives should be determined on both levels: the mechatronic systems and function modules. Most objectives of the function modules will naturally be mean objectives, thus also the attributes should be defined on the level of function modules. The decision alternatives in the multi-agent planning problem are the operation modes, more precisely the set of decision alternatives is the cartesian product overall sets of operations modes. Of course the definition of operation modes should be influenced by objectives and an operation mode should intend to achive a high level regarding a subset of objectives. For the definition of the hierarchical model of objectives a combined top-down and bottom-up approach seems suitable. The starting point for definition should be a set of individual models for both the overall system and the function modules. The task of hierarchical model construction is then to connect these submodels in an appropriate fashion. Attributes should be measurable on the level of mechatronic function modules. Otherwise an evaluation of the decisions made is not possible.

6.1 Application Example

An important application example for the work in the Collaborative Research Centre 614: “Self-optimizing concepts and structures in mechanical engineering” is the RailCab system that is developed within the project “Neue Bahntechnik Paderborn” (NBP) [17]. The RailCab system consists of small autonomously driven rail-bound vehicles that are driven by a doubly fed linear motor. The vehicles encompass several innovative subsystems (MFMs) that are designed to perform specific tasks. Each subsystem has its own information processing to enable special self-optimization techniques. However, their tasks and behavior are not independent from each other. To coordinate the MFMs, multi-agent planning can be used. Here we focus on the coordination of three subsystems: the driving module including the adjustment system that controls the air gap between the stator at the track and the secondary motor part in the vehicle, the active suspension module and the power supply module.

6.1.1 The Function Modules The propulsion system of the RailCab vehicles is realized by a doubly fed linear drive [18]. The linear drive is comparable to a sliced asynchronous three-phase induction motor. The primary motor part called stator is installed between the rails. The secondary motor part is mounted to the vehicle. The main idea is to enable the operation of RailCabs with different velocities on the same stator section. Furthermore the drive is able to transfer power from the stator into the vehicle, which leads to the omission of overhead contact lines or conductor rails. The self-optimizing Air Gap Adjustment System (AGAS) is an extension for the linear drive [19]. Its task is to optimize the drive’s efficiency or its propulsion force by adjusting the motor's air gap. Additional actuators move the secondary motor part vertically, which is suspended by mechanical spring elements, depending on the system's objectives. Reducing the air gap increases the efficiency of the motor and reduces the current needed to generate a defined propulsion force. Otherwise the propulsion force can be maximized by a given power consumption.

The primary power supply of the on-board electrical system of the RailCab is the power transfer via the doubly fed linear motor. However, this power transfer is dependent on the operating conditions, thus it may be limited and to some extend not sufficient. To offer a continuous power supply of the function modules of the RailCab, a hybrid power supply module (PSM) is installed on the vehicle. It consists of a combination of NiMH batteries and double layer capacitors. Its main task is to compensate for the difference between the transferred power of the motor and the demanded power of the modules [20, 21].

The RailCab vehicles feature an active suspension module to increase the comfort for the passengers. The basic idea of this suspension system is to omit passive dampers as they would transmit high-frequency disturbances from the railtrack to the coach body. So the body is connected to the carriage only via springs. The necessary forces to damp the coach body movement are generated by displacing the spring bases via hydraulic cylinders depending on the current movement of the body.

6.1.2 Decision Context

Information gathered during the early phases of design, like the enviromental model or the list of requirements help to define the decision context. For the application example of a RailCab vehicle the elements of the decision context can be defined as follows:

Decision Problem: Which operations are carried out by the mechatronic function modules?
Decision Maker: Planning agents representing the mechatronic function modules
Stakeholders: Operator and passengers
Technical Context: System's state and enviroment's state

The relevance of the operator, passenger and the system's state and enviroment's state imply, that the definition of a value tree and the system of objective is situation dependent. With new operator or passenger as well as for changing states a new system of objectives has to be defined. The redefinition will be limited to changes in the weighting of objectives and in some cases modification in the preference definition.

6.1.3 Objectives

On the level of the vehicle we are able to identify the objectives in the decision problem. The decision makers in the context of a RailCab vehicle are the planning agents representing the mechatronic function modules. Their

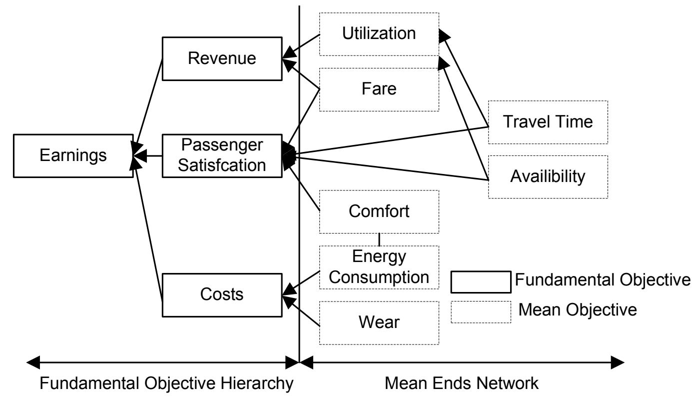

Figure 5. HIERARCHICAL MODEL OF OBJECTIVES OF AN RAILCAB VEHICLE

principal is clearly the operator or the owner of the vehicle. Thus, the overall fundamental objective most reflects the interest of the operator. In commercially used vehicles this interest is usually to maximize the earnings. To achieve this objective in the long-term, the objectives of the stakeholder passenger cannot be ignored. Thus, we idenfied a first mean end network in fig. 5. The first and second level of the network contain fundamental objectives, while the last level contains mean objectives which are only included because of their relevance towards the fundamental objectives. To maximize the earnings of a vehicle, the costs have to be minimized, the revenue maximized, and passenger satisfaction maximized for long-term issues. The means to achieve this objectives is maximization of fare and utilization (revenue), the minization of energy consumption and wear (costs), and the maximization of comfort and the minimization of fare and travel time (passenger satisfaction).

The same process of objective identification is performed for each relevant function module in the RailCab. Naturally the objectives on the level of function modules tend to be be more specific and more technical.

The optimal **drive module** possesses two fundamental objectives. The first one represents the *maximization of the power transmission*. The *maximization of the propulsion / brake force* constitutes the second objective. For instance a maximal force is needed for the vehicle's acceleration within a station or for an emergency stop. The AGAS extending the drive module also features two fundamental objectives. The objective *maximize propulsion force* is achieved by an adjustment of the secondary motor part to a minimal air gap. In that case, the system's consumed adjustment power is not influencing the objectives evaluation. This results in an increasing propulsion or brake force, but also in extra power consumption. The *maximization of the drive's efficiency* is another objective of the AGAS. A minimization of the air gap and a minimization of the needed energy for the adjustment are the mean objectives in order to achieve an optimal drive's efficiency. The objectives of the optimal drive, which consist of the drive module and the AGAS, can be condensed to three fundamental objectives as shown in fig. 7.

An optimal **power supply module** has to absorb excess or deliver lacking power of the on-board electrical system to ensure the unrestrained functionality of the other modules of the RailCab while keeping the costs at a minimum. Thus, the fundamental objectives of the PSM are *balance the power of the on-board electrical system* and *minimize costs*.

The fundamental objectives of the **active suspension module** are *maximizing the riding comfort* for the passengers while *consuming a minimum amount of energy*. Also the *maximum needed power* is to be minimized or at least to be kept beneath an acceptable limit.

6.1.4 Decision Alternatives

The operation modes of the AGAS within the **drive module** can be differentiated by the frequency of the adjustment per track section and the concurrent vertical acceleration. During the first operation mode the air gap is adjusted *once per section*. In the majority of cases this mode is used for unknown track sections in order to adjust to a safe air gap. Neither a higher efficiency of the drive, nor a higher propulsion force can be achieved by the usage of this mode. Also this mode features two characteristics of acceleration. The adjustment of the air gap is usually performed with a low vertical acceleration, only in case of an emergency it also can be adjusted with a high acceleration. The next mode *moderate adjustment* can be used regarding the displacement of the stators in order to increase the drive's efficiency as well as the propulsion force. The pertinent acceleration is chosen depending on the persuaded objective. This mode features low and medium acceleration. The *continuous adjustment mode*, which is the third mode, features all three kinds of acceleration. If the objective maximization of the propulsion force is persuaded, the continuous adjustment is executed with a high acceleration. In this case a small air gap can be achieved, but also the consumed energy for the adjustment increases. A smaller air gap is also achieved by a lower acceleration, but for the persuading of the objective maximization of the drive's efficiency the consumed adjustment energy should be minimized. Figure 6 shows the different modes and their possible characteristics.

	Acceleration Characteristic		
Adjustment Mode	low	medium	high
M1: once per section	X	- - -	X
M2: moderate adjustment	X	X	- - -
M3: Continuous adjustment	X	X	X

Figure 6. MODES AND ACCELERATION CHARACTERISTICS OF THE AGAS

The **energy supply module** can operate in five different modes of operation: *absorb high power*, *absorb low power*, *deliver high power*, *deliver low power* and *inactive*. In *absorb high power* and *deliver high power* mode, a high amount of excess or lacking power from the on-board electrical system will be compensated for by the PSM. Thus, the currents of the PSM are high as well as the stresses to the storage devices. In modes *absorb low power* and *deliver low power*, lower amounts of power are compensated for. In mode *inactive*, the PSM does not interact with the on-board electrical system. The matching mode of operation has to be chosen by the power demand of the on-board electrical system.

In order to pursue its different objectives the **active suspension module** has three basic modes of operation, called *inactive*, *active* and *active with compensation*. Using the *inactive* mode consumes least amount of energy as the suspension system only carries the body without generating any damping forces. This mode can be used on very smooth tracks, however the riding comfort on rough tracks would be rather poor. The *active* mode induces damping forces to the coach body depending on its absolute movement and on the relative movement between the body and the carriage. This is the usual operating mode of active suspension systems. However, the riding comfort can be increased even more by compensating for track excitations that are retrieved from the information processing located at the track before the vehicle passes the track section in view. This is done using the mode of operation called *active with compensation*. Each mode of operation can be divided into submodes depending on the choosen level of the hydraulic supply pressure. For three pressure levels (*low*, *medium*, *high*, e.g.) this yields a total of nine modes of operation for the active suspension module.

6.1.5 Hierarchical Model of Objectives

A combined top-down and bottum-up approach is used to define the hierarchical model of objectives. The upper part of the hierachical model is defined by the objectives of the overall system as shown in fig. 5. The lower-levels of the models are given by objectives of the function modules. These partial systems have to be integrated in order to define the value tree of the RailCab coordination problem. The first step to do so is to remove all objectives from the hierarchy, which are not influenced by modes of the function modules. In the network in fig. 5 this is clearly the case for *fare*. Thus it is removed from the hierarchy and will be modelled as part of the decision context. The next step is the definition of seperated hierarchies for the overall system and each module. This *divide&conquer* approach enables a straight forward definition of the objective hierarchies. Figure 7 shows the hierarchical models of the function modules.

The hierarchy of the **optimal drive module** contains the

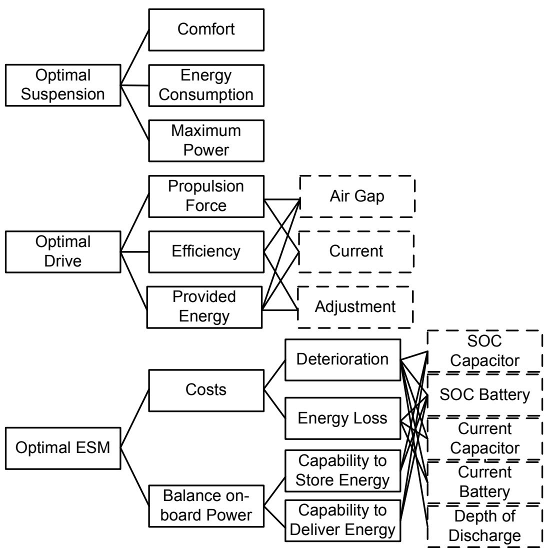

Figure 7. HIERARCHCIAL MODEL OF THE FUNCTION MODULES

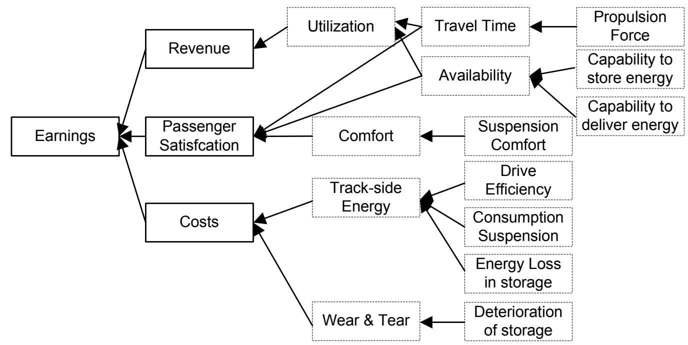

Figure 8. INTEGRATED HIERARCHICAL MODEL OF A RAILCAB

three fundamental objectives *maximize propulsion force*, *maximize drive's efficiency*, and *maximize energy transmission*. The fundamental objective maximize propulsion force can be split up into the mean objective of the AGAS *minimize drive's air gap* and the mean objective *maximize drive's current*, which is persuaded by the drive module. Furthermore the objective maximize drive's efficiency consists of the mean objectives *minimize air gap* hand *minimize the consumed energy* of the AGAS. Finally the third objective maximize transmission of energy can be subdivided into the mean objectives *minimize the drive's current*, *minimize the air gap*, and *minimize consumed energy*.

The optimal operation of the **power supply module** can be obtained by *minimizing the costs* of operating the storage and by *maximizing the ability to balance the on-board electrical power*. The first objective "costs" can be split up into the *deterioration of the energy storage*, including maintainance and investment expenses, and the *power losses* while accumulating and delivering energy. The second objective "ability to balance" can be divided into the *ability to absorb excess power and to deliver lacking power*.

The objective hierarchy of the **active suspension module** contains only its fundamental objectives: Maximize the *comfort*, minimize the *energy consumption* and minimize the *maximum power* on the track section in view. No additional mean objectives are needed because the different modes of operation directly affect these fundamental objectives.

Finally, the several models have to be integrated. For this integration, the objectives from the vehicle hierarchy and the module hierarchy are matched against each other. If an objective from a module matches an objective from the vehicle hierarchy, it is connected to vehicle objective. A module objective matches a vehicle objective if it is a mean to achieve the vehicle objective. Consequently the module objective is connected as a mean to the vehicle objective. The residuary hierarchy beneath the module objective is not changed. In this manner the integrated hierarchical model for the RailCab is defined as shown in fig. 8 (due to the lack of space only the first level of the module hierarchy is shown).

6.1.6 Specifying the attributes

In order to realize the mean objectives of the optimal **drive module** three measured or calculated attributes are used. The directly measured *consumed energy* for the adjustment is the first attribute. It is calculated by the temporal integral of the power during adjustment. The *current air gap*, which is the second attribute, can be measured by a sensor. Another attribute is the *propulsion force*, which cannot be measured directly without any considerable expenditure. A calculation, which is based on the current speed, the elevation profile of the track, the vehicle's mass, its velocity, and the drive's current, delivers the effective propulsion force.

The realization of the mean objectives of the **power supply module** can be determined by different attributes. The deterioration of the energy storages can be estimated by electrical values like *storage current or voltage*, *depth of discharge* and *state of charge*. The ability to balance the on-board electrical system can be calculated by the *state of charge* of both the NiMH battery and the double layer capacitor.

To get numerical values for the objectives of the **active suspension module** also special attributes are chosen. A typical measure for the riding comfort is the *frequency filtered acceleration* of the coach body. It is used for the lateral and vertical movement of the coach and its rotation around the longitudinal axle. The attributes for the second objective (minimizing the *energy consumption*) and the third objective (minimizing the *maximum power*) can be directly measured and calculated respectively. The energy needed for the active suspension system on a specified track section is a measure for the second objective, as

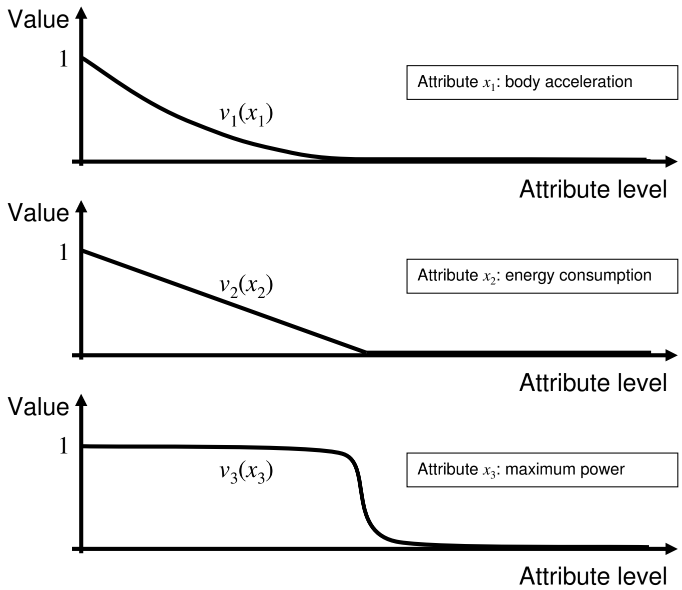

Figure 9. VALUE FUNCTIONS FOR THE ASM

well as the maximum needed power on that track section gives a measure for the third one.

6.1.7 Preference Elicitation

For each attribute a value function has to be given to calculate the total value of a selected alternative based on a specified situation. The shapes of the value functions depend on the attibutes. Figure 9 shows examples of value functions for the active suspension module, which were chosen because of the representive shapes. The time integrated frequency weighted accelerations of the coach body X_1 as a measure for the riding comfort should be minimized. No accelerations at all mean the absolute optimum, so the value function $v_1(0)$ yields 1 in that case. When exceeding a certain level (depending on the length of the track section in view) the riding comfort is as very poor so that the value function yields 0. The shape of the value function in between can be designed by the developer of the system, here a quadratical shape is chosen. The value function of the energy consumed for the suspension system on a given track section as second attribute X_2 is linear between 0 and a maximum possible value as in a first step the energy can be assumed proportional to the costs. The third objective (minimize the *maximum power*) is more like a constraint than a real objective. The maximum power required by the active suspension module on a track section must not be exceeded. Therefore the value function for the third attribute X_3 is nearly set to 1 as long as the maximum power is not exceeded and set to 0 otherwise.

To complete the preference elicitation, the weighting of all objectives is required. The weighting has to be done in such a way, that the weights of all children of objective sum up to one. An interesting example is weighting of the mean objectives for *track side provided energy* in fig. 8. The main part of the *track side provided energy* arises from the energy consumption on the vehicle - in our example represented by the consumer active suspension module. Thus this objective has the highest weight (0.8) regarding the *track side provided energy*. Both, drive efficiency and energy loss in the storage have minor influence to *track side provided energy* - they can only reduce the consumed energy by a certain percentage. Thus, the residual weight is evenly splitted up between them.

6.1.8 Application to the MAS Planning Problem

Self-optimizing mechatronic systems are able to consider external objectives. With the fundamental objective hierarchy of the overall system an interface towards external systems or humans is defined. An external system or user has the possibility to select its indiviual weighting of selected level in the fundamental objective hierarchy. With this input, the system is able to calculate the importance of all mean objectives by multiplying the weighting along all paths towards a mean objectives and summing up the weighting of every paths. Finally, the results of VTA provide the elements of the MAS planning problem:

The set of objectives Ω is defined by the set of mean objectives
$weight : \Omega \rightarrow [0,1]$, with $\sum weight(\omega) = 1$ is the calculated weight of the mean objectives
$eval : \Omega \rightarrow [0,1]$ is defined by the value function

The VTA provides the common system of objectives and the comparability of the level of achivement overall objectives. Thus, the interactions between the modes of operations and hence the social metric of every mode of operation in every planning step can be calculated.

7 CONCLUSION AND FURTHER WORK

From our work and experience in the CRC 614 we suggest MAS planning techniques as a suitable means to coordinate function module within a mechatronic system. Our approach prerequisties the definition of a common system of objectives over all function modules and the comparability of the level achievement of different objectives. Thus, we introduced the application of value tree analysis (VTA), a method well established in business and management. The application of VTA to the problem of proper objective definition in mechatronic systems was exemplified through an application example.

The process of VTA is less linear then described here. Actually, the definition of modes of operations, mean objectives and attributes required several iteration. These items are so closely related and influence each other, that such iteration are unavoidable.

Further work mainly concerns the support of the VTA process. There are several software packages which support the VTA process (cf [22, 23]). Like VTA itself, they are mainly applied to business decision making. Thus, they do not suffiecently support the VTA process for the objective definition in mechatronic products. For instance they do not support a combined bottom-up/top-down approach and most methods for the preference elicitation support only discrete attributes. The VTA process, especially if performed in a team of engineers, can be handled much more efficiently with a software application specially implemented for this use case. This software application should especially feature continuous value functions, technical attributes and a cooperative bottom-up/top-down approach. Functions for the support of dicussion in the team of engineers are crucial.

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