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OPTIMIZATION OF MECHATRONIC SYSTEMS USING DEPENDABILITY ORIENTED DESIGN METHODS

The research project "Railcab" designs a shuttle-based transportation system, which combines innovative mechatronic technologies with existing railway tracks. The traction and braking forces are generated by a linear electromagnetic drive while the tracking and guidance is performed using classical wheel/rail technology. By adopting different mechatronic modules, a modular structuring of the overall system, the driving safety, vehicle dynamics and the travelling comfort can be increased.

In the present paper, we concentrate on the development of the active tracking module which reduces the sensitivity of the system behaviour with respect to the friction in the wheel/rail contact. Basic ideas of the tracking module are self-optimizing active tracking, camber adjustment, and mechanical locking device. Based on a-priori identified risks, like e.g. strong cross-wind, frosted rails and crossing of switches, the safety concepts are described in detail together with the methodology that was used in the design process.

1. Introduction

In the field of mechatronic research, the interdisciplinary project "Railcab" (German translation: Neue Bahntechnik Paderborn) was established at the University of Paderborn. A new shuttle based transportation system was developed, which uses innovative technologies from the field of mechatronics and combines them with the existing infrastructure of classical railway tracks. According to the design process of VDI Guideline 2006, a hierarchical structure of the overall systems was developed.

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One of the most distinctive features of the transportation system is the active tracking module, which achieves higher comfort and navigates on passive switches. The reliability and safety of the tracking and guidance module, frequently subsumed under the heading of dependability, is therefore of particular importance for the overall system performance. The paper describes the evolution and present state of the chassis design on the background of mechatronic design principles. In particular, the active tracking module exemplifies the implementation of dependability oriented design methods. To this end, the individual safety concepts for driving on a passive switch are analysed with respect to functional hierarchy and redundancy concepts. Fail-Safe backup levels are defined and their realizations are described in detail.

In order to this introduction the structure of the paper is as follows: We start with a short presentation of the design methodology for mechatronic systems, advanced by a process-approach for "design for dependability". In section 3 we introduce the overall design of Railcab subdivided into most important modules for this paper. Then, regarding to the results from the dependability oriented system design, different solutions for safety are described in detail in section 4 before we conclude the paper.

2. Dependability oriented mechanic system design

Certainly, Railcab is a safety-critical application like any other transportation system. But in particular, there are higher requirements, because of applying new technologies in a field where humans and nature are involved. Thus, the design process has to follow a structured methodology and different methods and concepts from the field of dependability must be applied. One approach to take these methods and concepts into account of a design methodology is given in [3],[4].

2.1. VDI Guideline 2206 on design methodology for mechatronic systems

The VDI Guideline 2206 on "Design methodology for mechatronic systems" deals with the development of a modern mechatronic product in its entirety. The guideline, published by the association of German engineers in 2004, promotes interdisciplinary cooperation, which has proven to be an outstanding factor in the success of the development of mechatronic systems.

The systematic procedure for the design of mechatronic systems can be described by a V Model. It starts with requirements and results in the product. Basic elements inside the V Model are system design, domain-specific design, system integration, assurance of properties, and modelling with model analysis. The logical order of these elements is shown in figure 1. Especially the assurance of properties points up the benefit of the V-shape: requirements and specifications from the phase system design can be verified and validated in different steps of the system integration. Another important aspect in this guideline is the way of structuring mechatronic systems. The V-Model and an example of a hierarchical structure of a mechatronic system are shown in Fig. 1 [VDI 2206].

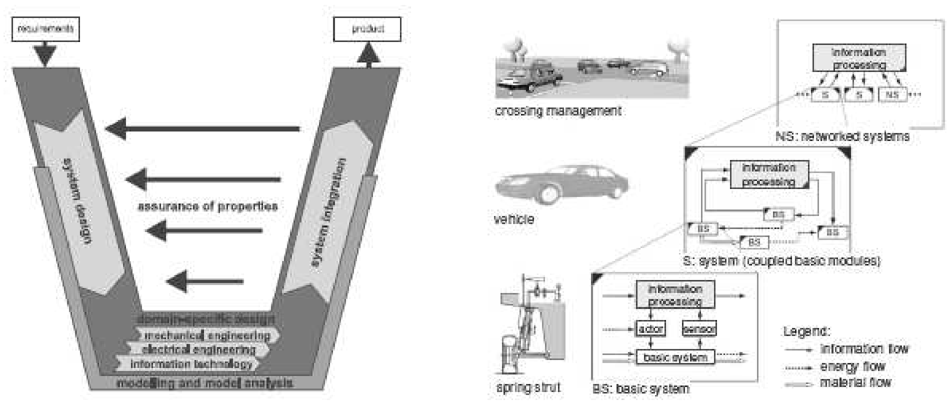

Fig. 1. V Model for the design f mechatronic systems and an example of structuring mechatronic systems [VDI 2206]

2.2. Design of dependability

The "Design for Dependability" bases on aforementioned procedure. The V Model is extended by another V, which takes aspects of dependability into account to the design methodology for mechatronic systems [4].

In detail, the system design is extended by the analysis of dependability requirements, failure-, hazard- and risk analyses and in particular by the conceptual dependability design. Typical methods for these analyses are riskgraphs or failure mode and effects analysis. Last-mentioned aspect of the conceptual dependability design is main topic of the present paper and is explained in-depth in the next sections. In the domain of specific design, the dependability concepts are elaborated. Most important aspects for dependability inside the system integration are analyses for correct cooperation between modules and the prevention of incompatibilities, e.g. methods for testing, verification and validation. Figure 2 shows the "Design for Dependability" .

General concepts for dependability, called dependability patterns, extend the general process mentioned before. They represent the root of the matter for different solutions in the field of dependability. Of course, there are infinite

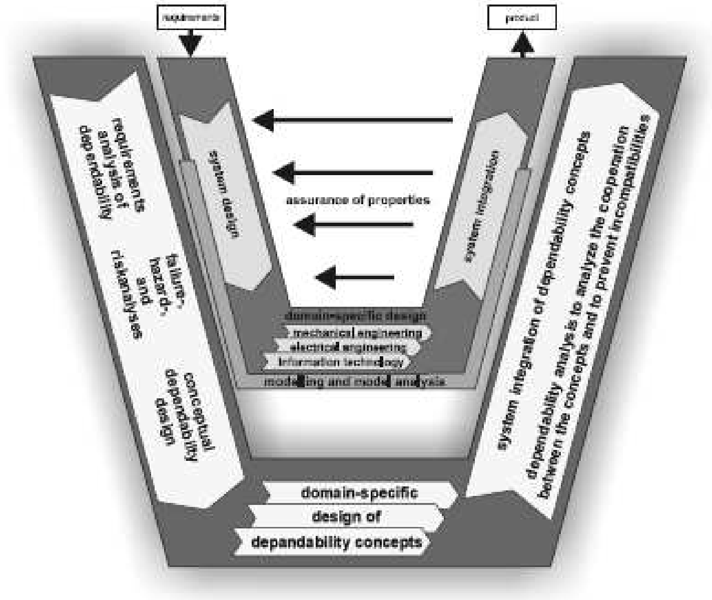

Fig. 2. Design for Dependability

specific solutions for specific problems, but often they base on the same idea. Therefore, dependability patterns result from specific solutions and probably their number is infinite, too. Because of that, this paper can only explain the main categories.

The dependability patterns can be structured by the alternatives to stop fault expansion. The different alternatives result from the cause-and-effect chain for faults by [Laprie 1992]. This chain starts with the fault which stands for the real cause of a problem; then the error could follow. In case of error, the fault has been activated, but a failure is still avoidable. A failure would be the next step in the cause-and-effect chain and would mean that a system is non-operational anymore. Alternatives to stop the fault expansion can be realized before or while the occurrences of faults, errors or failures. The main categories of dependability patterns result from these three opportunities:

- fault prevention – to prevent the real cause,
- fault/error monitoring – to detect an fault/error, diagnose and realize first counteractive measures,
- fault tolerance – to operate the system with all functionalities instead of fault/error occurrence.

A fourth category could be called minimization of consequences, e.g. by using an airbag. But this should not be a part of this paper.

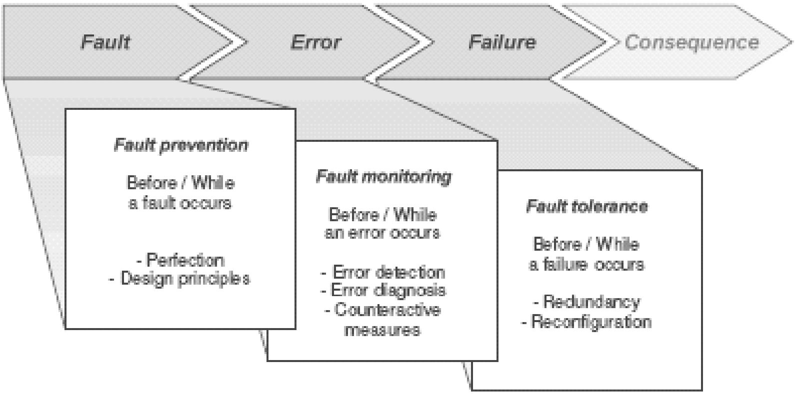

Fig. 3. Cause-and-effect chain for faults extended by concepts of dependability

Aformentioned procedure and especially the approach of the pedependability patterns are used to design the Railcab, which is explained in below.

3. The transport system Railcab

Constantly rising density of traffic volume provides heavy utilisation and up to overload of the road system. The public suburban und long-distance traffic offer the feasibility to solve this problem. But inflexibility and timetable-steered structure of these systems prevent the fulfilment of the requirements from individual traffic. Unfortunately, the common railway-systems still possess obsolete techniques. Therefore, they are not able to extend the utilisation. Due to changeovers, the travelling time is extended.

The Railcab combines the advantages of individual and public traffic. Small autonomous vehicles of van size (called Shuttle) use the existing railway tracks to travel to their destination without changeovers.

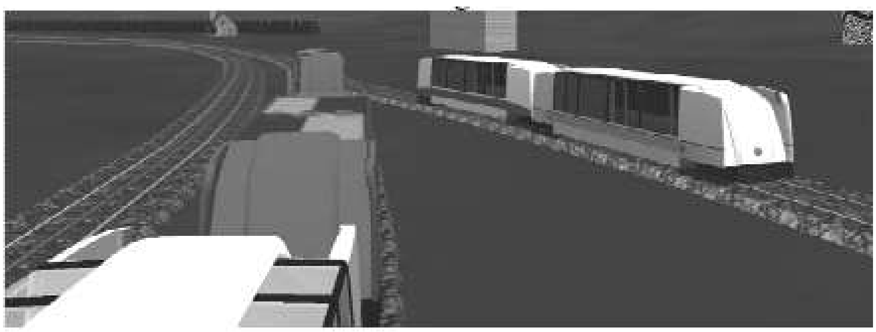

Fig. 4. Railcab convoy at a switch

A loose convoy group accomplish the possibility to individual vehicles to thread and separate independently. This permits an individual and goal-pure route planning of the individual shuttles. Furthermore, the utilisation of the track is increased and maximized in relation to the present systems.

The complete system was hierarchically developed by a consistent implementation of the VDI2206. Thereby, it was divided into individual function modules.

3.1. The design of Railcab

The shuttle structure is based on different mechatronic modules, which are designed according to their function assignment. These individual function modules are both mechanically, and information-technically coupled.

Fig. 5. Modules of Railcab prototype scaled 1:2,5

The drive and brake module consists of two double fed asynchronous linear motors which are located in the vehicle. The counterparts are stator segments laying in the track. This design is also needed for the contactless power exchange between the stator and the vehicle. Thus, results from this design are short force flow chains and signal flow chains as well as a high reliability.

The active suspension guarantees an optimum for the driving comfort. In curves, it is able to tilt the cabin in order to reduce the lateral acceleration for the passengers. Furthermore, it is possible to guide the cabin actively to the platform edge for a convenient boarding.

3.2. Passive switch

The passive switch itself is not a part of the shuttle, but it belongs to the function group "steering". The need for a passive switch results from the requirement of a loose convoy operation. Conventional switches are active and lead vehicles in a given direction. The shifting process takes at least several seconds. However, safety margins must be kept during the shifting processes and between the vehicles.

The distance between two sequential vehicles results in more than 2 km at a travelling speed of 160 km/h. This means that the application of passive switches in combination with actively steering vehicles allows reducing the distance between the shuttles. The switching part of the switch is removed. Through the remaining two open bars, the vehicles have to drive with active steering.

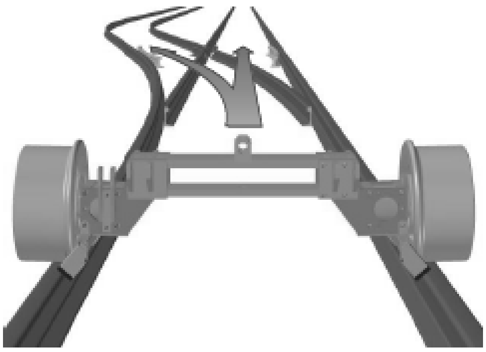

Fig. 6. Active tracking module on a passive switch

3.3. Active tracking module

The subframe carries the sub modules and also the drive and brake module. The Railcab uses single loose and cylindrical wheels to support the active steering and tracking. In opposite to classical train chassis, a self centring by a sinus run is not necessary and, due to losses in comfort and safety, not even preferable. Eddy current sensors detect permanently the position of the chassis in opposite to the rail in order to guide the chassis in such a way that it remains safely in the trace.

If the vehicle approaches a passive switch, the target for the chassis switches from “ideal central position on the trace” to “straightforward travel” or to “turn off”. The chassis orients itself by the right or left bar of the switch. An additional brake will be used for parking, as well as emergency brake.

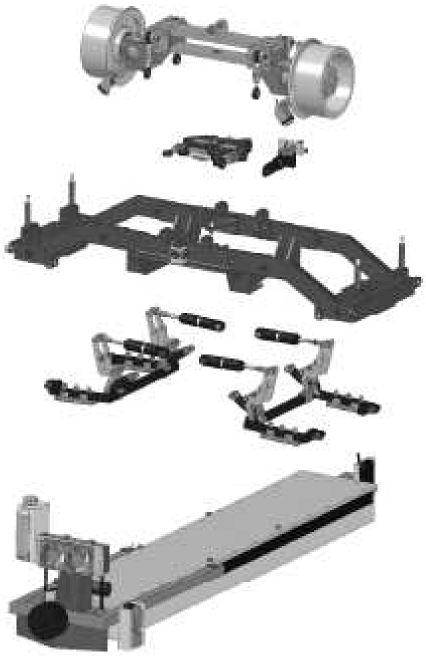

Fig. 7. Exploded sketch of the tracking modul

4. Dependability oriented system design of Railcab

According to the dependability oriented design process, in section 2 we identified several critical items. To adopt these identified hazards, several dependability concepts were used for safety subroutines in all hierarchical level of the control system; some of them with a direct access to the emergency brake. Additionally, an update for the design of the tracking module becomes necessary due to other identified hazards.

The sensors have been identified as a critical item due to dependence of their signals performance to the tracking function. For identifying the position of the axle according to the track, only two sensors are necessary. However, for a classical redundancy concept, four sensors are used. Plausibility queries continuously check the performance of the sensor signals.

A malfunction of the tracking module in the passive switch can cause a derailing of the whole vehicle. Therefore, a “mechanical track locking

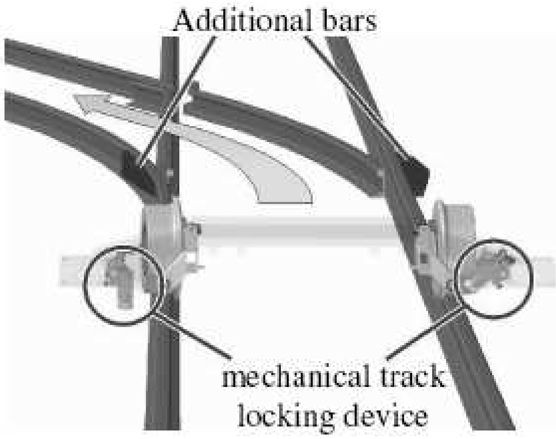

Fig. 8. Steering active suspension in a passive switch

device" was implemented to provide an additional steering as a hierarchical backup level. It will be activated several distances in front of a switch and provides hot standby roller. If the active steering does not work as desired, the boogie will be leaded by an interlocked connection in the given direction.

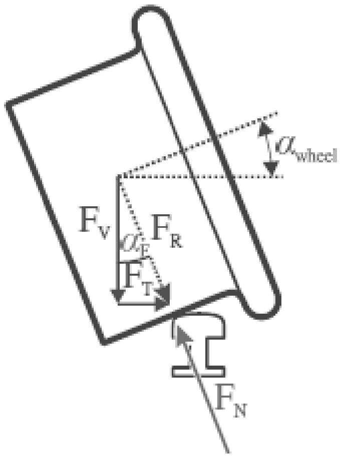

Fig. 9. Forces at the camber adjusted wheel

Another important result of the dependability examination is the influence of the friction between the wheels and the track. The contact point is with railway vehicles of existential importance, because the forces needed for propelling, brakes and leading are transferred there.

Transverse forces arise mainly in consequence of driving along curves. If unfavourable friction conditions exist, then these forces can not be transferred between wheel and rail any longer.

Therefore, the next step was to decouple the dependence of the guidance force from the friction. In case of lateral forces in the tracking module, the camber of the wheels can be adjusted. Since the rails possess a spherical cross section profile, the wheels can support themselves at this. To eliminate the friction in the contact point, the camber has to be adjusted in a way that the angel of the wheel (α_{wheel}, see Fig. 1) is the same as the angel α_F between the resulting forces F_R made of the vertical force F_V and lateral force F_T. With this only normal forces will be transmitted in the contact point.

The necessary angel α_{wheel}, which is needed for the drive through a curve, is calculated out of the formula $\alpha_{wheel} = v^2/rg$, with $v \equiv$ vehicle celocity [m/s]; r ≡ steering radii [m]; g ≡ acceleration of gravity (= 9,81 m/s^2).

The result of these experiences is an active tracing module with camber adjustment, including a mechanical track locking device and four eddy current sensors.

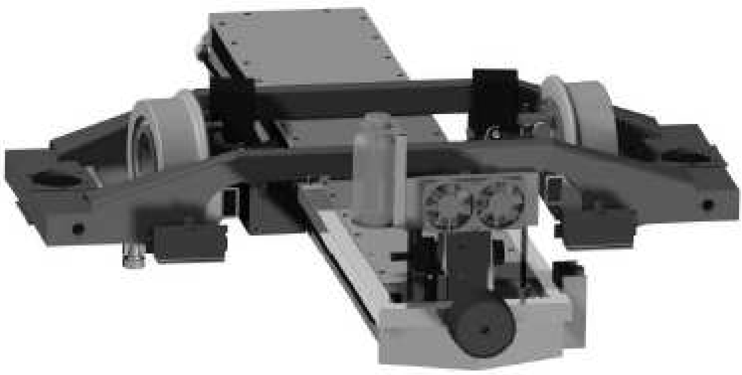

Fig. 10. Active tracking module with camber adjustment

5. Conclusion

In the present paper, we introduced the adoption of dependability methods to the design process of mechatronic systems to guarantee a save and dependable design and furthermore to optimise the systems to the requirements. The outcome, an active tracking module with camber adjustment, was presented.

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Optymizacja układów mechatronicznych z zastosowaniem metodologii projektowania ukierunkowanych na bezpieczeństwo

S t r e s z c z e n i e

W projekcie badawczym "Railcab" zaprojektowano system transportu wahadłowego, w którym połączono innowacyjne technologie mechatroniczne z istniejącą siecią kolejową. Siły trakcyjne i hamujące są generowane przez liniowy napęd elektromagnetyczny, podczas gdy śledzenie i sterowanie jest realizowane przy użyciu klasycznej technologii kołowo-szynowej. Dzięki zastosowaniu różnych modułów mechatronicznych, modularnej strukturyzacji całego systemu, osiągnięto wzrost bezpieczeństwa i komfortu jazdy oraz poprawę dynamiki pojazdu.

W prezentowanej pracy autorzy skupiają uwagę na opracowaniu aktywnego modułu śledzącego, który zmniejsza wrażliwość systemu na tarcie między kołem i szyną. Zasadniczymi koncepcjami, na których oparto działanie tego modułu są: aktywne śledzenie z samoczynną optymalizacją, regulacja pochylenia kół i mechaniczne urządzenie blokujące. Na podstawie zagrożeń zdefiniowanych a priori, takich jak np. silny wiatr boczny, oblodzenie szyn i krosowanie przełączników, sformułowano szczegółowe koncepcje bezpieczeństwa wraz z metodologią, która została użyta w procesie projektowania.