Time-efficient and Accurate Spatial Localization of Automotive Function Architectures with Function-oriented 3D Visualization

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ABSTRACT

A primary challenge in the automotive industry is the continued increasing complexity of modern cars caused by the ever increasing amount of complex vehicle functions. These functions are implemented as mechatronic systems consisting of multiple individual components. A promising, relatively new approach to manage the increasing complexity in the development process is the function-oriented design that focuses on the interdisciplinary, holistic development of such functions. A frequent and important task in function-oriented design is the identification of the spatial distribution of the components and their connections of a specific function. In this paper, we present a very time-efficient and accurate solution to this task. Our solution uses virtual reality 3D visualization methods, based on consistent integration of function-oriented data with CAD data. We evaluated our method in several user studies and the results show that it is capable of fulfilling the task in a much more a time-efficient and more accurate way than the traditional method.

Keywords: Function-oriented Development, Virtual Technologies, Virtual Prototyping, Digital Mock-Up, Spatial Cognition.

1 INTRODUCTION

Today, the ever increasing complexity of modern vehicles is one of the primary challenges in the automotive industry [7],[16]. One significant complexity driver is the high amount of vehicle electronics respectively vehicle functions, like parking assistance, light assistance or start-stop automatic. Such functions are implemented as complex, distributed mechatronic systems, consisting of sensors, actuators and controllers. Implementations of these systems may differ between vehicle projects as well as between variants, configurations, and derivatives within the same vehicle projects. Moreover, new vehicle functions are more and more realized by using components of already existing systems, exceeding the capabilities of traditional component-driven approaches to the development process. A function-oriented approach to the development addresses the many challenges the traditional approach is facing by interdisciplinary implementation of such vehicle functions and systems. This approach complements a component-driven development by extending the overall focus on functions rather than single components. There is growing evidence and awareness in the automotive industry that only such an approach will be able to handle the increasing complexity in automotive development for the foreseeable future [7],[15],[26].

Virtual technologies are interactive, 3D (preferably immersive), computer-based methods for the processing of virtual product prototypes [25] and provide an important tool in the automotive product lifecycle management (PLM) [14],[19][27]. Moreover, virtual technologies help to master the increasing product complexity and they can be beneficial in many aspects like product quality, time-to-market and cost competiveness. A typical field of application is a digital mock-up (DMU), which describes a virtual product model, usually a 3D model based on CAD data, which is used within different areas of the PLM, like design, validation and simulation.

At this stage, however, the capabilities of virtual technologies are not yet fully exploited for a function-oriented development because function-oriented data structures are not yet integrated with geometric CAD data. Traditional methods are not able to provide a holistic view on the data that includes both, function-oriented and spatial, geometric information on virtual prototypes. Thus, in our previous work, we have proposed an approach for consistent data integration of automotive function architectures with CAD models (see Fig. 1) to exploit synergies and to develop novel, improved methodologies and workflows for the development, validation, and servicing of vehicle functions [2-3]. The term *function architecture* denotes, by our definition, a methodology that allows to identify all components that make up a specific function of the vehicle including the connections between these components. So, a function architecture should provide a means to identify all components and electrical connections in the vehicle necessary to implement, for instance, the wipers (a simple example) or the Park Assist (a rather complex example).

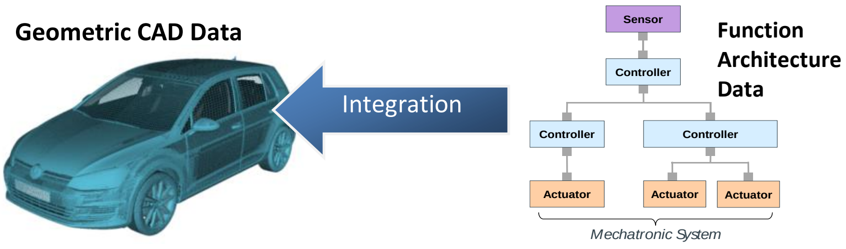


Fig. 1: Consistent data integration of automotive function architectures with CAD models.

In this paper, we build upon our recent approach of data integration. We present a solution to one of the major challenges with function-oriented automotive design: identifying quickly the spatial distribution of a function's components and connections. We have conducted a user study, in which we compared our novel function-oriented methodology with a conventional, currently available method. We present the results and our findings of that user study. In addition, we propose new features for 3D visualization tools that greatly support the function-oriented development process.

2 RELATED WORK

In this section, we review related work in the fields of virtual prototyping and CAD data synthesis, exploring an increasing need for interdisciplinary data integration, standards and interfaces due to the increasing complexity in the automotive industry. In addition, recent research works show that one promising approach in mastering those challenges is provided by 3D visualization methods which enhance information access, communication and cognition of complex product data.

In the manufacturing industries, a typical and established application of virtual prototyping is a digital mock-up (DMU), which facilitates the utilization of CAD models for geometric investigations, such as assembly analysis or collision detection. For example, [21] show how challenges of heterogeneous, collaborative CAD assembly can be handled by DMU approaches. Moreover, approaches like [8], [13] and [19] focus on streamlining interfaces between CAD data and immersive virtual reality environments to enable high-quality rendering and improve immersive design reviews. However, such approaches focus on geometric analyses and do not incorporate function-oriented data.

A functional (digital) mock-up (FMU/FDMU) enhances traditional DMU by integrating numerical simulation models, like those created with MATLAB/SIMULINK, with CAD data to enable visual, functional simulation of product properties [5],[9]. For instance, an FMU framework has been proposed by [20] which helps to shorten development times of multi-domain systems and which allows integration tests at early stages of development. [12] used a wireless, real-time transmission to transfer simulation data to a rich 3D environment creating a comprehensible visualization of such data. Thus, their work assists in validation and presentation of simulation data, especially for non-exports.

In support of mastering the challenges of complex automotive systems, [18] provided a dual-view visualization for exploring functional dependency chains of in-car communication processes, featuring a view for hardware component dependencies and a view for functional correlations. In addition, [17] have proposed a visual tool for exploring and communicating an automotive bus technology to support automotive engineers in the development of car communication networks. As a result, the authors have found beneficial application in utilizing new methods for information visualization in a complex domain, in which the only access to data was textual so far. [22] developed a system for visualizing spatial sensor data to assist in the development of automotive driver-assistance systems based on environmental perception. [6] proposed an interdisciplinary approach to functional prototyping, coupling different simulators to address the necessity of timely simulation, review and debugging of multiple mechatronic components in complex automotive systems. The results indicate that the author’s work allows early functional design reviews and assists in the specification and evaluation of mechatronic systems.

[1] reported a lack in independent standards for model exchange and co-simulation and therefore introduced the Functional Mockup Interface (FMI). This tool-independent standard focuses on the exchange of dynamic models and on streamlining co-simulation to improve collaboration between suppliers and OEMs. Differences, advantages and disadvantages of both concepts, FMU and FMI, have been explored by [5]. The authors highlight the FMU focus on interactive 3D visualization including functional simulation and the FMI focus on efficient co-simulation and model exchange. By the proposal of three options, the authors argue that these concepts can be complementary combined for comprehensive investigation of multi physical systems with promising results.

In the research area of spatial cognition, there are several studies that deal with the differences of 2D and 3D presentation of data and information. Results of [23-24] show that such comparisons strongly depend on the particular context and, in many cases, that a combination of both 2D and 3D visualization can be superior to each variant on its own. The studies in our paper contribute in this field by investigation complex visualization variants both 2D and 3D in the area of electromechanical systems.

While virtual prototyping is beneficial in multiple areas, it concurrently generates particular challenges due the diversity of heterogeneous systems, domains and collaborators involved in automotive design processes. Recent proceedings in related work indicate the potentials of novel approaches of data integration and information visualization to assist in virtual prototyping. In many cases, such approaches are based on cross-system solutions and interdisciplinary interfaces. However, we did not recognized research works with particular focus on the task of spatial localization of automotive function architectures. Therefore, this paper contributes in this field by focusing an efficient method for performing this task, based on the synthesis of automotive function architectures with CAD/DMU data.

3 EFFICIENT SPATIAL LOCALIZATION OF AUTOMOTIVE FUNCTION ARCHITECTURES WITH FUNCTION-ORIENTED 3D VISUALIZATION

This section includes our primary research contribution focusing on the spatial localization of automotive function architectures using function-oriented 3D visualization. First, we propose our definition of the geometric function localization task and introduce some preconditions for the corresponding studies. Second, we evaluate our 3D visualization methodology and present a user study that compares our method to a traditional approach based on classic electric wiring diagrams. Moreover, we evaluate the two methods in terms of usability and user’s acceptance. In addition, we propose an approach using geometric clusters and we use it to evaluate the capabilities of our method regarding accurate, manual GFLT performance. Finally, we show that the cluster approach can of beneficial use for further use cases and we propose novel features for function-oriented 3D visualization tools.

3.1 Definition of the Geometric Function Localization Task

The spatial localization of the distribution of components and wiring harness of a specific vehicle's function in the design of new car models is an important task throughout the automotive development process. We define this task as *Geometric Function Localization Task* (GFLT). Since this task occurs numerous times, it is important that users, like engineers, designers, tester and service technicians, are able to perform it very time-efficient and accurate.

The GFLT can be crucial in many use cases. Such use cases include, for instance, the design of inter-vehicle networks, evaluation of critical function aspects, identification of synergy and savings potentials, making statements on functional dependencies on crash zones, communication and the creation of mutual understanding of function architectures, service and maintenance, and the function-oriented development in general. Moreover, an efficient solution for this task is particularly important given that the locations and the distribution of components and wiring harness of a specific function do not only differ between vehicle projects, but also between variants, configurations, and derivatives within the same vehicle projects. Therefore, adequate methods are necessary to handle the high resulting complexity.

In current automotive development practice, performing the GFLT is very cumbersome. One possible way for obtaining some information on spatial locations of function components is to contact each person who is responsible for a specific function or function component. However, this way is very time-consuming and prone to errors, because information have to be gathered across multiple different departments and different domains, and many vehicle functions consist of a larger number of components, sometimes 20, or even more. This problem is aggravated by the fact that there are usually frequent changes in the vehicle projects, components and implementation variants.

Another way of information retrieval is to use wiring harness diagrams (see Fig. 2). While such diagrams do provide information on connections between components, a user needs to manually identify the components and connections related to a particular vehicle function, which is very time-consuming too. Moreover, while wiring diagrams may provide a rough orientation and traceability of the function architecture distribution from a top-down perspective, they do not provide any information on the exact spatial location of these components and wires in a particular vehicle project.

Exact spatial information of vehicle parts are available in CAD data and digital mock-ups. Today, however, such data does not originally include any function-oriented information so it is again necessary to contact responsible persons or compare complex data tables in order to identify the parts that are related to particular vehicle functions, making the task, again, very time-consuming and prone to errors.

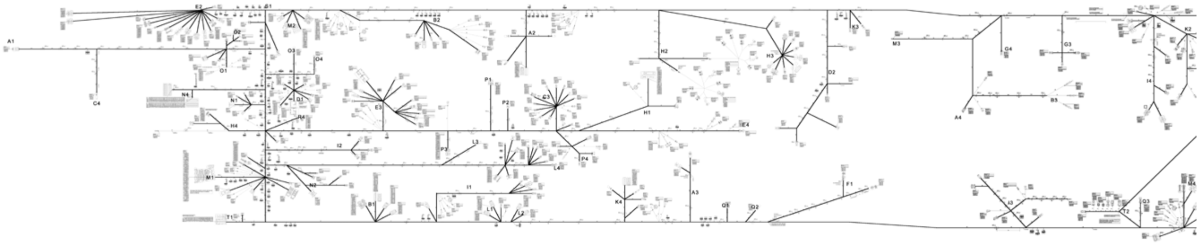


Fig. 2: Section of a hypothetical automotive wiring harness diagram; identification of function-related components and connections is a cumbersome process using this type of data due to its complexity.

In this work, we propose interactive 3D tools to solve the GFLT, based on our function-oriented visualization methodology, combining function-oriented data with CAD data [2-3]. We show that these tools are capable of successfully performing this task in a time-efficient and accurate way. To do so, we present a study that compares our method to a usual method based on classic wiring harness diagrams to assess task completion time and solution correctness. Moreover, we have performed a usability study based on the Nielsen heuristics to assess the subject’s subjective perception of both methods with respect to usability and suitability. Finally, we present a 3D-grid approach using geometric clusters to further investigate the capabilities of our methodology in order to provide accurate spatial recognition of geometric function architecture distributions in vehicle projects.

3.2 Evaluation Preconditions

A function-oriented development requires a highly interdisciplinary collaboration between many different domains and departments of automotive development such as architecture design, wiring harness development and virtual prototyping. Successful performance of the GFLT is crucial for those heterogeneous domains and a high diversity of use cases. Thus, we assume in this work that the target audience of the GFLT is a wide range of users, without the necessity for any particular expert knowledge in one specific automotive domain in order to solve the task. Therefore, all subjects in our user studies have been students with technical background but without expert knowledge in any particular field of automotive development. Another benefit of this set of subjects is that the results of our study are not distorted or biased due to knowledge mismatch.

In the following studies, we used three hypothetical vehicle functions. The first function (F1) has a relatively simple spatial distribution and we regard it under the aspect that subjects need to go through a small learning curve to get used to the method. The second function (F2) is considered as the most relevant function for our research because it represents a decent task difficulty due to a non-intuitive spatial distribution of the function architecture, and, at this point, the subjects are considered to be familiar with the respective method. Thus, we define F2 as the *focus function* of the study. The third function (F3) involves elements of the previous functions; thus it represents a case in which task-performance is potentially influenced by information available from previous tasks.

3.3 Part I: Task-Performance Evaluation

In this study, we assess and compare two different methods (A, B) for performing the GFLT by measuring task completion time and task solution correctness. Method A is based on using conventional wiring harness diagrams (see Fig. 2), while method B utilizes our function-oriented 3D visualization tool. The study used a between-group-design and involved a total of 26 subjects, which were equally split into two groups, A and B, one group for each method. Concerning other study conditions, the subjects were aged between 25 and 35 and all had normal or corrected-to-normal vision.

The task involved the correct identification of the electrical connections between a given set of function components for a specific vehicle function. All subjects had to solve the task for the three different vehicle functions (described in Section 3.2). The order of the tasks was the same for all experiments so the subjects always started with F1, followed by F2 and F3. Thus, we were able to detect possible learning curves of the methods. The steps of the task included identification of the function-relevant electrical connections between the function-relevant components and proper transfer of this information to a special template (see Fig. 3). Group A used printed out wiring harness diagrams and text markers. Group B used our function-oriented method implemented within an established 3D visualization tool. All subjects were given a brief introduction on how to use the respective method. By drawing the correct wire routings into the template, we could measure correctness of the results. In addition, we measured task completion time.

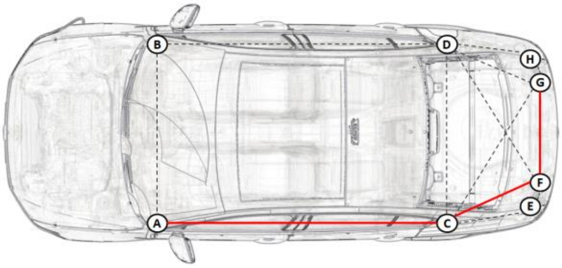


Fig. 3: Our GFLT task solution template properly filled for an exemplary function architecture.

The template simplifies the task in two ways: It shows a top-down view including X and Y dimension but not Z, and positions of function components (A to H) and valid routings are predefined. Leaving out the Z dimension enables comparison between our novel method and the conventional wiring harness method because the latter is not able to provide the Z information at all. Thus, we emphasize that method A is only able to provide reliable results if a top-down view is sufficient and if the spatial functional distribution involves no significant occlusions in the Z direction. Otherwise, full 3D views are necessary to understand the spatial function architecture distribution throughout a vehicle, which will be particularly covered in section 3.5, including the Z dimension for accurate GFLT performance.

The top-down view is still sufficient for many use cases, and, in particular, for the tasks of this study. Even under these simplifications, we demonstrate that our function-oriented visualization method already provides a significant benefit for successfully performing the GFLT. Thus, we conjecture that it will be of even greater benefit for more complex tasks.

Fig. 4 shows two screenshots recorded with our function-oriented 3D visualization (method B). In contrast to method A, the elements related to particular vehicle functions can be quickly accessed due to a hierarchical function-oriented navigation menu for method B. Moreover, the 3D visualization provides all typical features of 3D visualization tools like zooming, rotating, switching views, choosing orthographic or perspective views, etc. Thus, a user can relatively easily highlight and recognize the respective components and wires.

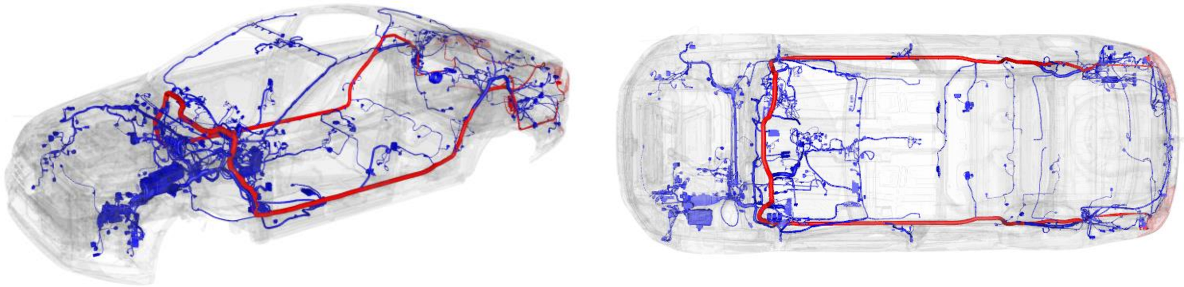


Fig. 4: Function-oriented 3D visualizations created with our methodology, highlighting the relevant wires (red) of a specific function and clarifying their distribution in a particular vehicle.

Figure 5 shows the complete results for our measurements of task completion time and solution correctness, including the particular results for all 26 subjects. We note that there is a large difference in task completion time between F1 and F2 with method A. This indicates that the traditional method requires a high learning curve. In contrast, method B seems to be much more intuitive as there is no significant difference between F1 and F2.

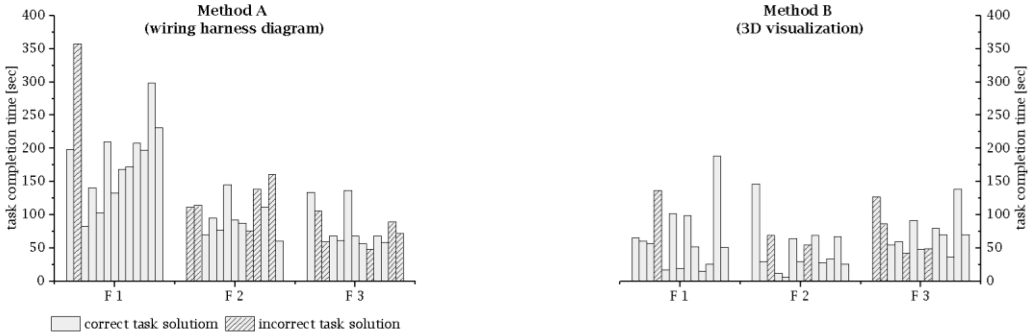


Fig. 5: Evaluation results comparing the wiring harness method to our 3D visualization method. Each bar represents one subject.

With method A, we found that the most time-consuming aspect of the task was the identification of the function-relevant components in the diagram. In addition, it was difficult for some subjects to correctly match the data for the many branches of the wiring harness diagrams. We found that those subjects who took notes and proceeded systematically (e.g. marking sections in the diagram) were significantly faster than those who did not.

With method B, we noticed that some subjects spent a lot of time analyzing different 3D perspectives on the data to gain additional information that was not actually needed for the task solution. Thus, we believe that task completion time will be even lower with method B if users are more experienced with the particular task. While some subjects had general experience with 3D tools, we did not notice that those subjects had an advantage to solve the task with method B.

Figure 6 shows the comparison of method A and B for all three functions, using median values in order to provide statistically robust results.

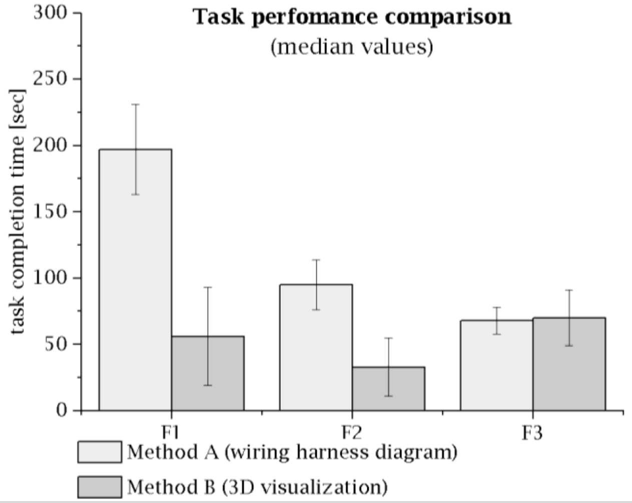


Fig. 6: Results of our study comparing task completion time (median values, incl. median absolute deviation) between the wiring harness method (A) and our 3D visualization method (B).

Interestingly, the average task completion times are nearly equal between both methods for F3. We believe that this finding can be explained by F3 being a composition of elements of F1 and F2. Thus, subjects could reuse information gained in the previous tasks to solve the task for this function, reducing the time for the search activities.

In total, the results show that task completion time is significantly lower with method B than method A (see Fig. 6). In this study, compared to the traditional wiring harness method, our 3D visualization method is nearly four times faster for F1 and three times faster for the focus function F2.

Concerning task solution correctness, we noticed that mistakes were made with both methods (see Fig. 5 and Tab. 1). Particularly; with method B, a few subjects were confused with the mapping of the 3D information to the 2D template which led to some errors, especially in F3. We believe that those mistakes can be reduced by additionally rendering metadata in the 3D visualization of method B, which we have identified as a topic for future work.

Measures	***Method A*** *(wiring harness diagram)*				***Method B*** *(3D visualization)*			
	F1	**F2**	**F3**	Mean	**F1**	**F2**	**F3**	Mean
Avg. solution correctness (%)	92.3	61.5	61.5	71.8	92.3	84.6	69.2	82.1

Tab. 1: Evaluation results of comparing solution correctness for both methods.

Interestingly, the task solution correctness for F1 is equal between both methods (see Tab. 1) and slightly different when comparing the mean over use cases F1-F3, with method B featuring a higher solution correctness. Because F3 involves information of F2, chances are that some subjects made subsequent faults resulting from mistakes already made in F2. Thus, the most significant statement should not be based on the mean, but on the focus function F2. For this function, we identify a task solution correctness of 61.5% for method A and 83.3% for method B. This outcome indicates that our 3D visualization method yields better user performance in terms of correctness.

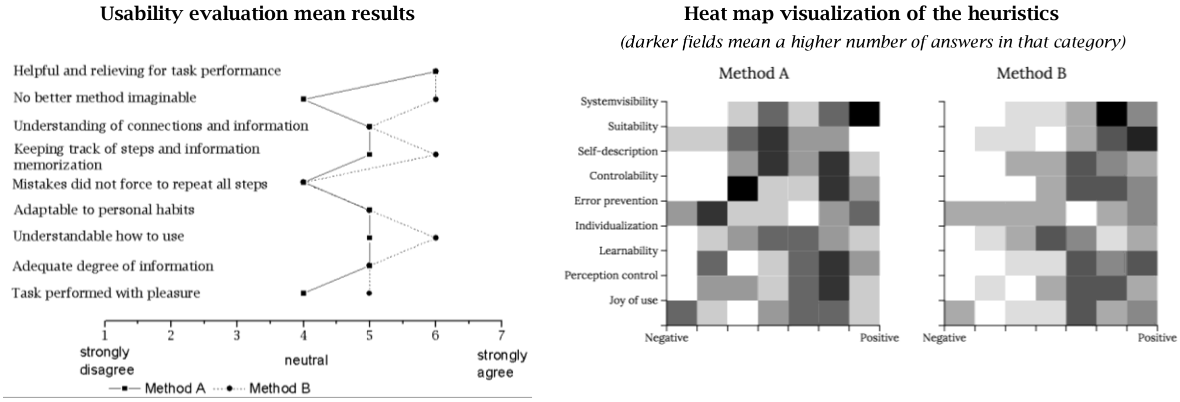
During the study, some subjects expressed their wish to have multiple different views at the same time as well as to hide unnecessary information. These options are not possible with method A, but can be easily implemented for method B. Thus, we consider them as potentially beneficial features for function-oriented 3D visualization for successful GFLT performance. We will focus on them in future work.

In summary, the results of this study indicate that method B is superior to method A in terms of both task completion time and solution correctness. In addition, we found optimization potentials for method B so that we believe that this method can be optimized in order to further improve GFLT performance.

3.4 Part II: Usability Evaluation

To get a deeper understanding of the subject's perception of the usability and suitability of the methods, we have conducted a follow-up study were all 26 subjects of the previous study had to fill a questionnaire derived from the Nielsen usability heuristics [10-11].

The results (see Fig. 7) show that both methods were graded helpful and relieving for task performance and rated equally concerning adequate degree and understandability of information and connections. However, a significant difference between the methods can be found in the question whether the subjects can imagine a better way to solve the tasks or not. While the subjects had a neutral opinion for method A on average, there is strong indication that most of the subjects think that method B is an ideal solution for the given task. In addition, the results indicate that method B is superior to method A regarding memorization of information which fits with prior research works on beneficial effects of spatial information for memorization tasks. Method B also was rated more understandable to use for the given task which fits with our findings in the previous study. Finally, we note that method B has been rated more positively concerning hedonic qualities [4] of the user experience.



Usability evaluation mean results

Heat map visualization of the heuristics

(darker fields mean a higher number of answers in that category)

Fig. 7: Evaluation results comparing method A (wiring harness) and method B (3D visualization).

In summary, the subjects think that both methods provide adequate and sufficient assistance to accomplish the GFLT. However, method B is rated superior in terms of task-suitability, information memorization, understandability, and joy of use. Overall, the results provide significant evidence that our novel method is a suitable tool for very efficient GFLT user performance and user acceptance.

3.5 Part III: A 3D Cluster Approach for Function-oriented Visualization

A rough, top-down recognition of the spatial distribution of automotive function architectures is sufficient for many use cases. Nevertheless, there are still a considerable number of use cases that benefit from a highest as possible accuracy in terms of the GFLT. Especially with high scene complexity and occlusions, a top-down view will not be sufficient for proper GFLT performance. In addition, for example, an engineer might be interested in the precise overall distribution percentage of a vehicle function network throughout the vehicle in order to determine the functions overall impact or the wiring length. Moreover, many use cases are based on dividing the vehicle into different geometric areas. For example, there are areas in a vehicle with statistically high probabilities of being affected in crash situations. Other examples for area-based approaches include different temperature zones, vibration stress areas, mechanical shock areas and areas prone to dust and splash water.

Considering use cases like in the above-mentioned examples, we extend the scope of the GFLT in a way that it requires full spatial recognition of the function architecture distribution, including X, Y and Z dimension. In order to measure the capability of our method to fulfill this advanced task, we propose a 3D-grid approach using geometric clusters. Thus, we implemented a 3D visualization method that overlays the vehicle geometry with a number of N rectangular volumes, each one representing a cluster. The measure used in the following user study is based on determining which cluster cells are touched by the elements of a particular function architecture (components and wire segments).

We have implemented two different variants of the cluster approach. The first variant (variant 1) involves an asymmetrical grid with cluster cells of different sizes, representing specific user-defined areas in the vehicle. For this exemplary case, these areas represent crash-relevant zones in the vehicle with different deformation risks in crash situations: green (low risk), yellow (medium risk) and red (high risk) (see Fig. 8, left). In contrast, the second variant (variant 2) features a higher number of clusters and uses identical cells (in particular, all cluster cells are of equal size) which flawlessly cover the complete vehicle geometry (see Fig. 8, right). The latter approach is scalable, while a higher number of cluster cells (more, smaller cells instead of fewer, bigger ones) corresponds with a higher granularity in assessing the spatial function architecture distribution.

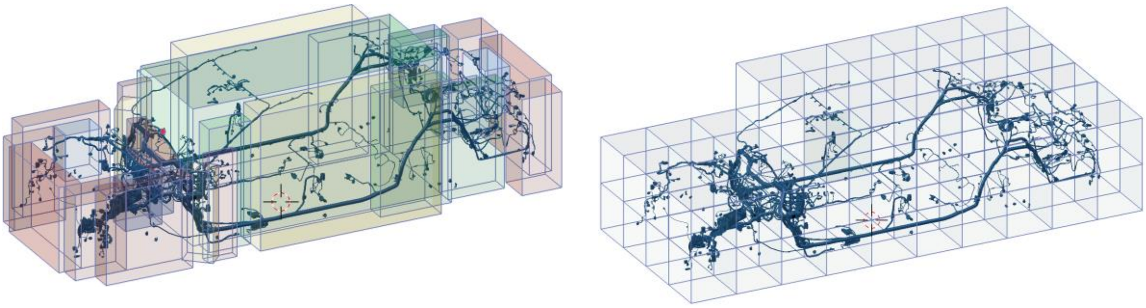


Fig. 8: Two variants of our geometric cluster approach. Variant 1 (left) uses volumes with different deformation risks in crash situations, variant 2 (right) uses a 3D grid of congruent cluster cells. Both variants enable beneficial new features for function-oriented 3D visualization tools.

Based on these two different implementations of the cluster approach, we conducted a user study with 11 subjects to evaluate our function-oriented 3D visualization method concerning its capabilities of providing precise statements on the spatial distribution of automotive function architectures. In this study, the subjects had to determine the number of cluster cells being occupied by the given function architectures of F1, F2 and F3. Therefore, the subjects had to perform a manual analysis of the 3D data, involving zooming, rotating, selecting and highlighting particular cluster cells, and counting the cells touched by the respective geometry. For variant 1, we asked for: (1) number of red cells touched by F1, (2) yellow cells touched by F2 and (3) green cells touched by F3. This use case enables statements on the crash criticality of the functions. For variant 2, we asked for the total number of cells touched by the respective functions. This second use case enables statements on the total distribution of a function architecture throughout a vehicle.

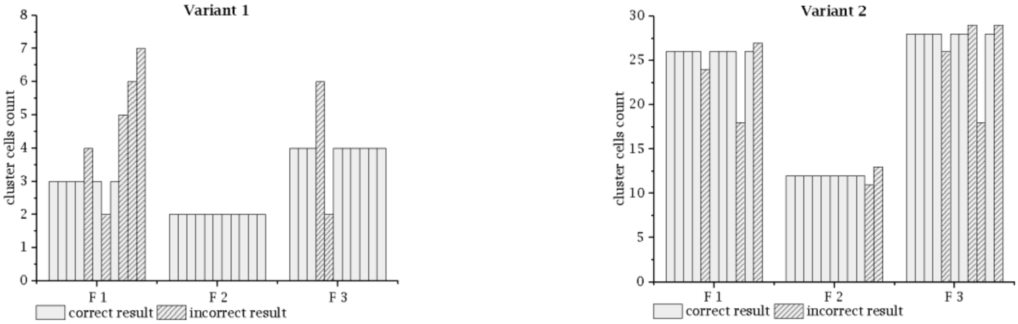


Fig. 9: The evaluation results of the cluster approach, comparing numbers of function-relevant cells counted by the subjects for clustering variant 1 (crash zones) and variant 2 (symmetric grid).

Especially for F1 in variant 1, the results show significant differences for task solution correctness (see Fig. 9 and Tab. 2) between the different combinations of cluster cells and functions. This outcome indicates that the quality of the statements based on the manual 3D data analysis significantly depends on the specific locations of the cluster cells and the specific geometry, respectively on the actual scene complexity. In addition, we noted that this task is considerably dependent on the user's spatial cognition abilities, colors and choices of visualization. We also found that orthographic projection makes it easier to identify the occupied cells in this task in comparison to perspective projection.

As it concerns the incorrect solutions, for variant 2, we noted that many of the solutions only involved minor deviations from the correct solutions (deviations of +/-1 deviation in number count). Presumably, a higher geometric complexity and higher number of cluster cells increases both task completion time and error probability. Interestingly, although variant 2 involves a higher number of cluster cells, the solution correctness is not significantly lower, which likely can be explained by a smaller scene complexity, because variant 2 involves a more structured, systematic and thus traceable design of the cluster cells.

Measures	***Variant 1*** *(crash zones)*				***Variant 2*** *(symmetric grid)*			
	F1	**F2**	**F3**	**Mean**	**F1**	**F2**	**F3**	**Mean**
Avg. task completion time (sec.)	109.3	31.8	99.3	*80.1*	108.1	45.8	63.6	81.5
Avg. solution correctness (%)	54.3	100.0	81.9	*78.8*	63.6	81.8	63.6	69.7

Tab. 2: Evaluation results of comparing task completion time and solution correctness for both methods.

Overall, we noticed that most of the subjects were uncertain about the correctness of their result and errors were made in all experiments with the only exception of F2 in variant 1. Thus, while we found that manual performance of the cluster approach task is possible in reasonable times (see Tab. 2), we noticed that it can be considerably prone to errors, especially when scenes are getting more complex, which can be confirmed by findings of [23-24]. Thus, we strongly suggest an automation of this task in order to eliminate the error probability. Especially in such use cases, where preferably precise statements are needed, and actually in general, this approach should ultimately be automated and implemented as a feature within a 3D visualization tool. By doing so, this method is able to provide hundred percent accurate statements at nearly instant speed.

Concerning tool implementation, clusters could be made classifiable by the end users, so that the users can create cluster variants that fit their specific use cases, for example, by defining their crash criticality. With this exemplary classification, a possible feature for a respective tool could be a report on the percentage of the function architecture that is located in critical areas, in order to classify the crash-sensitivity of the function. In addition, many other use cases are possible and can be addressed in future work.

4 CONCLUSIONS AND FUTURE WORK

The increasing complexity in the development process in the automotive industry calls for an urgent need for novel and adequate methods to handle the consequential challenges. In this paper, we have proposed one of the major challenges within a function oriented-development as well as a solution using our novel 3D visualization method. We have evaluated our method in several user studies and we have compared it to traditional methods. In addition, we have proposed novel, function-oriented features for 3D visualization tools.

The results of our research show that our function-oriented 3D visualization methodology provides an efficient solution to identify and recognize the spatial distribution of function architectures in specific vehicle projects. By several user studies that compared a conventional method using wiring harness diagrams with our novel VR-based method, we found that our proposed method overcomes limitations of the traditional method in terms of users' information gain and users' task performance. More precisely, our method is three times more time-efficient and about 20% less prone to errors. In addition, our evaluation of usability based on Nielsen's heuristics confirms the usability and task-suitability of our method with four heuristics being rated significantly more positive than the traditional method. Moreover, we showed that our method is easily applicable for non-experts and thus can be used across multiple domains of automotive development.

Furthermore, we have presented two further approaches to evaluating task performance and accuracy of our method which are based on geometric clusters. While our corresponding user study showed that manual task performance provides reasonable results, we found that the highest advantage of these approaches can be taken by full automation within a 3D visualization tool in order to generate most accurate results and to enable beneficial, novel features for function-oriented use cases.

In summary, our methodology can improve the effectiveness of function-oriented development processes and it can greatly increase task performance of users working with that novel approach. Since the learning curve is also much lower, it can be easily employed in many use cases across different automotive domains, including development, test, service and maintenance. Thus, it supports automotive engineers in mastering the challenges of current, highly-interdisciplinary function-oriented development, and, in general, the ever increasing complexity in automotive development.

Finally, our research leaves multiple potential fields of future work. Such fields include optimization of our 3D visualization methodology based on the findings of our studies, like rendering of additional metadata in the 3D visualization and proposal of multiple simultaneous views. In addition, future work could address multiple other, novel function-oriented features to be implemented in 3D visualization tools. For instance, based on one of our user studies we suggest to fully automate analyses and reports on function's geometric crash sensitivity and their overall distribution percentages. Finally, such features and tools should be evaluated using appropriate usability studies, in order to improve usability and user experience.

REFERENCES

[1] Blochwitz, T.; Otter, M.; Akesson, J.; Arnold M.; Clauß C.; Elmqvist, H.: Functional Mockup Interface 2.0, 9th International Modelica Conference, Munich, 2012.

[2] Cohrs, M.; Klimke, S.; Zachmann. G.: Streamlining Function-oriented Development by Consistent Integration of Automotive Function Architectures with CAD Models, Computer Aided Design and Applications 11 (4), 2014, 399-410. http://dx.doi.org/10.1080/16864360.2014.881182

[3] Cohrs, M.; Klimke, S.; Zachmann. G.: A Methodology for Interactive Spatial Visualization of Automotive Function Architectures for Development and Maintenance, Advances in Visual Computing, 9th International Symposium, ISVC 2013, Proceedings, Part II, Springer Berlin Heidelberg, 2014, 25-35. http://dx.doi.org/10.1007/978-3-642-41939-3_3

[4] Diefenbach, S.; Hassenzahl, M.: The dilemma of the hedonic–Appreciated, but hard to justify, Interacting with Computers 23 (5), 2011, 461-472.

[5] Enge-Rosenblatt, O.; Clauß, C.; Schneider, A.; Schneider P.: Functional digital mock-up and the functional mock-up interface, Proceedings of the 8th international Modelica Conference, Dresden, 2011, 748-755.

[6] Farkas, T.; Hinnerichs, A.; Neumann, C.: An Interdisciplinary Approach to Functional Prototyping for Mechatronic Systems using Multi-Domain Simulation with Model-Based Debugging, Proceedings of the International Multi-Conference on Engineering and Technological Innovation, Orlando, Florida, 2008.

[7] Gottschalk, B.; Kalmbach, R. (Eds.): Mastering Automotive Challenges, Kogan Page, London, 2007.

[8] Kim, S.; Weissmann, D.: Middleware-based integration of multiple CAD and PDM systems into virtual reality environment, Computer-Aided Design & Applications 3(5), 2006, 547-556.

[9] Krause, F.; Franke, H.; Gausemeier, J.: Innovationspotenziale in der Produktentwicklung, Carl-Hanser Verlag, München, 2007.

[10] Nielsen, J.: Ten usability heuristics, http://www.nngroup.com/articles/ten-usability-heuristics/, (accessed on January 20th, 2015), 2005.

[11] Nielsen, J.: Enhancing the Explanatory Power of Usability Heuristics, Proceedings of the SIGChi Conference on Human Factors in Computing Systems, ACM, 1994, 152-158.

[12] Nybacka, M.; Karlsson, T.; Larsson, T.: Vehicle validation visualization, Proceedings of Virtual Concepts, 2006.

[13] Paillot, D.; Merienne, F.; Thivent, S.: CAD/CAE visualization in virtual environment for automotive industry, Proceedings of the workshop on Virtual environments, New York, 2003, 315-316.

[14] Rao, N. R.: Innovation through Virtual Technologies, Virtual Technologies for Business and Industrial Applications, Business Science Reference, Hershey, New York, 2011, 1-13.

[15] Revermann, K.: Function-oriented Development, edaWorkshop 09 Proceedings, VDE, Berlin, 2009. https://www.edacentrum.de/content/function-oriented-development

[16] SAE-China; FISITA (Eds.): Proceedings of the FISITA 2012 World Automotive Congress, 6, Springer, Berlin, 2013.

[17] Sedlmair, M.; Bernhold, C.; Herrscher, D. Boring, S.; Butz, A.: Mostvis: An interactive visualization supporting automotive engineers in most catalog exploration. Information visualization, 13th International Conference, 2009, 173-182.

[18] Sedlmair, M.; Hintermaier, W.; Stocker, K.; Buring, T.; Butz, A.: A dual-view visualization of in-car communication processes, Information Visualization, 12th International Conference, 2008, 157-162.

[19] Schilling, A; Kim, S.; Weissmann, D.; Tang, Z.; Choi, S.: CAD-VR geometry and meta data synchronization for design review applications, Journal of Zhejiang Univ. Sci. A, 7(9), 2006, 1482-1491

[20] Schneider, P.; Clauß, C.; Schneider, A.; Stork, A.; Bruder, T.; Farkas, T.: Towards more insight with functional digital mockup, European Automotive Simulation Conference, 2009.

[21] Song, I.; Chung, S.: Synthesis of the digital mock-up system for heterogeneous CAD assembly, Computers in Industry 60 (5), 2009, 285-295.

[22] Tonnis, M.; Lindl, R.; Walchshausl, L.; Klinker, G.: Visualization of Spatial Sensor Data in the Context of Automotive Environment Perception Systems, Mixed and Augmented Reality, ISMAR 2007, 6th IEEE and ACM international Symposium, 2007, 1-9.

[23] Tory, M.; Moller, T.; Atkins, M. S.; Kirkpatrick, A. E.: (2004, April). Combining 2D and 3D views for orientation and relative position tasks, Proceedings of the SIGCHI conference on Human factors in computing systems, ACM, 2004, 73-80.

[24] Tory, M.; Kirkpatrick, A. E.; Atkins, M. S.; Moller, T.: Visualization task performance with 2D, 3D, and combination displays, Visualization and Computer Graphics, IEEE Transactions on, 12 (1), 2006, 2-13.

[25] Wang, G.: Definition and Review of Virtual Prototyping, Journal of Computing and Information Science in Engineering, 2(3), 2002, 232-237.

[26] Weber, J.: Automotive Development Processes, Springer, New York, 2009. http://dx.doi.org/10.1007/978-3-642-01253-2

[27] Zachmann, G.: VR-Techniques for Industrial Applications, Virtual Reality for Industrial Applications, Springer, Berlin, 1998, 13-38. http://dx.doi.org/10.1007/978-3-642-46847-6_2