3D Interaction in Virtual Environments for Systems Engineering

M. Bougaa, S. Bornhofen, H. Kadima, and A. Rivière

Abstract—**This paper discusses the potential benefits of applying Virtual Reality (VR) technology to the context of Systems Engineering (SE), for both educational and industrial purposes.**

After an introductive presentation of the two fields and their state of the art, we explore if and how VR can be of assistance to the processes involved in a typical SE approach. We especially focus on commonly used 3D interaction techniques in VR and argue that the design of appropriate 3D interactions is a key ingredient for the success of VR in SE. We suggest three research directions that may be considered for this design: interaction generality, context awareness and adaptability. The 3D interactions should adapt, manually or automatically, to the VR device, the virtual scene and the user context.

Index Terms—**Virtual reality, virtual environment, systems engineering, 3d interaction, adaptive interaction.**

I. INTRODUCTION

Over the last decades, the engineering of physical systems and the management of their life cycle have grown more and more complex. Military, aerospace, automotive and medical industries are confronted with the challenge of building systems that have large architectures and require interdisciplinary competence. Moreover, the systems must not only be functional, but also reliable, maintainable and safe. As an example, Fig. 1 illustrates the multidisciplinary nature of the design process of an aerospace launch vehicle at the Onera research center [1].

The understanding and the design of such complex systems cannot be achieved any more by a simple Systems Design approach which is the concept, specification, implementation, verification and validation of a technical system for achieving a specific (and mostly functional) objective [2]. New goal-independent methodological approaches and modeling techniques are required, such as Systems Engineering (SE) whose first concern is not a specific design objective, but the optimization of all involved engineering processes. As defined by the International Council on Systems Engineering (INCOSE): "Systems engineering is an interdisciplinary

approach and means to enable the realization of successful systems. It focuses on defining customer needs and required functionality early in the development cycle, documenting requirements, and then proceeding with design synthesis and system validation while considering the complete problem: operations, cost and schedule, performance, training and support, test, manufacturing, and disposal. SE considers both the business and the technical needs of all customers with the goal of providing a quality product that meets the user needs". [3].

Much research effort has focused on proposing appropriate tools for SE. Dedicated modeling languages have been introduced, such as SysML [4], a visual modeling language, and LML (Lifecycle Modeling Language) [5], providing a simple way to understand and communicate cost, schedule and performance design information to all stakeholders in a standard manner. Other successful standardizations are ISO/IEC 15288 [6], defining a common framework for the life cycle of systems, EIA 632 [7] proposing the blueprint of all processes and requirements necessary for engineering a system, or IEEE 1220 [8] providing the next-level-of-detail description of SE processes defined in EIA 632. However, not all technologies that might support the SE approach had full attention of the industrial and academic communities so far, either because they are recent like Big Data, or because up until recently they were immature and unaffordable, like Virtual Reality (VR).

As a matter of fact, only little research has been done on VR for SE, although its potential has already been discovered especially for educational needs [9]. This paper pursues the assessment of the benefits of VR in the context of SE. We intent to develop a collaborative VR based environment for using and learning SE, we are particularly interested in the study of 3D interaction techniques and explore if and how they should be improved or adapted, in order for systems engineers to take maximum advantages from a VR environment.

The paper is organized as follows: Section II discusses the requirements to be met by a typical SE environment. Section III reviews the state of the art in VR, and distinguishes between the components sufficiently mature to be applied to SE and those that require improvements. Section IV focuses on immersive 3D interaction techniques and puts forward some directions to explore, in order to take VR to a higher level of maturity, in terms of precision and ease of use.

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II. SYSTEMS ENGINEERING ENVIRONMENTS

This section identifies the requirements that need to be met by any appropriate SE environment in both academia and

industry (not to be confused with the requirements of a system to be engineered). For this purpose, we consider the thirteen processes in a typical SE approach as defined by the EIA 632 standard [7]. The processes are illustrated in Fig. 2. They may be adapted to the specificities of the domain, the product type, and other industrial or pedagogical constraints.
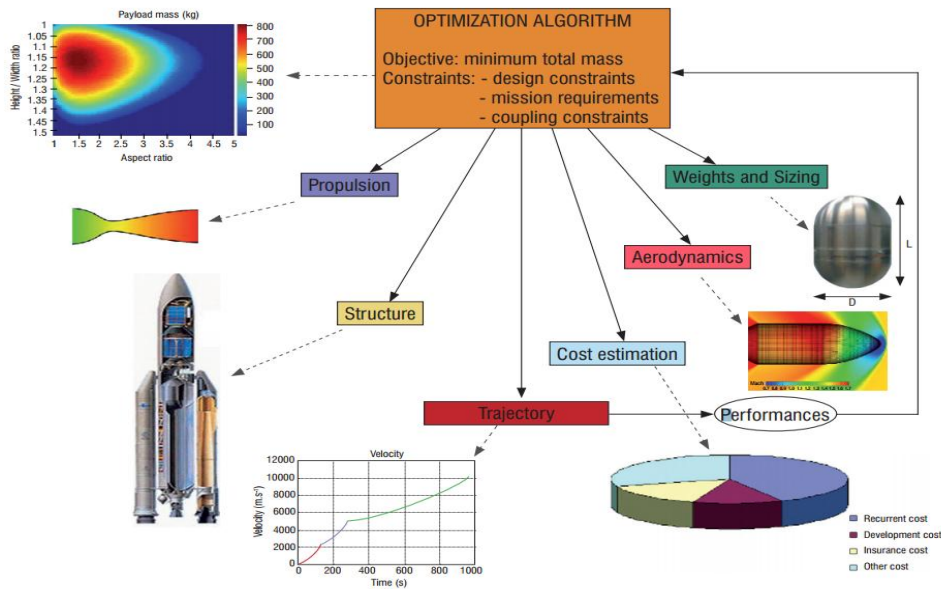

Fig. 1. Multidisciplinary design process of an aerospace launch vehicle [1].
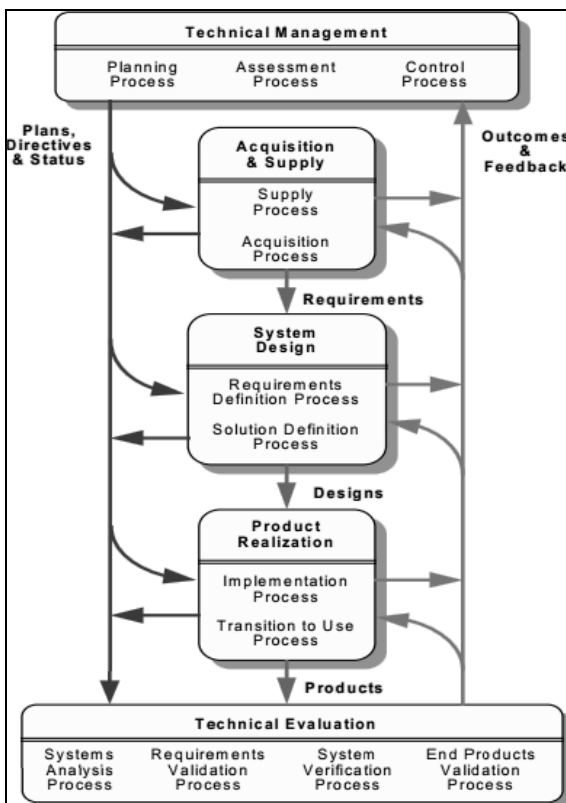

Fig. 2. Processes for systems engineering as defined by EIA 632 [7].

Abulrub *et al.* [9] explored the benefits of VR for engineering education and training through a series of case studies at the University of Warwick. The authors showed how VR can encourage the creative learning of engineering material and environments, and concluded that some VR promises for SE are: the development of autonomous problem solving skills, the sharing of complex information with team members, and the analysis of engineering problems under different points of view. Maurer and Winner [2] discussed the upcoming challenges for SE in the automotive and supplier

industry. Some of them are: requirements engineering, the design of test and validation strategies and tool.

Based on these two similar works, we pre-selected five EIA 632 processes where the use of VR is particularly promising in the context of SE. These processes will be addressed in the scope of this paper (processes definitions taken from [7]):

1) Requirements Definition Process: transform stakeholder requirements into a set of system technical requirements.
2) Solution Definition Process: generate an acceptable design solution (specifications, drawings, models, etc.).
3) Implementation Process: transform the characterized design solution into an integrated end product that conforms to its specified requirements.
4) Requirements Validation Process: assure that the subject set of requirements describes the input requirements and objectives such that the resulting system products can satisfy the requirements and objectives.
5) System Verification Process: ascertain some points such as: the system design solution is consistent with the source requirements, the end products meet at each level their specified requirements, etc.

A. Industry

In order to enhance the SE approach in terms of efficiency, simplicity and flexibility, we particularly focus on the SE environment requirements to obtain better results during the five previously cited processes. In this section we illustrate the results of our reflection on the definition of these requirements, and we discuss which requirement affects which processes:

We identified some shared requirements for the two *Systems Design* processes, in order to improve the results of the Requirements Definition Process and the Solution Definition Process. The SE environment should offer tools and techniques to:

1) Improve the design of digital prototypes/mockups with

higher quality and realism.

2) Enhance collaboration and break down distances and multidisciplinary barriers;

3) Help the engineers in their critical thinking and problem solving;

4) Adopt different points of view of the system, because the perception of the system depends on the engineer's scientific background;

5) Do efficient project reviews and increase the reliability of early-stage decisions;

6) Use knowledge bases in order to identify significant design issues at early stages.

Some of these requirements are shared between more than two processes, such as the points 5) and 6), which can highly affect costs and time-to-market and so they affect the Implementation Process. Point 4) has a significant impact on the Requirements Validation and the System Verification Processes.

In addition to these system design requirements, we identified one requirement for the Implementation Process, which is the ability of the SE environment to offer tools for:

7) Efficient task and time planning as well as resource management to improve the implementation process,

Two other requirements for the Requirements Validation and the System Verification Processes:

8) The ability to ensure the system compliance with the requirements;

9) Efficient tools for knowledge sharing, transmission and validation,

And finally, one shared requirement for the last three processes:

10) The use of techniques such as Failure Mode and Effects Analysis (FMEA) techniques [10] in virtual prototyping, for realistic simulations, in order to prevent systems assembly or behavior problems and defaults at early stage of the engineering process.

Fig. 3 summarizes these requirements and specifies which process is concerned by each requirement.
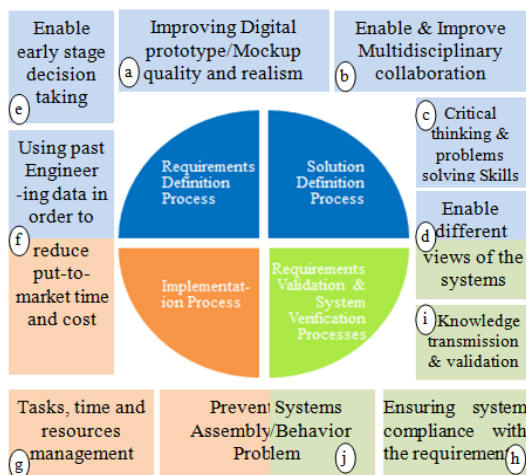

Fig. 3. Processes (quadrants) and their requirements (rectangles).

B. Academia

A good SE platform should provide the students with tools to acquire essential skills [9], [11]. Naturally, many of the requirements for SE education and learning solutions are identical to the previously cited requirements for SE in industry, such as getting the user to learn how to:

1) Ensure system performance and functionality by respecting compliance with the requirements during the engineering processes;

2) Optimize task, time and resource management;

3) Adopt the best practices for collaborative work, especially in geographically dispersed, multidisciplinary teams.

4) Acquire critical thinking and problems solving skills for real life engineering challenges;

5) Understand the benefits of inspecting engineering problems from different points of view (global view, components view, functional view, conceptual view, etc.);

6) Be able to make key decisions since the first stages of the engineering processes, especially encouraging innovation;

On the other hand, SE learning environments also have some specific requirements like:

7) Giving the ability to the instructor to fix learning goals before the training phase, in order to assess and validate the students' results.

8) Enable engineering students to experience an environment or a problem when it is difficult to do otherwise in real-life [9]

9) Encourage active participation and amplify student interaction and collaboration [9].

III. VIRTUAL REALITY FOR SYSTEMS ENGINEERING

After having reviewed the requirements for the engineering processes that we are focusing on, this section inspects which VR components are already mature, and suggests how they could be integrated in a SE environment.

VR is a technology that allows users to immerse in an artificial reality and to have interactive experiences via sensorimotor channels [12], [13]. The first VR systems appeared more than 50 years ago, such as the Sensorama simulator which it is one of the earliest known examples of immersive, multi-sensory (multimodal) technology [14]. However, VR has been democratized only in the last decade, and therefore has in many ways the flavor of a new research field. It is experiencing a rapid growth, as well as various related technologies: *gesture control, speech recognition, gamification, wearable user interfaces, brain computer interface,* etc.

The quality of the user experience in a VR system can be evaluated through several components. J. Tisseau considers that a VR application is defined as a function of three components [15]:

1) **Autonomy**: A behavior will be considered as autonomous, it if can adapt to unknown changes in its environment: meaning it must have the means to perceive, act and coordinate perceptions and actions, to be able to react realistically to these changes [16];

2) **Immersion**: exposing the user to a virtual environment using fully or partially real-world occulting devices [17];

3) **Interaction**: a communication language between the user and the machine. It is a set of actions/reactions via

sensorimotor interfaces and interaction techniques [18]. Burdea and Coiffet defined the basic VR components as Immersion, Interaction, and Imagination [19]: Imagination characterizes the interpretation of the parameters that result from a VR experience.

If we want to apply VR in the context of SE, these components must be taken into account, especially the *Immersion* and *Interaction* components.

A. Industry

1) The immersion dimension

Immersion is a key element for efficient VR solutions, though its quality depends on the equipment and the techniques used for visualization and interaction. First, good immersion allows for a better perception of the environment. As a matter of fact, it has been shown that users estimate the depth of 3D models with greater accuracy using stereoscopic immersive systems compared to traditional display systems [20]. Second, immersion enhances the sense of presence especially by real-time user tracking and by visual feedback of the user's hands and body [21], [22]. Third, it enriches the possibilities of 3D interaction techniques for grabbing and manipulating virtual objects [23].

We claim that the immersion component of VR could considerably improve the SE processes requirements. The quality and the realism of digital prototype/mockup using VR allow for more reliable decision making, and therefore reduce costs and time-to-market. Another improvement resides in the use of failure analysis techniques, such as FMEA/FTA [10], and knowledge bases coupled to the 3D content, describing the object attributes and their interaction at early stages of the design. This approach helps preventing system anomalies that may occur in the later realization stage [24]. As a conclusion, the immersion component of VR can allow for a comprehensible 3D visualization of SE data and therefore improve the Requirements Validation, System Verification and Implementation Processes.

2) The interaction dimension

We can differentiate between two types of interaction in a VR based SE environment: the interaction with other users which are collaborating to engineer a system and the interaction with the virtual environment itself. VR and recent technologies offers mature tools for the first category, such as the collaborative design in virtual environments [24], improving collaboration and diminishing distance and multidisciplinary barriers. For the second category, the situation is more difficult. There is a variety of well-known 3D interaction techniques in VR, addressing all human senses including haptics and force feedback [23], [25]-[27]. However, their precision, accuracy, availability, and adaptability do not always deliver a good performance [28], [29]. For example, interaction with objects in a crowded virtual environment is different to a non-crowded one, especially for SE where the user typically does not interact with the entire complex system, but only with a part of it. Similar problems arise for tasks that need high precision interaction, compared to other tasks that do not need such accuracy. Many excellent states of the art on 3D interaction have been done in the past [26], [28], [30], [31]. Improving

and adapting these techniques in the context of SE is the main subject of our work. We will study this topic in section 4 and suggest some promising research avenues.

B. Academia

Thanks to the interaction and immersion components that provide the students with a high level of realism and interactivity, VR is a well-suited tool for education and training. It offers a safe, fully controllable and cost-effective learning experience. VR teaches the students how to develop autonomous problem solving skills, and gives the instructor the ability to create realistic learning situations which are difficult, unaffordable or even impossible to set up in a classic learning context.

It has been shown that teaching and training is considerably improved by having the students apply theoretical knowledge to concrete industrial problems using VR technologies. Creativity, innovation, communication, problem solving, team work and business skills can be improved by using VR environments, which offers an unlimited experience on virtualized real-life situations [9].

IV. 3D INTERACTION AND POSSIBLE IMPROVEMENTS

This section discusses the current state of the art on 3D interaction techniques. We present the most famous ones together with some possible classifications and review a number of improvements that have been done until now. We conclude by suggesting some promising leads on what may be the future of 3D interaction techniques.

A. Interaction Techniques and Classifications

3D interactions have often been classified into distinct virtual behavioral primitives [13], [32]:
1) Techniques for observing the virtual world;
2) Techniques for moving and acting in the virtual word;
3) Techniques for communicating with others or with the environment.

Another approach consists in classifying the techniques according to two main categories:
1) The egocentric techniques, where the user interacts with the environment "from the inside", as in reality, using his hands to select a virtual object;
2) The exocentric techniques where the user interacts with the environment "from the outside", meaning that the user is not considered as a part of the virtual scene;

Each of which has three sub-categories: direct manipulation, physical control and virtual control techniques [31].

Most often, a 3D interaction technique is related to an interaction task, which also allows classifying interaction techniques according to elementary tasks: navigation, selection, manipulation, and application control [33].

As two of the most frequently used 3D interaction techniques, we cite
1) The virtual hand metaphor [34], where the user touches the virtual object with his hand to select it, then he validates the selection by staying in contact with the object for a certain lapse of time or by closing his hand.
2) The ray-casting technique [35] which is a pointing

technique based on the virtual ray metaphor, where an infinite laser pointer extends from the virtual hand of the user and traverses the virtual environment. The first object that intersects the ray can be selected.

B. Limits of 3D Interaction Techniques

The two previously cited techniques have several drawbacks. Ray-casting suffers from the fact that the object is attached to the end of the ray, so there is no simple method to apply rotation to the selected object. The virtual hand technique suffers from the difficulty of grabbing remote objects.

For these reasons, a variety of new techniques have been explored. The improved virtual pointer metaphor [36] and the flexible pointer [37] enhance the ray-casting selection by allowing the control of the ray direction and therefore the selection of hidden objects. Also, several arm-extension techniques like the go-go technique [38] and its variant *fast go-go* [39] are improvements over the classic virtual hand for grabbing and manipulating remote objects. The go-go technique [26] gives the user the ability to select and manipulate distant objects, by calculating the virtual hand position using a non-linear function allowing it to go further than the real user hand after a certain distance threshold. The fast go-go technique is similar to the go-go technique, except that it does not have a distance threshold.

Such improvements may work in a specific virtual environment, however in a complex environment for SE, they can quickly become unusable. We illustrate this argumentation by a concrete use case. One of the interaction improvements is an adaptive technique where the user performs the navigation, selection and manipulation tasks sequentially, and the system switches automatically from one task to the next [40]. In some specific SE scenarios this technique may be very helpful and can save the user much time and cognitive load: in the case of a virtual system assembly with hundreds of pieces, the user repeats for each piece the same series of operations (navigate to the piece, select it, and put it in the right place). However, for another engineering problem where the user manipulates the products in a virtual production line, he does not need to use the navigation task neither the selection task because the objects can be automatically picked by the system. In this case, the rigid implementation of the previous technique would not be helpful.

This example illustrates we need some kind of adaptation possibilities for interaction techniques, we will discuss about adaptation at the end of the next section.

C. New Directions

As we have seen, 3D interaction is a key component of VR, and more research effort should be invested in order to conceive new interaction techniques or improve on the existing ones. In this section we suggest some directions where this research might concentrate on. We start by assuming some requirements which the 3D interaction techniques may need to satisfy in the same virtual environment:
1) For two different functionalities, we may use two different selection techniques, with the same or different

devices, or even by natural interaction;
2) To achieve a navigation or manipulation task, more than one technique may be used simultaneously;
3) The interaction technique may change between two tasks.

1) Generality vs. specificity

Encouraging specificity when designing 3D interaction techniques is the first recommendation among four proposed in [41]:
1) Encourage specificity: design specific 3D interactions for specific domains, specific tasks, specific devices, and specific users.
2) Produce variants of existing 3D interaction techniques: by adding features or complexity to the basics techniques, to improve their usability.
3) Address the implementation issues: improve the implementation of 3D interactions by allowing the 3D interactions to handle a greater amount and variety of input data, create standards for 3D interactions, etc.
4) Apply 3D interactions to emerging technologies or technological concepts, such as wide-area tracking technologies, pervasive computing technology, etc., which also provides an opportunity for further 3D interaction research.

Although there is no guarantee that any interaction technique produced by this method (specificity) can be reused in any other domain, the authors suggest designing dedicated interaction techniques for each domain or application from scratch. Based on a specificity approach and not a generality approach, the authors recommend designing techniques for specific tasks rather than for a general task category. They also suggest device-specific techniques, and user-specific techniques.

We do not completely agree with this proposition. We think that focusing on specificity, especially application specificity will increase the number of 3D interaction techniques, and as a consequence future developers will be lost in choosing from existing techniques. Moreover, developing a new technique for each application and for each device is definitely not the best solution in order to make VR more usable.

We assume two conditions for this purpose: first, the interaction technique must be intuitive and ensure minimum cognitive load, by encouraging task continuity [40]. Second, after analyzing and decomposing all existing techniques into low level primitives, we propose that all of them should be grouped into one smart interaction solution. Keeping that in mind and that domain specificity may be encouraged, but not application specificity, our first research direction is:

> *"Find a compromise between specificity and generality, and forget about the classic task, user behavior, or device type classifications of VR interaction techniques"*

2) Context-awareness and user intention

Previously, we suggested considering generality rather than specificity, but this approach does not have to prevent the system from taking useful environment information into consideration when performing interaction tasks, such as:
1) The extent of the virtual environment and information

about the objects inside it: shapes, object sizes and density, inter-object relations…etc.

2) The task scenario: what does the user need to do next?
3) Detecting user intention based on previous uses of the system. Hence, our second research direction is:

> *"The interaction solution must be smart and have the ability to react according to the environment information as well as to the user behavior, to be more suitable and more accurate to the task requirements."*

3) Adaptative interaction techniques

Keeping in mind the two previously proposed directions, we can note that the interaction technique solution to be designed needs to be adaptable, according to the retrieved information from the virtual environment, task requirements, and user intention. Some initiatives have already been undertaken to adapt basic interaction techniques, such as:

1) Switch between two or more interaction techniques when manipulating virtual objects in the same virtual environment.
2) Adapt an existing technique itself, for specific context use.
3) Improve existing techniques by including new interaction modalities, like speech control, eye tracking, haptic devices, etc.
4) Automatic execution of a part of the interaction task, like automatic selection of a specific form/color object, etc.

Many benefits of such adaptations have been highlighted, including: *acceleration, personalization* and *diminution of cognitive load* [42]. Even though our vision of adaptive 3D interactions implies the implementation of already conceived basic adaptations, we do not suggest cumulating individual adaptations. We rather suggest the implementation of these adaptations in the scope of one single interaction framework, according to our two previous research directions. Our goal is not providing assistance to the existing interaction techniques, but creating a fully adaptive 3D interaction solution. Therefore, our third direction is:

> *"After breaking down all the existing interaction techniques into low level primitives and the proposition of other required ones for each specific domain, we suggest the conception of one single adaptive solution regrouping all the interaction primitives."*

Some kinds of adaptation that need to be taken into consideration for the creation of an adaptive 3D interaction technique in virtual environments are:

1) Adaptation performed automatically according to the interaction requirements, or manually by the user.
2) Adaptation according to the task requirement, to the user intention and to the task scenario analysis.
3) Adaptation according to the environment: the size of the object to be selected, object-object and user-object distances, velocities…etc.
4) Multi-device and multimodal adaptations: for a multi-user VR environment, featuring different devices, different modalities, etc.
5) Adaptation based on the user purpose: for a student,

acquiring skills is more important than simplified interaction. In contrast, to systems engineering experts, the interaction must be as intuitive and as accurate as possible.

Each adaptation may be part of the previously cited initiatives (switching between two interaction techniques, the adaptation of the existing technique itself, improvements using new modalities, the automatic execution of part of the task), or they may be of another kind, such as adapting the user point of view (zooming or redirection), the geometry of the 3D cursor, etc.

V. CONCLUSION AND FUTURE WORK

In the field of VR, much work has addressed the design of 3D interaction techniques in virtual environments, but the results are not sufficient to democratize the use of VR technologies in certain domains, such as Systems Engineering. This paper suggested some new research directions to focus on, in order to improve future VR systems for industrial and educational needs, by improving the accuracy and the adaptability of 3D interaction techniques.

We plan on continuing our research and consider this paper as a starting point for our next contributions. The implementation of a VR environment for systems engineering in the automotive industry is already in progress.

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