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Analyzing the potential of Virtual Reality for engineering design review

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ABSTRACT

Virtual Reality (VR) technology still needs to evolve, but as the pace of innovations accelerates, systems allow for more novel modes of visualization and interaction to support engineering design reviews. Currently, the classic design review process is often performed on a PC with the support of CAD software packages. However, CAD on a screen cannot always meet all the requirements in regard to the functional and ergonomic validations of complex 3D models. In this paper, the development and evaluation of a VR-based tool to support engineering design review is described. “VRSmart” visualizes CAD data and allows for an intuitive interaction. In a preliminary user study, the tool was checked for its usability and user experience. VRSmart was then evaluated in a real industrial environment and tested in an authentic design review. The results indicate that a VR-supported design review allows users to see slightly more faults in a 3D model than in a CAD software-based approach on a PC screen. Furthermore, VR reduces the risk of exclusion of certain professional groups from the design review process. In addition, the intuitive interaction with the VR system allowed for a much faster entry into the design review. In summary, VR will not replace the traditional design review process on screen, but it provides a useful addition to engineering companies.

1. Introduction

Current Virtual Reality (VR) technologies build upon ideas that date back to the 1960s and earlier. In 1968, Ivan Sutherland [1] created the first head-mounted display that rendered simple wireframe models for the viewer's changing pose. This invention laid the foundations for the technologies we now call Virtual Reality (VR), Augmented Reality (AR), and Mixed Reality (MR), as defined by Milgram et al. [2] in their reality-virtuality continuum. The term denotes a continuous scale ranging between the completely virtual and the completely real. VR is commonly described as computer-generated environments or realities that are designed to simulate a person's physical presence in an immersive and convincing environment. The purpose of VR is to allow a person to experience and manipulate the environment as if it were the real world. The VR subject experiences “hypes” at regular intervals, and they disappear shortly thereafter. With the advent of more powerful graphics hardware and innovative tracking technologies, the topic has been revisited in recent years. According to Gartner's hype cycle [3], VR has finally reached the “plateau of productivity”.

The first applications can be found in the areas of gaming, marketing and advertising. For industrial applications, VR offers great potential that goes beyond just looking at virtual models. The idea of “Virtual Prototyping” (VP) or “Virtual Design Review” allows users to examine prototypes in a realistic way starting in the earliest design stages. Many companies conduct design reviews to detect errors in their products early on before the physical product is manufactured. Today, the classic design review process is often performed directly on the PC with the support of CAD software packages. The CAD model is viewed on the PC screen and examined for possible defects. The problem here is that people who are unfamiliar with CAD software may be excluded from this design review process. In addition, the mere consideration of complex CAD models on a two-dimensional screen creates the danger that the impressions of the dimensions and scales are lost. Therefore, ergonomic considerations, such as the accessibility of certain components, may be difficult to be carried out in CAD software.

In this paper, the development and evaluation of a VR-based tool to support engineering design review is described. The tool, which is called “VRSmart”, visualizes complex CAD data and allows for an easy-to-learn interaction with the 3D data. Construction groups can be assembled and disassembled as required, and the original design hierarchy is taken from the CAD file. In a preliminary user study with 72 participants, the tool was assessed with respect to its usability and user experience. In the next step, VRSmart was evaluated in real industrial environment and tested in an authentic design review setup on qualitative basis. The participants examined 3D models of two power units for predefined weaknesses and defects. The results of the study indicate that the VR-supported design review approach allows users to see slightly more faults in a 3D model than in a traditional CAD software-

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based approach on a PC screen. We also noticed differences in the acceptance of both approaches. Those people who work in service and test-stand prefer the VR Tool because watching and walking around the machinery components resembles their real work routine. Seeing the model as a CAD representation on screen was described as “unnatural”. Here, VR reduces the risk of exclusion of certain professional groups from the design review process. Furthermore, the intuitive controlling of the VR system allowed users to conduct standard interactions like changing the view, moving and rotating parts quicker than in a CAD software-based approach. Consequently, the VR system allowed for a much faster entry into the design review.

In summary, VR will not replace the design review process on a screen, but it is a useful addition for engineering companies that conduct design reviews on CAD engineering data of machines or machinery parts on a regular basis.

2. Background

VR presents a variety of new possibilities across a wide spectrum of industries. VR provides a safe, immersive and realistic experience for users, some of which are hard to recreate in real world settings. One of the main focuses in Industry 4.0 is the bridging of the digital, virtual and physical worlds, which are called cyber-physical systems. VR (and all related mixed-reality technologies) offers great potential to support this endeavor. Kovar et al. [4] sum up the various applications in Industry 4.0 and state that VR can effectively reduce costs and time during the design of new machines. The most obvious key benefit of VR is having the ability to test a number of factors without undertaking the time and costs of building the structure, thereby reducing the number of errors present in the completed product. Thus, VR supports a decision making process for optimally designed products, where virtual prototypes are examined in a realistic way from the earliest stages of design. In the past, VR technology was used primarily in the development of premium products since it was known for its low return on investment (ROI) due to its high costs [5]. However, today, VR technology has become common in industry and has become more cost competitive.

2.1. The case of design review

This paper focuses on the potential of VR for engineering design review. According to EC-61160 [6], design review meetings are important milestones within a product development process. If properly implemented, design reviews enhance the potential for delivering a product with the required dependability, quality, performance, safety and potential for reducing costs and delivery times. It is primarily intended to provide verification of the work of the design development team and to provide recommendations, where possible, to improve the product or process and its realization. It is a cognitive process where expert information must be communicated to collaborators for efficient decisions [7]. Communication during the design process has a substantial role because it exchanges messages and conveys ideas to people with different skills and interests. Currently, decision making is heavily influenced and complicated by increased technical complexities, a growing shortage of experienced workers, and time and budgetary pressures. The trend towards a complete digital design process, where physical products do not exist until most of the design has been complete, raise another communication barrier, especially for people outside the engineering community. For all the mentioned areas, 2D and 3D CAD on a screen has been the tool of choice so far. CAD is used as a construction and communication tool to convey design ideas during the design process [8]. However, CAD on a screen cannot meet all requirements, especially in regard to the functional and ergonomic validation processes. Moreover, CAD software does not allow for an intuitive analysis and manipulation of 3D models for users without a CAD or computer science background [9]. VR offers novel ways of interacting with the data. According to Zhang [10], VR provides a completely immersive and intuitive experience with very low learning requirements. The technology enables engineers to view their project in 3D and gain a greater understanding of how it works. This new way of visualization has the potential to simplify the decision making process by intuitively checking for faults, structural weaknesses and other design issues.

2.2. Related projects

Over the course of the last years, many research papers have covered VR topics for industrial applications with varying focuses. Prior to our work in this field, an extensive literature review was conducted to analyze the current state-of-the-art methods. The following section sums up the most relevant works with a special focus on VR-supported prototyping, decision making and design review for industry.

2.2.1. Virtual prototyping and decision making

The most common work-related applications of VR in industrial settings are those that utilize its interactive nature to support virtual prototyping and product design. Already in 1999, Gomes and Zachmann [11] predicted that virtual prototyping would soon play an important role in automotive (and probably other) industries by improving overall product quality. VR is a promising tool for obtaining quick answers in an intuitive way in the concept phase of the business process of a product, because in that phase data often change and are available only in a rough form. Designer can compare concepts and present them to their customers, who can see the results with their own eyes, making decisions much easier before the construction process starts [12]. Assembly planning and virtual prototyping are important steps in the product design process in which details about the appearance and how parts of a new product will be put together are formalized. Seth et al. [13] point out that virtual prototyping saves time and money compared to physical prototyping by addressing various aspects of the product life cycle such as ergonomic, workstation layout, tooling design, maintenance, and serviceability. In an early work from 2003, Bullinger et al. [14] propose a system for integrated virtual prototyping and testing of various systems, such as driver assistance, driver information, and multimedia components in a VR-supported driving simulator. In the same context, Bordegoni and Caruso [15] present a methodology that enables collaborative design review and modification of automotive interior components. The work of Peng [16] uses VR for evaluating the reachability of door handles within a vehicle. Bordegoni and Ferrise [17] studied the use of virtual prototyping based on visual, haptic and acoustic elements, which can be effectively used instead of physical products for the communication of a new product, and for the evaluation of its features. Ferrise et al. [18] present a set of case studies where interactive virtual prototypes are used to substitute the corresponding physical ones during activities concerning the product conceptualization and design. In the field of factory planning, Gebhard et al. [19] present a VR application, which fosters the layout planning process by granting planners the ability to perform realistic walkthroughs in digital factory models. Sampaio et al. [20] developed virtual models as tools to support decision-making in the planning of construction management and maintenance. VR models were created to support the maintenance process of exterior closures and interior finishes of walls and in the construction of buildings. In a recent work by Boton [21], the author proposes not only to view a model in three dimensions, but also to include the construction process as a function of time (4D) to conduct constructability analysis meetings.

Big parts of research on VR for industry describe tools to support maintenance activities and remote inspections. In order to optimize the manual maintenance processes, Linn et al. [22] developed a concept for visual remote inspections of manufacturing machines based on VR. The approach focuses on the usage of real-world recordings that enable the viewer to virtually move to another place. The recent work of Louison et al. [23] describes an accessibility study for assembly and maintenance scenarios using VR operators feedback to assess the feasibility of accessibility or maintenance processes. The latter work also contributes to the field of VR supported design review for ergonomic considerations.

2.2.2. Design review

Due to its visual nature, VR holds great potential for reviewing designs of CAD-based concepts. Already in the late '90s, a concept for VR tools for use in design reviews of mechanical products is proposed [24]. The work results in a 3D-interface that allows users, especially engineers, to evaluate different configurations of a product and gives them direct access to the product structure. In 1999, Gomes and Zachmann [11] presented several new interaction paradigms so that engineers and designers can experiment naturally with an engineering prototype. As innovation picks up pace, VR applications to support design review are getting more and more covered in research work. Santos et al. [25] present a unique effort in hardware and software research and development to facilitate collaborative mixed reality design reviews in indoor and outdoor scenes with mobile users. Naef and Payne [9] developed a VR-supported tool to enable intuitive analysis and manipulation of 3Dmodels for users without a CAD or computer science background. Bassanino et al. [8] investigate the impact that VR technology can have on visualization of a design review scenario in construction. Although the use of VR in this particular scenario was limited to test the design, its impact was huge to save the project cost and time. The present study by Bruno and Muzzupappa [26] aims to evaluate the feasibility and the efficacy of an innovative participatory design approach for a tool to evaluate the usability of the virtual product interface. According to the authors, VR is a valid tool to support participatory design, because it facilitates collaboration among designers and users. Choi et al. [27] emphasize VR's important role as an effective tool to support collaboration. The authors introduce a novel approach for an integrated virtual design review system, whereby the design idea can be communicated easily and realistically while the overall process of design review is supported. Bordegoni and Caruso [15] present the results of research work aimed at studying the use of virtual prototyping based on visual, haptic and acoustic elements, which can be effectively used instead of physical products for the communication of a new product, and for the evaluation of its features. The authors agree that VR can be used to support communication and interaction between different stakeholders.

Most recent work takes advantage of current graphics hardware, first consumer-ready VR devices and affordable tracking technologies, which enable natural movement and intuitive hand interaction. Martini et al. [28] present a 3D user interface with a focus on novel approaches in interface design for VR design review. The proposed 3D user interface is designed to be user-friendly while, at the same time, offering immersive CAD functionalities. Freeman et al. [29] performed user experiments to explore the hypothesis that allowing users to perform CAD-like view transformations and geometric manipulations in VR design reviews improves design understanding and decision making. Analysis of the experiment results show that enhanced interaction tools provide statistically significant advantages over a baseline VR design review environment for complex 3D models. Aromaa et al. [30] investigate, if the use of VP supports design reviews and identifies critical issues related to it. Two design review cases were studied related to a maintenance platform. Participants felt that the use of VP supports design reviews because it provides a common understanding of the design object, and also supports communication and interaction. Madathil and Greenstein [31] have developed a virtual collaborative three-dimensional remote moderated usability testing laboratory and employed it in a controlled study to evaluate its effectiveness. According to their results the VR environment is basically equivalent to the traditional lab and WebEx-based method in terms of the time taken by the test participants to complete the tasks and the number of defects identified.

2.3. Discussion of related projects

Analyzing the related work indicates that current VR tools to support design review can have a positive effect on the review outcomes quality. In fact, the reduction of costs and the enhancement of hardware and software quality have led VR to being widely used in the automotive industry [32]. Most scientific works investigate VR's potential with user studies in a laboratory setup in the form of questionnaires and usability studies on a qualitative basis. The latter work cited (Madathil and Greenstein [31]) is the only work so far that followed a quantitative approach by comparing the number of defects identified in VR and a traditional design review approach. Nevertheless, further research of VR-supported design review in real-world industrial settings based on authentic CAD models is needed, until companies can fully benefit from the technology's potential.

The work described in this paper contributes to this field of research and investigates VR's potential for an Austrian-based engineering company in a realistic design review situation with expert participants. The papers presented above form the basis for our implementation of a VR system for engineering design review. The following section describes the challenges that arise when using CAD data in VR, followed by a description of the prototype's features and components. Afterwards, we focus on its two-step evaluation approach.

3. System description

The interaction paradigm of the described prototype is based on the vision of VR as a valuable tool for the assembly and disassembly verification of complex 3D engineering models. According to Gomes and Zachmann [11], the VR system simulates and renders all characteristics that are relevant to the particular context as precisely and realistically as possible in an immersive environment. This section gives a brief overview of the prototype's implementation.

Commercial software for VR-supported decision making already exists (like *IC.IDO* or *TechViz*), but these systems need expert knowledge to be adapted to an existing manufacturing environment. In addition, most of them were developed for complex CAVE environments, which imply additional expenses for companies (see [33]). The advancements in computer 3D graphics technology and the latest emergence of powerful and affordable 3D graphics hardware have generated much interest in VR applications for industrial purposes for a comparably low price. For this prototype (called *VRSmart*), an HTC Vive headset was used as the VR hardware since its tracking sensors work reliably and its controllers allow for multimodal hand inputs. In addition, HTC Vive supports development in Unity3D, which has become the de facto standard for VR development. Unity3D facilitates the integration of scripted behavior and provides a simple import workflow for 3D data. The software runs on a PC with a powerful VR-ready GPU (GeForce GTX 1080 8GB). The educational license of 3dsMax is used for data conversion. We note that Unity3D and 3dsMax have separate pricing models for enterprise usage. In a first step, original CAD data was prepared for usage in Unity3D.

3.1. CAD data preparation

In general, getting CAD data into VR is a challenging task. Raposo et al. [34] describe the problems in detail. Difficulties arise because engineering models are not constructed to be visualized in real time. In some cases, the models are visually simplified representations, serving only as schematic representations of the characteristics to be analyzed. In other cases, the models are too large and complex to be visualized in real time. The number of polygons of a scene that is visualized significantly influences the number of frames that can be rendered within a second during runtime. For VR applications, a frame rate of not less than 90 frames per second is considered acceptable [35]. Due to the huge number of triangles produced when CAD models are converted

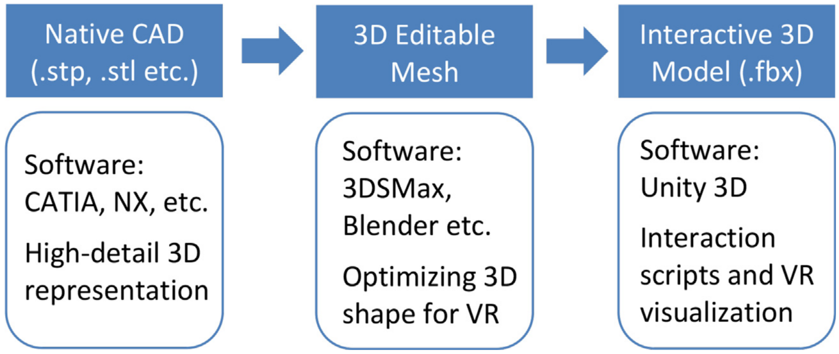

Fig. 1. CAD data is imported to 3D graphics software, converted to .fbx format and visualized in Unity3D.

into graphics models, the frame rate may quickly drop to an unacceptable level and could cause motion sickness. In the case of Unity3D, another challenge arises. The software (which has its origins in game development) does not support common CAD data formats such as STL (Standard Tessellation Language) or JT (Jupiter Tessellation). Instead, it uses file formats that are commonly used in games, such as FBX or OBJ. The trick to producing good low-polygon models is to select the edge that, when collapsed, will cause the smallest visual change to the model [36]. All relevant design features should be preserved during simplification. For example, edges on the contour should be found and retained.

In the context of model complexity, Lorenz et al. [37] propose a process for automatic CAD model reduction from the Siemens NX CAD system. The geometry data of CAD models is simplified by reduction algorithms and then loaded into a VR-software. Based on this approach, quick and easy ways to strip down the models details were explored to meet the desired frame rate while retaining enough details for an efficient design review. Fig. 1 depicts the workflow from the native CAD to an interactive 3D model in Unity3D.

The test object for visualizing CAD data in VR was the power unit depicted in Fig. 2. The original STL file was imported into 3ds Max, the mesh resolution was reduced and the final 3D model was converted to FBX format. FBX has the advantage that it does not omit the groups as defined by the engineer in the original CAD file. Next, this file was imported into Unity3D and placed within a simple test scene. Finally, the VR scene was tested with the HTC Vive. As long as Unity3D does not support the handling of native CAD file formats, it still needs this conversion step in between (Table 1).

Table 1
Reducing the mesh resolution of a 3D Model for visualization in VR.

	Mesh res 0	Mesh res −5	Mesh res −10
Polygons	32.830.926	11.056.848	1.120.696
Edges	98.492.778	33.170.544	3.362.088
Vertices	16.413.965	5.527.088	559.176

3.2. Interaction design

Interacting with standard CAD software requires some practice to select and modify objects with standard input devices like mouse and keyboard [9]. For this reason, it may be an obstacle for design review usage. The goal of VRSmart is to provide a set of easy-to-learn interactions to include various stakeholders with diverging needs and visions without any CAD or computer science background in the design review process.

VRSmart provides a way to visualize, manipulate and interact with complex data. The system can detect a user's input and modify the

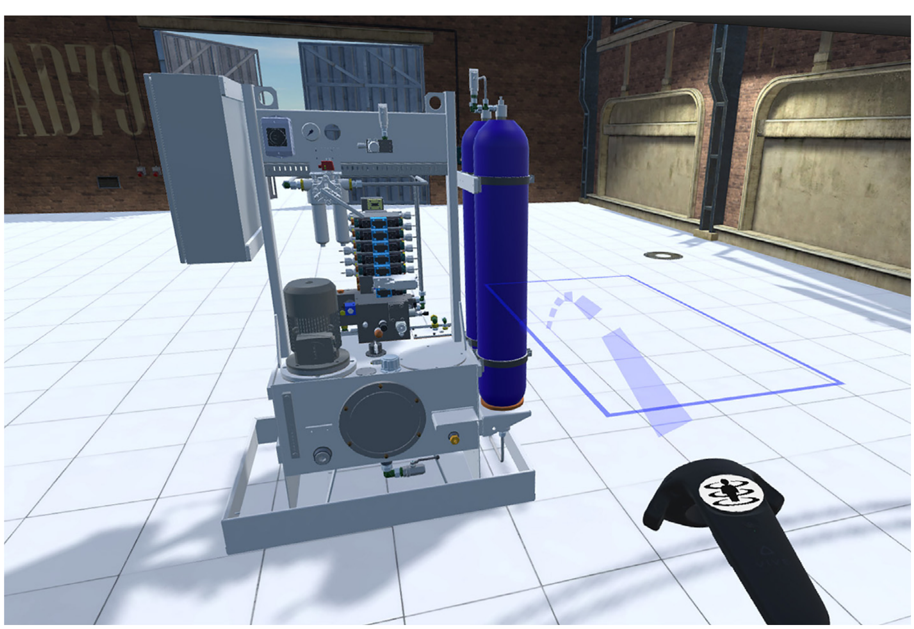

Fig. 2. Power unit based on CAD data. The blue square represents the real-world boundaries during the teleport. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

virtual world instantly while providing multimodal feedback. All scripts and functionalities can be activated by selecting the root node of the 3D file in Unity3D and picking a single menu option. There are no programming skills needed. This approach was also tested with power units that were noticeably bigger than the test object.

Based on the requirement analysis, the system supports the following interactions:

- Looking & walking: Standard features provided by the HTC Vives sensors;
- Touching & highlighting: Visual and haptic feedback provided when the user touches a component;
- Grabbing: Taking a component and changing its position in the 3D space;
- Separating & Merging: The dividing and joining of construction groups based on the CAD modeling structure; and
- Hiding & showing objects: Focusing the users view on specific components while hiding the rest.
- Teleport: This feature allows for traversing VR environments that are bigger that the physical interaction area (see the blue square in Fig. 2).

As soon as the Vive controller enters a construction group's collider, VRSmart triggers specific interactions. First tests showed that it is very important to let the user know which group he or she is currently interacting with. This user experience issue can be addressed by providing visual and haptic feedback. When the controller enters a collider, the system triggers a short vibration (using actuators integrated in the Vive controller). In addition, the system shows a highlighting effect that visually emphasizes the object of interest (see green squares in Fig. 3). Most of these interactions from the list of interactions are provided by *Steams* interaction demos and the *VR Toolkit* plugin in Unity3D and thus do not need to be implemented from scratch. However, some interactions were adapted to work with highly complex structures. A big challenge was caused by overlapping colliders. Normally, 3D games avoid placing many objects close together. The player always touches one collider at a time. For CAD data this is not possible, because many objects are placed in close proximity to each other or actually overlap (like a screw in a nut). So, if the user moves her controller into a 3D model, she may enter multiple colliders at a time. So, when the user wants to grab a specific part, she unintentionally grabs all parts that were currently touched by the controller. To address this issue VRSmart identifies the nearest collider during runtime and only lets the user interact with one (respectively the nearest) object at a time (see Wolfartsberger et al. [38] for details on this issue).

3.3. Assembly and disassembly

The VRSmart system enables users to separate and merge construction groups based on the CAD models structure. In other words, the structure and hierarchy of a 3D model created by an engineer in the CAD software can be accessed in VR. In real world settings, parts are disassembled by unscrewing, lifting or pushing parts to reach their inner components. Since we did not plan to evaluate the feasibility of construction steps, it was not necessary to exactly mimic these interactions in detail. Our goal was to develop a tool that allows users to quickly review construction groups to get an idea of the design and the underlying construction hierarchy. For this reason, the process of scrolling through the 3D models hierarchy was simplified, see Fig. 3 for a clear picture of the idea. The user moves a component in place and ungroups it. In the next step, she moves a subcomponent and ungroups it again until the lowest level in the construction hierarchy is reached. The same procedure also works the other way around to reassemble components.

4. Preliminary user study

The goal of this work is to evaluate VRSmart in a realistic industrial setting. To guarantee that the described system is ready for industrial usage, it had to fulfill the following requirements:

- Free of bugs and technical “fatal flaws”,
- Intuitive usage and easy-to-learn interactions, and
- Highly rated acceptance among users.

For this reason, a preliminary user study with students and visitors at the University of Applied Sciences Upper Austria was conducted with the goal to evaluate the tools usability and the user experience with VR and the hardware used. We restricted our selection to participants who had little or no practical experience with VR and CAD engineering with the goal to see, how quickly novice users learn to interact with the system. Experiences in design review were not required. They were first introduced to the HTC Vive headset and the purpose of VRSmart. They were then asked to use the tool and to fulfill the following tasks within a five to ten minute time-frame:

- Walk and “teleport” through the 3D environment, which was necessary to familiarize the users with VR;
- Look at and investigate the power unit;
- Take parts out of the power units; and
- Separate and merge the construction groups.

As soon as these tasks were done, the participants were asked to complete a questionnaire on demographic data and usability issues. The following subsection summarizes the results of the test session.

4.1. Results

Altogether, 72 participants (Male: 50, Female: 22) filled out the questionnaire. As a result, we collected data from a mostly young audience (M: 22.35 years, SD: 3.62). The first questions helped us to determine if the user group was tech-savvy and familiar with VR

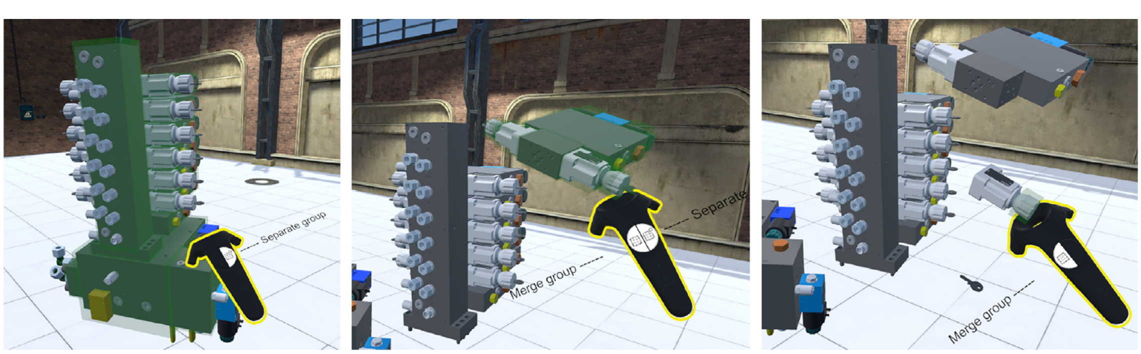

Fig. 3. Deconstructing a component from top level to lowest level following its CAD construction hierarchy.

Table 2
User survey of VRSmart in lab setup (n = 72), 1 - strongly agree, 5 - strongly disagree.

Questions	Mean	SD
Wearing the device is comfortable.	1,78	0,88
The interaction approach is intuitive.	1,53	0,73
Interacting with the components is fun.	1,36	0,59
The interaction is derived from real gestures.	1,69	0,78
The display resolution is sufficient.	1,51	0,77
I have been able to easily select and move parts of the power unit.	1,25	0,50
I have a good idea of the power unit's size.	1,25	0,52
The VR environment adds value compared to viewing the power unit on the screen.	1,28	0,54
Being in VR I feel insecure, because I do not know what is happening around me.	3,33	1,29
The cable on the back is annoying.	3,17	1,28
After removing the headset I felt dizzy.	4,44	1,03
I can imagine that this technology is used in an industrial working environment.	1,33	0,69
The application is future-oriented.	1,22	0,45

technologies. On average, their computer skills were estimated as "good" on average (M: 2.04, SD: 0.81, where 1 means "very good" and 5 means "very bad"), but they had no computer science background. They play computer games occasionally (M: 2.56, SD: 1.03, where 1 means "daily" and 4 means: "never"). Only seven participants have previously used a VR-headset. The previous knowledge about VR was estimated as "moderate" to "low" (M: 3.47, SD: 0.96). In summary, the test group tended to be tech-savvy with low practical experience with VR. The biggest potential for VR is seen in industry and production (66 mentions), medicine (51 mentions) and entertainment (including movies and gaming, 64 mentions).

The next questions focused solely on usability (5-point Likert scale from 1 - "totally agree" to 5 - "totally disagree"). A detailed list of questions and results is shown in Table 2. The usage of the VR-headset is considered as comfortable (M: 1.78, SD: 0.88) and intuitive (M: 1.53, SD: 0.73). The interaction with the components is enjoyable (M: 1.36, SD: 0.59) and the interactions are derived from real gestures (M: 1.69, SD: 0.78). Additionally, the display resolution of the HTC VIVE is considered as sufficient (M: 1.51, SD: 0.77). We asked them if they felt insecure while wearing the headset (for example, because they do not know what is happening around them or someone is talking). Being cut off from the real world was indeed a real problem for many participants (M: 3.33, SD: 1.29). We also noticed that many participants felt annoyed by the cable on the back of the headset, which connects the headset to the PC (M: 3.17, SD: 1.28). Motion sickness was not an issue for most users, mostly because of the short duration of the test sessions (M: 4.44, SD: 1.03). Only six out of 72 persons noted a certain feeling of dizziness. The participants had no problems selecting and moving the components of the 3D model (M: 1.25, SD: 0.50) and the tool provided a good idea of the power unit's overall size (M: 1.25, SD: 0.52). From their opinion, the VR environment adds value compared to viewing the power unit on the screen (M: 1.28, SD: 0.54). In general, they can imagine that this technology is used in an industrial working environment (M: 1.33, SD: 0.69) and the application is perceived as "future-oriented" (M: 1.22, SD: 0.45).

We concluded the questionnaire with free-text answers on what the users liked or disliked in particular. The participants positively highlighted the simple and easy-to-learn user interactions, the level of immersion and the high detail level of the 3D model. In contrast, users (again) criticized the cable at the back and that optical glasses significantly reduce the wearing comfort of the VR-headset. One user missed a feature to get a better impression of the power unit's weight. The latter comment provides an interesting direction for future work. The other issues are hardware related and could not be fixed within the scope of this work. Observations during the test sessions revealed some bugs when users used both VIVE controllers at the same time (with concurrent pressing of buttons). These bugs were corrected and other issues concerning the lighting situation and shader settings in the scene were improved for the final version.

Altogether, VRSmart received positive feedback. We note that it is difficult to distinguish between the immediate "wow"-effect induced by experiencing a VR system hands-on for the first time versus judging the actual success of the design against the set criteria. This effect was also mentioned by Naef and Payne [9]. Nonetheless, observing such a large number of users in an informal setting provided a good insight into how quickly people pick up different interaction methods in a 3D work space environment. Summing up, the preliminary user study underlined that VRSmart was ready to be tested in a realistic industrial setting.

5. User study in industrial context

In the next step, a design review session with an Austrian-located engineering company was organized. The company plans and builds power units for industrial usage, which are very different in their size and complexity. Design review meetings are important milestones within their product development process to provide verification of the work of the design development team and to provide recommendations, where possible, to improve the product or process and its realization. As stated in Section 2.1, it is a cognitive process where expert information must be communicated to collaborators for efficient decisions [7]. The company's design review approach follows the same principle. Meetings are conducted in small groups (normally no more than four people), where they discuss early designs and share their experiences from different points of view. For this reason, review teams are mixed, with each member having a different working background. Communication during the design process has a substantial role because it exchanges messages and conveys ideas to people with different skills and interests. The company uses the software "Creo View" during their design review session. It is a tool for visualizing and sharing 3D CAD product information, models, drawings, images and documents for interrogation and visual collaboration.

5.1. Methodology

The goal of this work is to compare the effectiveness of VR-supported design review to conventional approaches with CAD-software support. As stated before, CAD software does not allow for an intuitive analysis and manipulation of 3D models for users without a CAD or computer science background. Conversely, VR has the potential to simplify the process of decision making by intuitively checking for faults, structural weaknesses and other design issues. This statement is the basis for our research question:

Does a VR-supported design review approach allow users to see more faults in a 3D engineering model than in a CAD software-based design review approach?

To answer this research question, the evaluation was planned and conducted as follows.

5.1.1. Planning and test setup

In a first step, an experienced CAD design engineer from the company chose two power units to be reviewed for the evaluation. The later participants of the study have never seen the CAD models before. These power units were comparable in size and complexity (Fig. 4 shows the models, which are referred to as EVA1 and EVA2). Next, a list of 27 common defects and flaws were defined (see Tables 5 and 6 at the end of the document for detailed lists with descriptions) and integrated in the power units' CAD file. All of these flaws are realistic and documented (from the company's earlier projects). Note that there are some very similar flaws in EVA1 and EVA2, e.g., too small welding gaps (E1.9 and E2.7) or issues concerning the thermometer's position (E1.2 and 2.4). According to the CAD design engineer, it was not possible to find

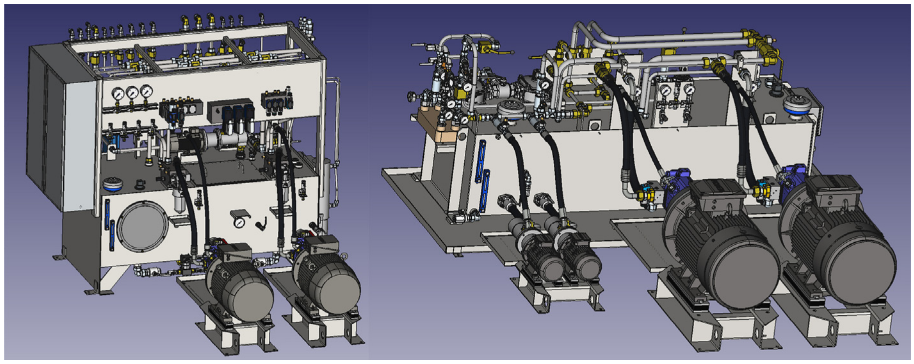

Fig. 4. The two 3D models used during design review evaluation. Left: EVA1, right: EVA2.

enough unique, comparable and still realistic flaws. Nevertheless, these similar flaws are never at the exact same position in the two test models. The flaws were then classified as follows:

- Ergonomic flaws: e.g., poor accessibility of parts (Fig. 6),
- Design flaws: e.g., collisions or inaccuracies, and
- Logical flaws: e.g., wrong circuit logic.

In the next step, 16 employees were asked to take part in the evaluation. They had diverse working backgrounds, but all of them regularly participated in design reviews. The team members were working in assembly (3), sales and distribution (6), service (1), production planning (2), test-stand (1) and CAD design engineering (3). Four teams of four people each were formed. Following the company's design review approach, the review teams were mixed, with each member having a different working background. For each group, a one hour timeframe was scheduled in which both design review approaches on different 3D models were tested. The sessions were audio-recorded, and interesting observations were written. In detail, the evaluation was conducted as follows:

- Introduction - 10 min
- Design review with VR support or Creo View support on 3D model EVA1 - 20 min
- Design review with the alternative method (not used in the previous step) on 3D model EVA2 - 20 min
- Questionnaire - 10 min (see Table 4)

In the introduction, the test procedure was explained and the participants were told to look for possible ergonomic, design-related and logical flaws in the shown 3D models. Group one started with the VR-supported design review and examined 3D model EVA1.The participants were requested to nominate one person to control the VR-headset. During the evaluation, they were allowed to pass the VR headset to other persons in the group. The other team members watched the streamed image from the VR view on a TV screen (see Fig. 5, right). After 20 min, the group switched to Creo View and examined 3D model EVA2. Again, one person operated the software and the others watched the screen (see Fig. 5, left). The starting method (VR or Creo View) was switched from group to group to prevent a certain learning effect (especially for similar flaws in the 3D models). When the group found and agreed on a flaw (meaning that everybody in the group agreed that the flaw was serious and had to be fixed), they said so, and the flaw was written down. Afterwards, every participant filled out a questionnaire to gather demographic information as well as feedback on both design review sessions using a 5-point Likert scale (Table 4).

5.2. Results

Altogether, 16 participants (Male: 14, Female: 2) took part in the evaluation. The average age was 35.44 years (SD: 10.49) and they ranged from 19 to 58 years. Their computer skills were estimated as “good” on average (M: 2.19, SD: SD: 0.75, where 1 means “very good” and 5 means “very bad”). Their previous knowledge about VR was estimated as “moderate” to “low” (M: 3.81, SD: 0.83). Additionally, their previous knowledge about CAD-software was estimated as “moderate” (M: 3.31, SD: 1.20) with an expected high variation due to the participants' diversified working backgrounds. 10 out of 16 participants have been able to test the VR application at the company's VR room in advance of the evaluation.

Table 3 displays the results of the design review evaluation. Altogether, the participants found 30 of 54 flaws in VR (55.6%) and 25 of 54 flaws in Creo View (46.%). All groups were more successful at finding flaws using VR than using Creo View, although the difference is small. Only three errors were not found at all with VR or with Creo View. Detailed breakdowns by flaw descriptions are shown in Table 7 (for EVA1) and Table 8 (for EVA2) at the end of the document.

The results indicate that a VR-supported design review allows users to see more faults in a 3D engineering model than a CAD software-based design review approach. Due to the small test sample, the evaluation can be considered as exploratory research, which forms the basis for more conclusive studies to clearly answer the research question from

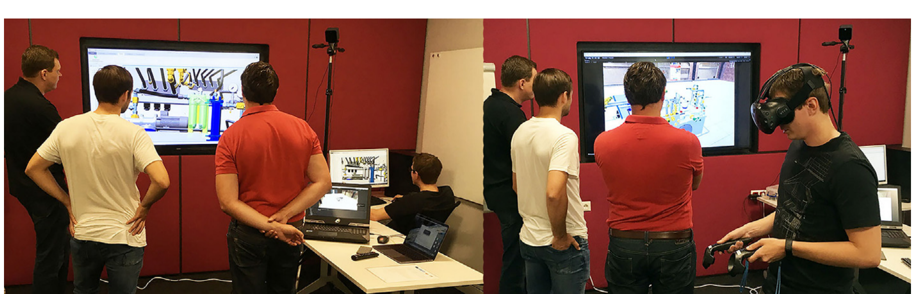

Fig. 5. Design review groups, left: Creo View, right: VR.

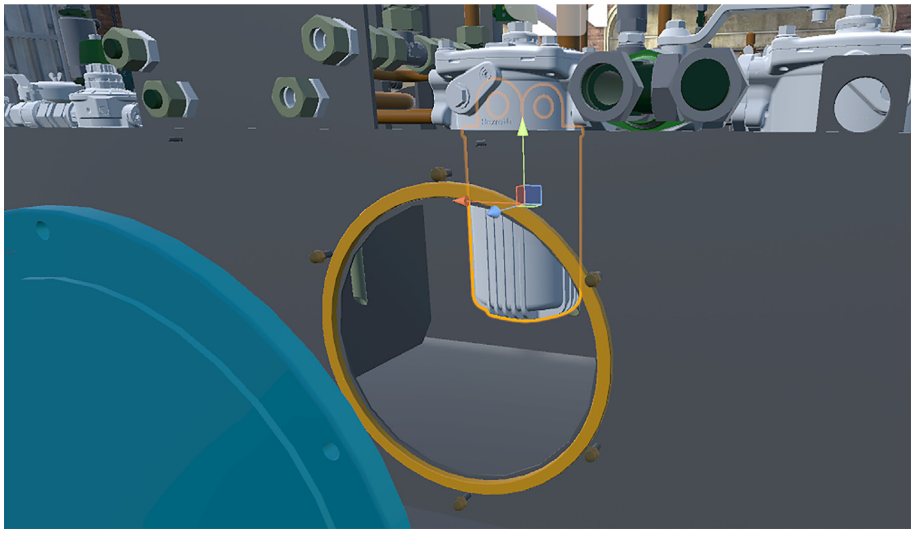

Fig. 6. Filter is placed in front of cleaning cover, the interior is difficult to access (E2.1).

Table 3
Results of the design review evaluation with VR and Creo View.

Group	Flaws found in VR	Flaws found in Creo View
1	5/15	4/12
2	7/12	5/15
3	9/15	6/12
4	9/12	10/15
Sum	30 (≅55,6%)	25 (≅46,3%)

Section 5.1. Nevertheless, the results revealed interesting points. A detailed look at the classification of flaws shows that participants found more design related issues with VR (21 in VR versus 18 in Creo View). Regarding logical issues, no method has an advantage (both two findings). Interestingly, the ergonomic issues do not reveal a big advantage for VR (7 in VR versus 5 in Creo View). Therefore, the assumption that CAD on a screen cannot meet all requirements in regard to functional and ergonomic validations cannot be fully confirmed.

The observations and findings taken from the audio recordings gave some interesting indications on how the technologies have influenced the communication and cooperation among group members. In groups where no team member was well acquainted with Creo View, problems occurred while choosing the right perspective on the 3D model or moving parts. The discussion was regularly interrupted, thus resulting in a noticeable loss of time. Conversely, the intuitive interaction with the VR system allowed for a much faster entry into the design review. Those users with little or no experience with CAD software immediately preferred using VR due to its easy-to-learn interaction concept. We hardly noticed any interruptions caused by usability issues and the discussion was continued undisturbed without losing the thread. In this context, a VR-related weakness came to light: The user chooses the right view on a specific component by moving her head. This interaction is very intuitive, but the image (also for the team members on the screen) is always in motion. Many participants said they had difficulty focusing on a particular component. The person in control of the VR headset was repeatedly asked to hold her head still so that the others could concentrate on a detail. The method was missing a function to "freeze" the image to be able to discuss the current view. This is an important direction for future work. According to the discussions, we also noticed differences in the acceptance of both approaches. Those people who work in service and test-stand prefer the VR Tool because watching and "walking around" the machinery components resembles their real work routine. Seeing the model as a CAD representation on a screen was described as "unnatural". Here, VR reduces the risk of exclusion of certain professional groups from the design review process.

These points are also reflected in the answers to the questionnaires. A detailed list of the questions and results is shown in Table 4. The VR tool is considered as easy to learn (Mean: 1.67, SD: 0.89, on a 5-point Likert scale from 1 - "totally agree" to 5 - "totally disagree"). Most participants agree that VR has a positive effect on the communication within the team (Mean: 2.13, SD: 1.15). We note that two participants (both over 45 years) did not agree here. Furthermore, they agree that the VR view adds value to design review compared to the view on the screen in Creo View (Mean: 1.88, SD: 0.96). Despite the issues discussed above, they also agree that VR makes it easier to take a specific view of the unit and to see parts in detail (Mean: 1.44, SD: 0.63). Interestingly, all participants working as CAD construction engineers (and thus were familiar with CAD software) fully agreed with this statement. Conversely, eight participants noted that in direct comparison, using Creo View is easier. These have been mostly users who were already familiar with Creo View (Mean: 2.30, SD: 1.06). Those who actively used the VR headset during the evaluation felt moderately isolated from their team (Mean: 3.20, SD: 1.32). Four users asked for features that make their colleagues perceptible in VR. This is also an important direction for future work. Some users agree that Creo View provides more useful tools for design review (Mean: 3.00, SD: 1.10), such as the layers and construction hierarchy in a separate window (something the VR tool does not provide). We also asked if they think VR has something playful, which hinders a serious design review process. They mainly

Table 4
User survey of VRSmart in a company (n = 16), 1 - strongly agree, 5 - strongly disagree.

Questions	Mean	SD
VR enables me to see flaws I could not see in Creo View.	2,56	1,03
VR has a positive effect on the communication.	2,13	1,15
The VR view adds value to design review compared to the view on the screen in Creo View.	1,88	0,96
VR makes it easier to take a specific view of the unit and to see parts in detail.	1,44	0,63
The interactions in VR are easy to learn.[a]	1,67	0,89
In direct comparison, using Creo View is easier.[a]	2,30	1,06
Using VR I felt isolated from my team.[a]	3,20	1,32
Creo View provides more useful tools for design review.	3,00	1,10
VR has something playful. This hinders a serious design review process.	3,88	0,96
VR is a useful addition to design review at our company.	1,88	1,02

[a] Only answered by those, who actively used VR during the evaluation.

Table 5
Flaw descriptions - EVA 1.

Flaw descriptions - EVA 1	Code
The tubes on the steel construction were not sealed with sheet metal, making the steel structure more susceptible to corrosion.	E1.1
The thermometer is installed too high, the oil level could be lower during operation.	E1.2
Installation space for filter bowl too low, drip tray was placed too close under the filter.	E1.3
Installation space for filter bowl too small, the console was planned too small.	E1.4
Flow filter directly in front of the servicing cover, thus poor accessibility of inner parts.	E1.5
There are no threads for eyebolts or other transport options.	E1.6
Pump bracket too short, shaft of pump and motor collide.	E1.7
The stopcock in the suction line cannot be operated or collides with the valve when closed.	E1.8
The welding gap for the return flow filter is too small.	E1.9
The lever on the filter cannot be turned completely by 180° (collision with return pipe).	E1.10
Piping collides with the manometer.	E1.11
Error in the circuit logic: The return flow of the filter cooling circuit should lead to the suction chamber of the main pumps.	E1.12
Terminal box too close to the guard plate, the cable entry below is no longer accessible.	E1.13
Front panel cut-out does not fit the block.	E1.14
The cover of the container collides with the return flow filter.	E1.15

Table 6
Flaw descriptions - EVA 2.

Flaw descriptions - EVA 2	Code
Return flow filter placed in front of cleaning cover, the interior is difficult to access.	E2.1
Placement of the lifting lugs prevents proper transport with the crane.	E2.2
The shaft of pump and motor collide, the pump bracket is too short.	E2.3
Thermometer too high: At low oil level, the temperature is not displayed correctly.	E2.4
The cover in the tank collides with the return flow filter.	E2.5
Container cut-out for return flow filter is wrong.	E2.6
Weld gap at the stiffening plate on the pump is too small.	E2.7
Errors in the circuit logic: The leak oil and the tank line of the pressure protection are returned directly into the suction area of the second main pump.	E2.8
Collision of the pipeline with the screw connection of the return pipe.	E2.9
The float switch collides with a radiator.	E2.10
Wrong pressure flange inserted.	E2.11
The lever on the filter cannot be turned completely by 180° (collision with piping).	E2.12

Table 7
Flaws with categories and results for model EVA1: + + flaw has been found by both groups using VR or Creo View on EVA1, + flaw has been found by one group, − flaw has not been found.

Flaws - EVA1	Category	VR	Creo view
E1.1	Design	–	+
E1.2	Design	+	+ +
E1.3	Ergonomics	+	+
E1.4	Ergonomics	+	+
E1.5	Ergonomics	–	+ +
E1.6	Design	+	+
E1.7	Design	+ +	–
E1.8	Ergonomics	+ +	–
E1.9	Design	–	–
E1.10	Ergonomics	+	–
E1.11	Design	+ +	+ +
E1.12	Logic	–	+ +
E1.13	Design	–	+
E1.14	Design	+ +	+
E1.15	Design	+	+

disagreed on this point (Mean: 3.88, SD: 0.96). In general, they think VR is a useful addition to design review at their company (Mean: 1.88, SD: 1.02).

6. Summary and conclusions

This work describes the design, implementation and evaluation of the VR-based tool VRSmart to support engineering design review. In a preliminary study with 72 users the tool was assessed with respect to its usability and user experience. The following evaluation was conducted in a realistic industrial setting with 16 participants from an Austrian engineering company. The VR-based design review approach was compared to a traditional method using Creo View on a PC screen. The results indicate that the VR-supported design review approach allows users to see slightly more faults in a 3D engineering model than a CAD software-based design review approach. Due to the small test sample, further studies in realistic settings are needed to clearly check VR's potential for design review. With our work, we want to encourage researchers to carry out evaluations in real-world settings rather than laboratory environments to get transferable results for industry applications.

Table 8
Flaws with categories and results for model EVA2: + + flaw has been found by both groups using VR or Creo View on EVA2, + flaw has been found by one group, − flaw has not been found.

Flaws EVA2	Category	VR	Creo view
E2.1	Ergonomics	+ +	–
E2.2	Design	+ +	+ +
E2.3	Design	+ +	+ +
E2.4	Design	+ +	+
E2.5	Design	+	–
E2.6	Design	–	–
E2.7	Design	–	–
E2.8	Logic	+ +	–
E2.9	Design	+ +	+
E2.10	Design	+ +	+ +
E2.11	Design	+	+
E2.12	Ergonomics	–	+

We see that VR's biggest advantage is its positive effect on the communication within the design review teams by reducing the risk of exclusion of certain professional groups from the review process. Furthermore, VR has a big potential to accelerate the design review process with a shorter training period. The evaluation also revealed interesting challenges for future work. Design review is a collaborative process, but VR isolates users from their team members. Users asked for features that make their colleagues perceptible in VR. There has been research on this topic. For example, Lankes et al. [39] designed a collaborative VR system where users can intervene in the virtual world from outside via tablets in the same tracking environment. By this means, the authors try to counteract the feeling of isolation. Another issue was raised by VR's interactive and intuitive moving concept. As the VR-user moves her head to get the right view of a component, the image on the screen is always in motion. The participants in the evaluation who were watching the VR scene on a TV screen had difficulties focusing on a particular component. They missed a function to "freeze" the image to be able to discuss the current view. In addition, the participants wished for a feature to update models in CAD and immediately see model changes in the VR headsets. Up to now, this feature is difficult to implement due to a lack of standards for an automated and efficient data transfer protocol. A first approach in this direction is presented by Du et al. [40]. In general, commonly used software packages for VR-development (like Unity3D) come from game development and do not support industry standards regarding data formats and CAD metadata. These limitations need to be addressed in future (see also [21]).

Altogether, the study reveals that VR is a useful addition, and not a replacement, to current design review approaches. The technology provides promising ways to visualize CAD data by offering the potential to simplify the decision making process by intuitively checking for design issues. The VR tool shown in this paper shows a great potential to improve workflow efficiency through enhanced common understanding. Nevertheless, further studies in realistic settings are needed to exploit VR's full potential.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.autcon.2019.03.018.

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