HOW DOES VIRTUAL REALITY (VR) FACILITATE DESIGN? A REVIEW OF VR USAGE IN EARLY-STAGE ENGINEERING DESIGN

Liao, Ting (1);
She, Jinjuan (2)

1: Stevens Institute of Technology;
2: Miami University

ABSTRACT

Virtual reality (VR) has been widely used in engineering design in different ways. It has the potential to enhance some design aspects, such as visualization and interaction, but might be incapable of solving the others. There are no consensus or general guidelines on how VR can facilitate design processes. This paper aims to understand how VR is currently used in engineering design at an early stage, so that researchers and practitioners can better know when and how to use VR for efficient design activities. Specifically, this paper reviews the research questions and applications addressed by using VR technology. The study helps identify the design questions currently studied, and gaps to be filled in order to use VR effectively for optimal design outcomes. This review also provides guidelines about when and how to use VR in design research and practices.

Keywords: Virtual reality, Conceptual design, Evaluation, prototyping, Design for X (DfX)

Contact:
She, Jinjuan
Miami University
United States of America
jshe@miamioh.edu

Cite this article: Liao, T., She, J. (2023) ‘How Does Virtual Reality (VR) Facilitate Design? A Review of VR Usage in Early-Stage Engineering Design’, in *Proceedings of the International Conference on Engineering Design (ICED23),* Bordeaux, France, 24-28 July 2023. DOI:10.1017/pds.2023.212

1 INTRODUCTION

Virtual reality (VR) – defined as "a computer-generated digital environment that can be experienced and interacted with as if it were real" – was invented in the last century, with Sutherland's head-mounted three-dimensional display (Jerald, 2016; Sutherland, 1968), and evolved with the advancements in computing technology and 3D software in the 1990s, providing a more interactive and immersive visualization of the simple Computer-Aided Design (CAD) models (Berta, 1999). After 2010, with the full maturity of VR technology due to the reduced cost and improved hardware usability, VR is not only used in the most predictable areas, such as gaming, but it also extensively spread to the medical, military (Liu et al., 2018), sport (Han et al., 2019), educational (Lau and Lee, 2015), and astronomical (West et al., 2018) fields, among others.

VR systems utilize devices that enable immersion to different degrees. These systems can be classified as head-mounted displays (HMD), the Cave Automatic Virtual Environment (CAVE) system or similar devices, and Desktop VR with stereo glasses for 3D visualization, based on Rebelo's taxonomy (Rebelo et al. 2011). Many VR systems also integrate supporting tools to allow users to interact with and modify the artifact in the Virtual Environment (VE) (Berni and Borgianni, 2020). These tools simulate senses and enhance interactivity with users, including hand controllers and gloves, sound inputs/outputs, and haptic feedback. In addition, biometric instruments (e.g., eye tracking, galvanic skin response) are increasingly used in design research to monitor unintended and inadvertent human reactions and behavior, providing more insightful data (Borgianni and MacCioni, 2020).

VR received increasing attention from researchers and practitioners in the engineering design community for its applications in many fields, such as product design, training, maintenance, assembly. Particularly, researchers saw the chance for VR's support in the initial design phases besides those that are "more naturally" juxtaposed to VR, namely, 3D modeling, virtual prototyping, and product evaluation (Ottosson, 2002). The early stages of engineering design, including ideation, evaluation, and prototyping, are crucial for successful product development (Berni and Borgianni, 2020). The early-stage design, which often involves non-geometric, qualitative information and multiple stakeholders, lacks effective visual representations and tools to enable designers to think creatively and work collaboratively (Dieter and Schmidt, 2008). Therefore, versatile VR applications have a great potential to facilitate designers to detect problems early, reduce design effort, and improve product quality. For example, VR systems can enhance product evaluation with VR interfaces related to human interaction with virtual prototypes (Soares Falcão and Márcio Soares, 2013; Stark et al., 2010). Despite its benefits, VR applications in early-stage design lack a systematic review, particularly regarding which design questions VR can effectively address. This paper aims to identify the research questions that relate to VR applications in early-stage design. Through this work, we help understand how VR is currently used in product design and how VR can effectively be used for optimal design outcomes.

2 METHODS

We conducted a systematic review of related studies following the PRISMA (Preferred Reporting Items for Systematic Reviews and Meta-Analyses) process (Bargelis et al., 2013). Starting with identification, we set the scope of the research, selected databases and search strings. We are interested in the usage of virtual reality in early-stage engineering design, especially physical product design. Therefore, we used the keywords "virtual reality" or "VR" combined with "product design" or "product development." The search was conducted on Web of Science and Google Scholar. Only including the articles in English within ten years (2012-2022) yielded 2281 items. Next, articles were screened by title to remove duplicates and non-relevant items. Moreover, nine additional articles were identified by scanning the references. In total, 547 papers remained after the initial screening. All identified papers were screened on abstracts to only include papers that focus on early-stage design and are engineering-related. After the screening, we considered 149 relevant papers for full text review. 100 papers were excluded for the following reasons: no full text and DOI numbers; focusing on the VR technology design or software; and using VR for training or strategy evaluation. Finally, we included 49 papers in the review, including some papers that do not explicitly distinguish VR with Augmented Reality (AR) and Mixed Reality (MR). The selection process is shown in Figure 1.

https://doi.org/10.1017/pds.2023.212 Published online by Cambridge University Press

The papers reviewed are grouped to focus on early-stage design processes, including concept generation, design evaluation, prototyping (Ulrich et al. 2020; Berni and Borgianni, 2020), and study platform validation. Within each process, papers were further categorized based on their motivations and topics, such as creativity, co-design, etc., as summarized and cross-validated by the two authors.

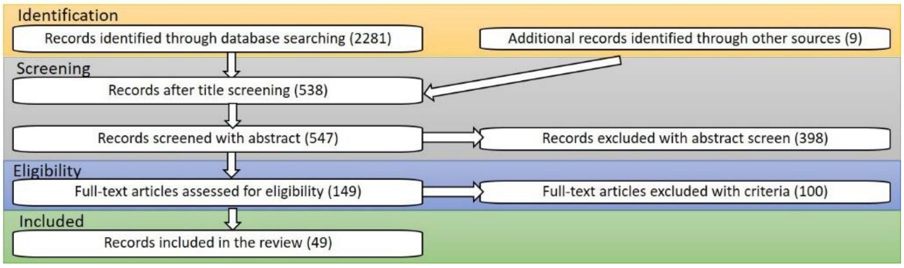

Figure 1. Paper selection process

3 FINDINGS

3.1 Concept generation

In concept generation (Table 1), VR is mainly used for creativity and co-design / participatory design. In addition, some researchers develop VR-based tools or compare tools in concept design.

Table 1. Summary of literature on concept generation

Research Questions	Key Takeaway
Creativity - In VR, are there any relationships between an individual's creativity, flow state, brainwave, and the quality of his or her design outcome? (Yang et al., 2019) - What are the effects of VR on an individual's design process and outcomes? (Chang et al., 2020; Chen et al., 2022) - What are the interventions in VR that affect an individual's creative performance? (Yang et al., 2019)	- VR creates an immersive and closed space, and is helpful in studying ideation activities. - Increased flow has positive effects on creativity. - Current creativity studies with VR technology are mostly focusing on people with less design experience and its effect on experts are less clear. - The effectiveness of VR is mostly drawn from quantitative analysis of controlled studies that involve simple design problems within a limited time period. - The novelty effect of VR on design cannot be ruled out.
Co-design - What are the values of VR technology for collaborative design? (Arrighi and Mougenot, 2019; Koutsabasis et al., 2012; Masclet et al., 2021) - How does VR effectively support early-stage design in user interface and interaction design? (Thalen and van der Voort, 2013)	- Most co-design studies use industry case studies to draw conclusions about the usefulness of VR. - VR is useful in design review and customer-centered evaluation of conceptual design due to increased communication, level of immersion and control without high dependency on technical expertise, - The visual details, rendering quality, and simulated physical behaviors are limited.
Tools - How does VR support end-user effective interactions? (Arrighi and Mougenot, 2019; Maurya et al., 2019) - How does immersive technology support protocol analysis? (Masclet et al., 2020) - What are the influences of representations in different modalities on design activities? (Filippi and Barattin, 2019) - Is there any benchmarking method for tool selection? (Germani et al., 2012)	- A platform that allows users to be immersive and directly perform design tasks and modify a virtual prototype helps them to be more engaged in the design tasks, and produce more creative outcomes. - Immersive technology can enhance the design activity, and capture design process data for research purposes. - Different representations have their unique advantages in design activities. - Structured benchmarking method is possible, but relies on expert judgements.

https://doi.org/10.1017/pds.2023.212 Published online by Cambridge University Press

Creativity. Studies about creativity in concept generation with VR were conducted with a variety of participants, including general public (Yang et al., 2019), college students (Yang et al., 2018), and K-12 students (Chang et al., 2020; Thalen and van der Voort, 2013). The conclusions were mostly drawn from quantitative analysis. Yang et al. (2019) studied the relationships between a person's behaviors and the brainwave state in creative activities by using VR as an immersive platform to reduce distractions and using brainwave equipment to measure attention and meditation value. Yang et al. (2018) explored the effects of immersive VR on an individual's creative performance and factors related to creativity, including flow, attention, and mental relaxation. Both studies showed that the participants in the immersive VR condition entered the flow state more easily and had higher-quality creative solutions than those in the paper-and-pencil condition.

More studies were conducted on K-12 students. Yang et al. (2019) studied the effect of different EEG feedback on creative design activities in a VR environment with high school students. Chang et al. (2020) found that VR significantly affects design processes, design outcomes, and experiential learning processes. The VR group exhibited active behaviors in reflective observation, higher frequencies of concrete experience, and active experimentation behaviors. The behavior transition patterns between VR and non-VR groups are different. Chen et al. (2022) investigated the influence of VR on middle school learners' design creativity and cognitive load. The study found VR significantly improved learning concepts, acquiring knowledge and creative motivation, but did not influence creative thinking ability. In addition, VR significantly improved the usefulness of ideas generated.

Co-design. The studies about co-design with VR mostly use industry case studies. Masclet et al. (2021) studied if AR and VR systems facilitate the co-design process. The protocol analysis suggested that the technology introduction did not impair the design activity, in terms of similar patterns in the cognitive activities and time commitment during the co-design. Moreover Koutsabasis et al. (2012) showed that the virtual environment could support collaborative design in various stages and activities, especially in the design review and customer-centered evaluation of the conceptual design. It provided a satisfactory collaboration environment with increased communication and situational awareness when the emphasis of design was on form and structure, rather than complex functions or processes. Arrighi and Mougenot (2019) created a mixed reality computer-aided design system that enables potential users to visualize a prototype in three dimensions and manipulate, and change it in a natural way through tangible user interfaces. Thalen and van der Voort (2013) studied if VR and AR can improve the design of user interfaces and interactions in the early stages. They found that reviewing and acting out workflows is a valuable addition to existing methods as it triggers participants to express knowledge and feedback that might otherwise be left out.

Developing and comparing VR-based tools to support concept design. Maurya et al. (2019) found that when users are provided with a tool that allows them to directly perform design tasks and modify a virtual prototype, as compared to when they have no control, they are more engaged in the design tasks, more satisfied with the design process and they produce more creative outcomes. Arrighi and Mougenot (2019) proposed a new modular digital tool to allow users to actively participate in the design process through a high-level of both immersion and control. The tool is based on MR with a case application in interior design as an example. Masclet et al. (2020) developed an AR-based method to support real-time coding for co-design protocol analysis. Analysis of the usability of the tool, coding accuracy, and time required to complete coding showed that the tool helped generate reliable datasets that are comparable to those obtained with a post-session coding method. VR brings new opportunities for designs, and also confuses designers and researchers regarding tool selection. A few studies examined the effect of different tools in design activities. Filippi and Barattin (2019) evaluated the influence of representations of shapes in VR, AR, and pure reality (PR) on interactive shape-based design activities. They suggested that if the design focuses more on novelty, then use VR; if more focus on usefulness, then use PR. To support tool selection (collaborative product design tool/platform) and impact evaluation of using the tool on synchronous and remote design collaboration, Germani et al. (2012) proposed and validated the usefulness of a structured benchmarking method based on expert judgements and defined a set of benchmarking weights.

3.2 Design evaluation

VR is widely used for design evaluation. The existing work (Table 2) mainly focuses on developing tools that enable evaluation in a virtual environment and comparing such tools with the existing ones as well as addressing specific evaluation criteria, including usability, creativity,

https://doi.org/10.1017/pds.2023.212 Published online by Cambridge University Press

aesthetics, and affect. The rest of them focus on creating a co-design framework, developing a preference model, streamlining the design review process, examining the influence of representation, and evaluating a specific design objective (e.g., ergonomics), while each paper can discuss more than one theme.

Table 2. Summary of literature on design evaluation

Research Questions	Key Takeaway
Tool Development How can design engineers timely and effectively design and get feedback in the virtual environment? (Arbeláez-Estrada and Osorio-Gómez, 2013; Bruno et al., 2013) Can paper models provide sensory feedback in VR? (Park et al., 2013)	- VR enables timely control and interactive feedback on digital prototypes. - VR can reduce development time for product design and analysis and overcome location limitations. - No universal solution or process exists. - Supporting tools such as paper models could be an accurate substitute for sensory feedbacks and enhance user experience in VR.
Metrics Development What are the relevant metrics that can be implemented in a virtual environment for product evaluation? (Di Gironimo et al., 2013; Valencia-Romero and Lugo, 2017; Naderi et al., 2020)	- The psycho-physiological parameters are suitable state-of-the-art solutions for capturing relevant customer emotional feedback in a VE. - The design environment needs to be congruent with design cues to elicit positive emotional and aesthetic responses.
Co-design How do we perform an evaluation during collaborative concept design? (Koutsabasis et al., 2012; Sivanathan et al.,, 2017)	- VR supports collaborative design for specific areas, such as interior design but requires more tools for designing functions and complex forms. - VR can enhance knowledge capture of teams with a multi-user collaborative interface.
Design for X How to leverage VR to evaluate assembly and ergonomics factors in early design? (Arroyave-Tobón and Osorio-Gómez, 2017; Azizi et al., 2019; Ng et al., 2013) Can VR help in maintenance simulation? (Guo et al., 2020)	- VR provides a platform to develop new methods that allow consideration of assembly and ergonomics issues in generating design components in early stages. - VR better helps designers take into account the spatial restrictions and determine the required improvements. - VR-based methods can be useful in helping predict design flaws and facilitate design decisions about maintenance considerations in the early design stage.

Tool development. As VR technology evolves rapidly, many design researchers tried to integrate such technology into design evaluation. The first and foremost challenge was to enable users to view, interact with, and evaluate designs in a virtual environment. Accordingly, researchers developed various tools, including software tools, virtual interfaces, and evaluation metrics, to enable virtual evaluation for individuals or among groups. Bruno et al. (2013) adopted a setup with an HMD and developed a software library to connect human-machine interface (HMI) behavior and interactive virtual environment (VE), which reduces the time needed to develop the digital prototype for product design and analysis. Besides software development, a mobile-based VR system was developed for connecting targeted users across locations and getting feedback of product aesthetics, as a lightweight solution (Arbeláez-Estrada and Osorio-Gómez, 2013). In addition, new hardware is sometimes needed as supporting tools. Park, Park and Jung (2013) showed that low-cost paper models could provide tangible pseudo feelings of manipulating products with human hands and could be an accurate substitute.

Metrics development. To support design evaluation in a virtual environment, researchers investigated the relevant metrics. Valencia-Romero and Lugo (2017) investigated the quantifications of symmetry, parallelism, and continuity for 3D representations using a VR-based discrete choice experiment and

https://doi.org/10.1017/pds.2023.212 Published online by Cambridge University Press

demonstrated VR as an effective tool to integrate aesthetics as a quantifiable property. Given the immersive environment brought by VR, researchers were also interested in understanding the combined effects of environment congruence and product design on consumers' aesthetic, affective and behavioral responses. A study suggests that a product's environment must be aligned with the design elements embedded in the product to evoke a relatable experience (Naderi et al., 2020). VR devices also serve as an additional instrument for researchers to measure user reactions and perception. Researchers explored various physiological measurements, including electromyography of the muscle activities (on the face), blood volume pulse, and electrodermal activity (on fingers), combined with the close-ended questions about the emotional effect of a car configuration design task in the CAVE automatic virtual environment. Given the extended capability of collecting experimental data in VR, Di Gironimo et al. (2013) proposes a usability assessment index to compare different product design alternatives during the definition phase in the participatory design session.

Co-design framework. Another benefit of implementing VR is to enable collaborative and distributed evaluation. A review system called the Virtual Aided Design Engineering Review (VADER) provides concurrent access by multiple distributed users during product design discussions using a virtual reality-based 3D model view display and substantially enhances their engineering task knowledge capture, rapid retrieval, and reuse capability (Sivanathan et al., 2017). Besides engineering design, VR can support collaborative conceptual design effectively in architectural design, interior design, and user interface design (Koutsabasis et al., 2012), with an emphasis on form and structure, rather than on sophisticated functions or processes.

Design for X (DFX). DFX shifts specific product objectives, such as easy manufacturing, optimized assembly, and low environmental impact, into the design stage, before the product is manufactured. A few papers specifically focus on certain objectives with the support of VR technologies, for example, design for ergonomics and design for maintenance.Ergonomics are typically considered in the detailed embodiment design stage, where the information of the parts and their interactions are clearly defined. VR technology provides opportunities to shift these considerations earlier in the conceptual design stage for efficient design iterations with lower cost. Ng et al. (2013) developed a methodology that integrates design and assembly planning in an AR environment so that users are allowed to consider assembly when generating the design components in the early stage. Azizi, Ghafoorpoor Yazdi and Hashemipour (2019) proposed an integrated approach to address ergonomic problems of designing and evaluating a production line with VR-based methods. Similarly, Arroyave-Tobón and Osorio-Gómez (2017) integrated an AR-based modeling tool with an Ergonomic Assessment Module to continuously evaluate the user's postures, movements, and forces related to the created parts. The tool helped designers to identify potential posture risks during assembly and usage, and determine the required improvements to minimize occupational risks in future interactions with the products. Guo et al. (2020) proposed a VR-based method of conducting immersive maintenance simulation to help designers evaluate maintainability and make decisions. Through fuzzy comprehensive evaluation (FCE), the proposed method was shown to have better abilities, in terms of visibility, reachability, etc. and facilitate design decisions about maintenance considerations in the early design stage.

3.3 Prototyping

Prototyping helps represent abstract design concepts in front of users and thus enables engineers to observe and analyze user reactions when interacting with them, and in turn, further improve the design. Prototypes vary in terms of fidelity levels, ranging from low, such as paper drawing, digital sketching, to high such as CAD models, VR-supported (VR/AR) mixed or virtual prototypes, real physical prototypes. Figure 2 summarizes the takeaway from the literature about prototyping with VR.
Ferrise et al. (2017) discussed the three types of prototypes based on the case studies the research team collaborated on with consumer goods industries. It is suggested that physical prototypes are more appropriate at the later stage (e.g., field tests) of the design, considering its drawbacks in cost, time required, and limited modifiability. VR-based virtual prototypes are modifiable (e.g., can be controlled and parameterized) and can be roughly explored at the very beginning of the design process. Yet, they are subject to software and hardware limitations, and limited knowledge of the human sensory/perceptual systems. The mixed prototypes, a coherent combination of real and virtual information, can help overcome limitations with the advantage that there is no need to reproduce virtually something that is already available.

https://doi.org/10.1017/pds.2023.212 Published online by Cambridge University Press

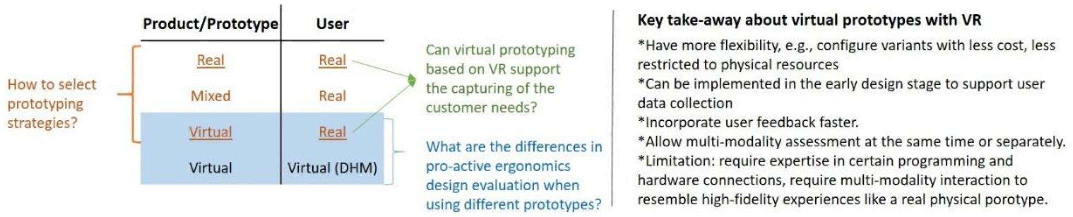

Figure 2. Summary of key takeaway about prototyping with VR

Ahmed et al. (2019) compared computational prototyping and mixed prototyping in proactive ergonomic design. Computational prototyping integrates CAD models of workplaces or products with Digital Human Modeling (DHM) to capture human postures in response to the product or workplace. Mixed prototyping builds on the computational prototyping and uses actual users to conduct product evaluations and reconfigurations in an immersive environment. Ahmed et al. (2019) evaluated the ergonomics of designs of a cockpit of Boeing 767 in non-emergent and emergent (i.e., during a fire) scenarios. They found that the two prototype methods produce similar results in terms of an ergonomic assessment. The mixed prototype is suitable for communicating design ideas and capturing the change in human performance due to subjectivity (e.g., sense of emergency, vision hindered by the fire) with the limitation that it cannot measure quantitative human performance in real-time. Carulli et al. (2013) presented VR-based prototyping to support the capturing of the voice of customers in regard to the visual, haptic, and auditory characteristics of products. A case study of a washing machine design showed that it is feasible to use a VR-based virtual prototype of the product for experimenting, evaluating, and determining user interaction behaviors, and thus collecting customer needs. In addition, the collected data about the customer needs of engineering requirements can be integrated within the virtual prototype easily.

VR enhances flexibility in prototyping in early-stage design. When compared with other prototyping methods, the VR-based approach reduces costs and time associated with prototyping activities, compared to manufacturing physical artefacts. The VR prototypes can be modified for its family products rather than starting over, and can be developed in low fidelity when the product idea is still rough. The virtual prototypes are less restricted to available materials, manufacturing technologies, and access to manufacturing facilities, which is especially useful for brand new product development. On the other hand, the multi-modality possibility in the early stage supports the assessment of some product features or behaviours that are less assessed in the early phases of product development, such as the haptic and auditory components. It also allows specific verification of certain aspects while having others remain the same, which might be hard to separate with real prototypes. Although the VR prototype has many benefits, its limitations cannot be ignored. Multi-modality experiences (e.g., haptic feedback) are needed to resemble high-fidelity experiences like a real physical prototype. The successful implementation of the VR prototypes also requires expertise in programming and hardware connections.

3.4 Study platform validation

While VR brings unique benefits such as flexibility and accessibility, researchers tend to conduct various design activities in the VE (Table 3). However, a ground truth needs to be set up regarding if human users behave similarly in a virtual space compared to the physical environment.

Ferrise et al. (2017) introduced and validated a tactile feedback mechanism with crude prototypes to capture ergonomics attributes for the virtual product development cycle. Kato (2019) compared the perception difference between actual space, photographed VR space, computer-generated VR, and paper, and showed no significant difference in perception regarding the perceived purchase intention, and style attribute between reality and the VR space. Computer-generated VR, which can define size with data, does not differ from photographed VR. Moreover, evaluation on paper is tested to have no significant difference from the actual car, which realizes overwhelming time and cost savings.

https://doi.org/10.1017/pds.2023.212 Published online by Cambridge University Press

Table 3. Key takeaway about tool evaluation

Research Questions	Key takeaway
- Can a tactile feedback mechanism simulate outcomes of physical experiment outcomes? (Demirel and Duffy, 2017) -What are the differences in designers' spatial perception in VR and non-VR environments? (Kato, 2019; Lukačević et al., 2020)	VR can provide an equivalent or superior experience of perceiving and evaluating designs.

In addition to testing the prototype that mimics a physical set-up, Lukačević et al. (2020) examined the differences in designers' spatial perception of spatial properties and relations of a design solution in immersive virtual environments (IVE) and non-immersive virtual environment (nIVE). The study shows that engineering students more accurately perceive spatial properties in the IVE than nIVE, but make judgment of spatial relations similarly in both VEs. In summary, VR can provide an equivalent or superior experience of perceiving and evaluating designs.

4 CONCLUSION

This paper reviews and discusses the existing work that utilizes VR in early-stage design, regarding concept generation, design evaluation, and prototyping. By consolidating the findings across the studies, it is agreed that VR is very useful in early-stage design. It provides an immersive environment to engage designers, a controllable and interactive prototyping and evaluation tool, and an effective communication channel between designers and users, and among distributed design teams. However, most researchers focus on enabling design activities in VR and examining its validity, rather than extending design space. During design activities, most researchers invent their own study protocols and systems. The lack of commonly accepted processes and platforms can impose barriers for more designers to implement VR for design. Due to the nature of VR technology, most studies rely on visual perceptions, with some supporting tools for sensory feedback. This can potentially limit the scope of VR applications in design. The authors hope this literature review can help better understand advantages and limitations of VR usage in the design process, and thus support future research investigation to propose a generic, high-level, overarching framework for VR-enabled design.

REFERENCES

Ahmed, S., Irshad, L., Demirel, H.O. and Tumer, I.Y. (2019), "A comparison between virtual reality and digital human modeling for proactive ergonomic design", in Duffy, V. (Ed.), Digital Human Modeling and Applications in Health, Safety, Ergonomics and Risk Management. Human Body and Motion. HCII 2019. Lecture Notes in Computer Science, Vol. 11581, Springer, Cham, pp. 3–21, https://dx.doi.org/10.1007/978-3-030-22216-1_1.

Arbeláez-Estrada, J.C. and Osorio-Gómez, G. (2013), "Augmented reality application for product concepts evaluation", Procedia Computer Science, Elsevier Masson SAS, Vol. 25, pp. 389–398, https://dx.doi.org/10.1016/j.procs.2013.11.048.

Arrighi, P.A. and Mougenot, C. (2019), "Towards user empowerment in product design: a mixed reality tool for interactive virtual prototyping", Journal of Intelligent Manufacturing, Springer New York LLC, Vol. 30 No. 2, pp. 743–754, https://dx.doi.org/10.1007/S10845-016-1276-0.

Arroyave-Tobón, S. and Osorio-Gómez, G. (2017), "Ergonomic analysis in conceptual design stage using a gesture-based modelling tool", International Journal on Interactive Design and Manufacturing (IJIDeM), Medellin, Colombia, Vol. 11 No. 3, pp. 481–488, https://dx.doi.org/10.1007/s12008-015-0289-9.

Azizi, A., Ghafoorpoor Yazdi, P. and Hashemipour, M. (2019), "Interactive design of storage unit utilizing virtual reality and ergonomic framework for production optimization in manufacturing industry", International Journal on Interactive Design and Manufacturing (IJIDeM), Muscat, Oman, Vol. 13 No. 1, pp. 373–381, https://dx.doi.org/10.1007/s12008-018-0501-9.

Bargelis, A., Baltrušaitis, A. and Dubinskas, E. (2013), "Forecasting model of manufacturing time at the early design stage of product and process", Mechanika, Vol. 19 No. 1, pp. 104–111, https://dx.doi.org/10.5755/J01.MECH.19.1.3620.

Berni, A. and Borgianni, Y. (2020), "Applications of virtual reality in engineering and product design: Why, what, how, when and where", Electronics (Switzerland), MDPI AG, 1 July, https://dx.doi.org/10.3390/electronics9071064.

Berta, J. (1999), "Integrating VR and CAD", IEEE Computer Graphics and Applications, Vol. 19 No. 5, pp. 14–19, https://dx.doi.org/10.1109/38.788793.

https://doi.org/10.1017/pds.2023.212 Published online by Cambridge University Press

Borgianni, Y. and MacCioni, L. (2020), “Review of the use of neurophysiological and biometric measures in experimental design research”, Artificial Intelligence for Engineering Design, Analysis and Manufacturing: AIEDAM, Cambridge University Press, 1 May, https://dx.doi.org/10.1017/S0890060420000062.
Bruno, F., Angilica, A., Cosco, F. and Muzzupappa, M. (2013), “Reliable behaviour simulation of product interface in mixed reality”, Engineering with Computers, Vol. 29 No. 3, pp. 375–387, https://dx.doi.org/10.1007/S00366-012-0293-7.
Carulli, M., Bordegoni, M. and Cugini, U. (2013), “An approach for capturing the Voice of the Customer based on Virtual Prototyping”, Journal of Intelligent Manufacturing, Milan, Italy, Vol. 24 No. 5, pp. 887–903, https://dx.doi.org/10.1007/s10845-012-0662-5.
Chang, Y.S., Chou, C.H., Chuang, M.J., Li, W.H. and Tsai, I.F. (2020), “Effects of virtual reality on creative design performance and creative experiential learning”, Interactive Learning Environments, Taylor & Francis, Vol. 0 No. 0, pp. 1–16, https://dx.doi.org/10.1080/10494820.2020.1821717.
Chen, Y.C., Chang, Y.S. and Chuang, M.J. (2022), “Virtual reality application influences cognitive load-mediated creativity components and creative performance in engineering design”, Journal of Computer Assisted Learning, https://dx.doi.org/10.1111/jcal.12588.
Demirel, H.O. and Duffy, V.G. (2017), “Incorporating Tactile Cues into Human-Centered Virtual Product Design”, Human Factors and Ergonomics In Manufacturing, John Wiley and Sons Inc., Vol. 27 No. 1, pp. 5–16, https://dx.doi.org/10.1002/HFM.20402.
Dieter, G. and Schmidt, L. (2008), Engineering Design, 4th ed., McGraw-Hill.
Ferrise, F., Graziosi, S. and Bordegoni, M. (2017), “Prototyping strategies for multisensory product experience engineering”, Journal of Intelligent Manufacturing, Springer New York LLC, Vol. 28 No. 7, pp. 1695–1707, https://dx.doi.org/10.1007/S10845-015-1163-0.
Filippi, S. and Barattin, D. (2019), “Influence of representations on shape-based design activities”, International Journal on Interactive Design and Manufacturing (IJIDeM), Udine, Italy, Vol. 13 No. 1, pp. 277–285, https://dx.doi.org/10.1007/s12008-019-00534-1.
Germani, M., Mengoni, M. and Peruzzini, M. (2012), “An approach to assessing virtual environments for synchronous and remote collaborative design”, Advanced Engineering Informatics, Ancona, Italy, Vol. 26 No. 4, pp. 793–813, https://dx.doi.org/10.1016/j.aei.2012.06.003.
Di Gironimo, G., Matrone, G., Tarallo, A., Trotta, M. and Lanzotti, A. (2013), “A virtual reality approach for usability assessment: case study on a wheelchair-mounted robot manipulator”, Engineering with Computers, Naples, Italy, Vol. 29 No. 3, pp. 359–373, https://dx.doi.org/10.1007/s00366-012-0274-x.
Guo, Z., Zhou, D., Zhou, Q., Mei, S., Zeng, S., Yu, D. and Chen, J. (2020), “A hybrid method for evaluation of maintainability towards a design process using virtual reality”, Computers & Industrial Engineering, Elsevier Ltd, Vol. 140, p. 106227, https://dx.doi.org/10.1016/j.cie.2019.106227.
Han, Y.S., Lee, J., Lee, J., Lee, W. and Lee, K. (2019), “3D CAD data extraction and conversion for application of augmented/virtual reality to the construction of ships and offshore structures”, International Journal of Computer Integrated Manufacturing, Taylor and Francis Ltd., Vol. 32 No. 7, pp. 658–668, https://dx.doi.org/10.1080/0951192X.2019.1599440.
Jerald, J. (2016), The VR Book Human-Centered Design for Virtual Reality.
Kato, T. (2019), “Verification of perception difference between actual space and VR space in car design”, International Journal of Interactive Design And Manufacturing - Ijidem, Saitama, Japan, Vol. 13 No. 3, pp. 1233–1244, https://dx.doi.org/10.1007/s12008-019-00568-5.
Koutsabasis, P., Vosinakis, S., Malisova, K. and Paparounas, N. (2012), “On the value of Virtual Worlds for collaborative design”, DESIGN STUDIES, Cyclades, Greece, Vol. 33 No. 4, pp. 357–390, https://dx.doi.org/10.1016/j.destud.2011.11.004.
Lau, K.W. and Lee, P.Y. (2015), “The use of virtual reality for creating unusual environmental stimulation to motivate students to explore creative ideas”, Interactive Learning Environments, Routledge, Vol. 23 No. 1, pp. 3–18, https://dx.doi.org/10.1080/10494820.2012.745426.
Liu, X., Zhang, J., Hou, G. and Wang, Z. (2018), “Virtual Reality and Its Application in Military”, IOP Conference Series: Earth and Environmental Science, Vol. 170, Institute of Physics Publishing, https://dx.doi.org/10.1088/1755-1315/170/3/032155.
Lukačević, F., Škec, S., Perišić, M.M., Horvat, N. and Štorga, M. (2020), “Spatial perception of 3D CAD model dimensions and affordances in virtual environments”, IEEE Access, Institute of Electrical and Electronics Engineers Inc., Vol. 8, pp. 174587–174604, https://dx.doi.org/10.1109/ACCESS.2020.3025634.
Masclet, C., Boujut, J.-F., Poulin, M. and Baldaccino, L. (2021), “A socio-cognitive analysis of evaluation and idea generation activities during co-creative design sessions supported by spatial augmented reality”, International Journal of Design Creativity and Innovation, Grenoble, France, Vol. 9 No. 1, pp. 20–40, https://dx.doi.org/10.1080/21650349.2020.1854122.
Masclet, C., Poulin, M., Boujut, J.F. and Becattini, N. (2020), “Real-time coding method and tool for artefact-centric interaction analysis in co-design situations assisted by augmented reality”, International Journal of Interactive Design And Manufacturing - Ijidem, Grenoble, France, Vol. 14 No. 4, pp. 1141–1157, https://dx.doi.org/10.1007/s12008-020-00683-8.

Maurya, S., Arai, K., Moriya, K., Arrighi, P.A. and Mougenot, C. (2019), “A mixed reality tool for end-users participation in early creative design tasks”, International Journal on Interactive Design and Manufacturing, Springer-Verlag France, Vol. 13 No. 1, pp. 163–182, https://dx.doi.org/10.1007/S12008-018-0499-Z.

Naderi, E., Naderi, I. and Balakrishnan, B. (2020), “Product design matters, but is it enough? Consumers' responses to product design and environment congruence”, Journal of Product And Brand Management, St Paul, MN, USA, Vol. 29 No. 7, pp. 939–954, https://dx.doi.org/10.1108/JPBM-08-2018-1975.

Ng, L.X., Wang, Z.B., Ong, S.K. and Nee, A.Y. (2013), “Integrated product design and assembly planning in an augmented reality environment”, ASSEMBLY AUTOMATION, Singapore, Vol. 33 No. 4, pp. 345–359, https://dx.doi.org/10.1108/AA-10-2012-058.

Ottosson, S. (2002), “Virtual reality in the product development process”, Journal of Engineering Design, Vol. 13 No. 2, pp. 159–172, https://dx.doi.org/10.1080/09544820210129823.

Park, H., Park, S.J. and Jung, H.K. (2013), “Note on Tangible Interaction Using Paper Models for AR-Based Design Evaluation”, Journal of Advanced Mechanical Design Systems and Manufacturing, Kwangju, South Korea, Vol. 7 No. 5, pp. 827–835, https://dx.doi.org/10.1299/jamdsm.7.827.

Rebelo, F., Duarte, E., Noriega, P. and Soares, M. (2011), “Virtual Reality in Consumer Product Design”, pp. 381–402, https://dx.doi.org/10.1201/b10950-28.

Sivanathan, A., Ritchie, J.M. and Lim, T. (2017), “A novel design engineering review system with searchable content: knowledge engineering via real-time multimodal recording”, Journal of Engineering Design, Midlothian, Scotland, Vol. 28 No. 10–12, pp. 681–708, https://dx.doi.org/10.1080/09544828.2017.1393655.

Soares Falcão, C. and Márcio Soares, M. (2013), Application of Virtual Reality Technologies in Consumer Product Usability, LNCS, Vol. 8015.

Stark, R., Krause, F.L., Kind, C., Rothenburg, U., Müller, P., Hayka, H. and Stöckert, H. (2010), “Competing in engineering design-The role of Virtual Product Creation”, CIRP Journal of Manufacturing Science and Technology, Vol. 3 No. 3, pp. 175–184, https://dx.doi.org/10.1016/j.cirpj.2010.08.003.

Sutherland, I.E. (1968), “A head-mounted three dimensional display”, Proceedings of the December 9-11, 1968, Fall Joint Computer Conference, Part I on - AFIPS '68 (Fall, Part I), ACM Press, New York, New York, USA, p. 757, https://dx.doi.org/10.1145/1476589.1476686.

Thalen, J. and van der Voort, M. (2013), “The Virtual Printshop: A case study on using Virtual Reality in early stages of user-centered product design”, Journal on Interactive Systems, Vol. 3 No. 3, p. 1, https://dx.doi.org/10.5753/jis.2012.616.

Ulrich, K.T., Eppinger, S.D. and Yang, M.C. (2020), Product Design and Development (Seventh Edition), McGraw Hill.

Valencia-Romero, A. and Lugo, J.E. (2017), “An immersive virtual discrete choice experiment for elicitation of product aesthetics using Gestalt principles”, Design Science, Mayaguez, USA, Vol. 3, https://dx.doi.org/10.1017/dsj.2017.12.

West, R., Johnson, V., Yeh, I.C., Thomas, Z., Tarlton, M. and Mendelowitz, E. (2018), “Experiencing a slice of the sky: Immersive rendering and sonification of antarctic astronomy data”, IS and T International Symposium on Electronic Imaging Science and Technology, Society for Imaging Science and Technology, https://dx.doi.org/10.2352/ISSN.2470-1173.2018.03.ERVR-449.

Yang, X., Cheng, P.-Y., Lin, L., Huang, Y.M. and Ren, Y. (2019), “Can an Integrated System of Electroencephalography and Virtual Reality Further the Understanding of Relationships Between Attention, Meditation, Flow State, and Creativity?”, Journal of Educational Computing Research, SAGE Publications Inc., Vol. 57 No. 4, pp. 846–876, https://dx.doi.org/10.1177/0735633118770800.

Yang, X., Lin, L., Cheng, P.-Y., Yang, X. and Ren, Y. (2019), “Which EEG feedback works better for creativity performance in immersive virtual reality: The reminder or encouraging feedback?”, Computers in Human Behavior, Shanghai, China, Vol. 99, pp. 345–351, https://dx.doi.org/10.1016/j.chb.2019.06.002.

Yang, X.Z., Lin, L., Cheng, P.Y., Yang, X., Ren, Y.Q. and Huang, Y.M. (2018), “Examining creativity through a virtual reality support system”, ETR&D-Educational Technology Research And Development, Shanghai, China, Vol. 66 No. 5, pp. 1231–1254, https://dx.doi.org/10.1007/s11423-018-9604-z.