The Potential of Virtual Reality for Aerospace Applications

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Abstract—**In the past decade, virtual reality (VR) technologies have become increasingly affordable, flexible, and accessible with the release of consumer versions such as the Oculus Rift or the HTC Vive. The immersive and interactive experiences enabled by this technology offer relevant, innovative use cases and training methods in a wide variety of fields. Therefore, VR is becoming more relevant in many areas outside classic entertainment. These include, for example, medical applications, educational environments, industrial applications, and design applications. In particular, immersive simulations and experiences that would often be too dangerous, expensive, difficult or even impossible to perform can be experienced in a safe environment. In this paper, the potential of VR technologies for different areas of aerospace applications is demonstrated and discussed. A systematic literature review based on the PRISMA guideline is conducted to identify relevant publications and applications from the databases IEEE, ACM, and Scopus. The analysis focuses on identifying various use cases of VR in aerospace research, design, manufacturing, operations, maintenance and education. Furthermore, the benefits, potential challenges and relevant technologies are discussed. This paper is designed to give readers a good overview of the state-of-the-art in VR, focusing on use cases and the potential and challenges, and discussing relevant future scenarios for this application field.**

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1. INTRODUCTION

Virtual Reality (VR) refers to simulated virtual experiences in which users can interact with the virtual environment in real- time. In the past, a wide variety of technologies and hardware solutions have been developed and explored to enable such an experience and to enhance the feeling users have of immersion and presence. This includes, for instance, room-based systems supported by projectors and 3D glasses (e.g. CAVE sys- tems) or systems using VR headsets (head-mounted displays, HMD), which enable a display of the virtual world through stereo projection. Various input systems, such as controllers or gloves, offer different ways of interacting with the virtual environment.

While development projects and studies have already been carried out with VR systems for many years [1], the introduction of the Oculus Rift in 2013, a low-cost variant that also allows a broad audience to use and develop VR applications, gave VR a new push and has kicked-off a ”second hype wave” for VR. This has opened up the space for different hardware competitors such as the Oculus Quest, HTC Vive, or smartphone-based solutions. Also, popular game engines such as Unity or Unreal started to boost the development of VR experiences by providing simplified ways to develop games and other experiences for the HMDs.

While there is currently a boost and hype around VR and new use cases and innovations are presented regularly, the knowledge about the power and development of VR experience did not emerge overnight. VR experience has been evaluated and tested for decades, and it has long been known that VR has great potential for a wide variety of areas such as education and training [2], medical applications [3], industry [4], or therapy [5].

In the field of aerospace applications, the potential of virtual environments was already discussed at a very early stage by R. Bowing Loftin [6] in an overview article in 1996. He describes early developments of virtual environments to enable flight team members of the Hubble Space Telescope repair and maintenance mission of 1993 to build a 3D mental model of the Hubble Space Telescope and to practice the procedures necessary for maintenance and repairs. One hundred five flight team members trained with these virtual environments. The potential for virtual training has been shown for several scenarios by NASA and has become a fundamental training tool.

While the potential of virtual environments and VR technologies is very established for training and simulation scenarios, the application fields and use cases are manifold and many studies and developments are reported in literature. This article is an attempt to summarize relevant use cases in the field of aerospace and discuss the potential and future roadmaps.

Research Goals

To achieve a better understanding of the VR landscape in the field of aerospace, we focus on the following research goals:

- How relevant is VR in the field of aerospace applications?
- What aerospace-related application fields are appropriate for VR?
- What technologies are used?
- What are the advantages and disadvantages?
- What are the future research and development fields?

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Related Work

While many publications report on the implementation and evaluation of virtual reality experiences relevant for aerospace applications, summaries, and overviews of these articles are scarce. Anthes et al. [7] presented 2016 a state-of-the-art report on VR technologies at the IEEE Aerospace Conference. This report provides a taxonomy of VR hardware deployments, demonstrating both the complexity and the potential of the current output and input devices. Their publication summarizes and explains to a great extend relevant VR technologies relevant for the aerospace field. This article will thus not focus on hardware and a technological introduction to the field, but instead it will discuss relevant VR experiences related to aerospace and their potential.

2. METHOD

The goal of this paper is to identify use cases and applications fields reported in scientific literature of virtual reality applications in the aerospace sector. Therefore, a review study based on the PRISMA (Preferred Reporting Items for Systematic reviews and Meta-Analyses) guidelines [8] was conducted to identify and collect relevant articles and papers. The databases for the collected papers were: ACM Digital Library, IEEE Xplore, and Scopus. These databases include relevant VR and Aerospace research conference such as IEEE VR, ACM VRST, or IEEE Aerospace. To be included, a paper must be written in English and peer-reviewed. This study focused on VR applications taking VR technologies into consideration that have been released since 2013 (the release of the consumer-version of the Oculus Rift). The following search term was used: *(”virtual reality” OR ”VR”) AND (”aerospace*”)*. The retrieval time was October 2021.

In total, 963 (ACM: 267 IEEE: 482 Scopus: 214) results were found over the three databases. Of these, 221 (ACM: 49 IEEE: 183 Scopus: 34) were screened and finally 36 (ACM: 6 IEEE: 25 Scopus: 5) included in the final presentation.

3. RESULTS

The second wave of the virtual reality is also reflected in the search results. As we can see in Figure 1, a significant increase in search results (*(”virtual reality” OR ”VR”) AND (”aerospace*”)* at ACM) is evident starting with 2013.

Based on the described relevance criteria, a total of 36 publications were included in the final analysis. Most of the papers were published in 2017 (see Figure 2). A large portion (7) of the papers was published within the IEEE Aerospace community. Four out of the 8 relevant publications in 2020 and 2021 were published at this venue.

The majority of the publications dealt with the topics of remote operations, virtual testbeds, astronaut training, or educational experiences. In the following chapter, we will discuss details of the potential application scenarios.

4. APPLICATIONS AND USE CASES

Aerospace is an important application field for virtual reality technologies, has been an early research and development area, and has also innovated and shaped many use cases. The potential applications of VR in the aerospace field includes many fields and can support the (1) virtual replication of real environments and scenarios (e.g. for training, planning, or decision-making), (2) the simulation of designed scenarios and environments, which do not (yet) exist in tangible form (e.g. for designing and planning), (3) a connection to real setups (e.g. for remote operation), and (4) an abstract visualization of complex procedures (e.g. for educational purpose or new forms of software development). This allows a wide variety of use cases for different target groups such as training of crew members, planning for manufacturers, support for decision-makers, education of the general public, to name a few. Following, an overview of various application fields, use cases, and examples from literature is given. Figure 3 gives an overview of the described applications.

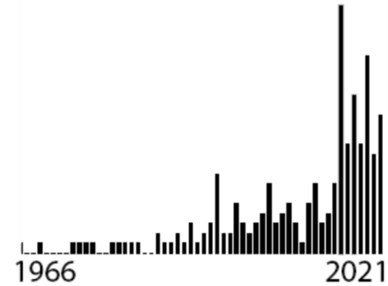

Figure 1. Search results for *(”virtual reality” OR ”VR”) AND (”aerospace*”)* on ACM DL

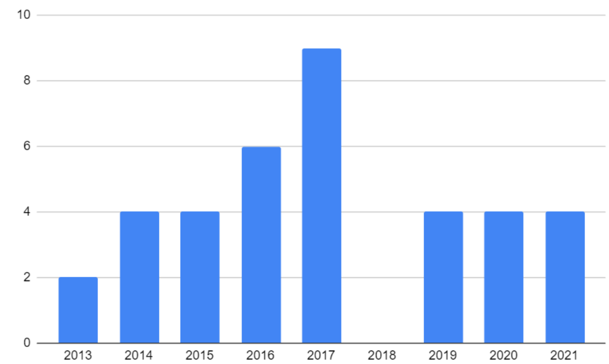

Figure 2. Included publications per year (retrieval date, October 2021).

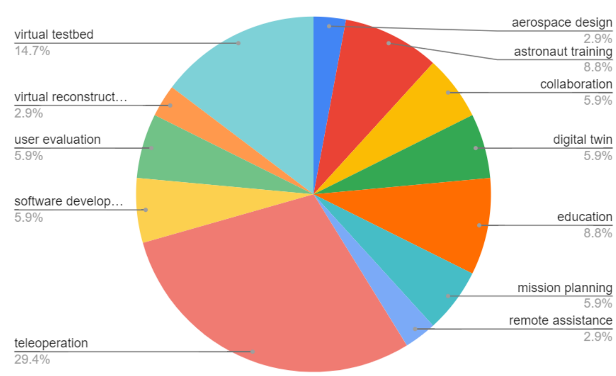

Figure 3. Overview of described application.

Virtual Training and Simulation

One of the most reported and discussed use cases for VR in the aerospace field is missions training for astronauts [9] and cosmonauts [10]. Training for missions is often a costly and time-intensive task. With VR, training sequences can be easily set up, changed, and adapted to support safe and flexible training without limitations of space and time. VR allows the creation of various training scenarios, such as mission training, working with different tools, stress tests, and/or and preparing for and assessing emergency scenarios [11].

In [12], the authors describe a virtual environment for analyzing, training, and programming on-orbit servicing tasks. While they underline the benefits of such scenarios, they also present several challenges linked to this, such as realistic interactions and the complex nature of creating a realistic simulation of many scenarios. In [13], the authors describe software to analyze and design space capsule experiences. In [14], the authors describe a VR aerospace manufacturing training system. They described a training module to recreate the drilling of a Carbon-fiber-reinforced polymer (CFPR) panel and showed that it could teach beginners CFRP drilling.

Emergency preparedness is also a crucial factor in all of this. VR allows experiencing scenarios in a very immersive but safe way. Preparedness is an important factor for reducing stress and fear, while also training correct behavior, and optimizing reaction time [15].

Flight simulators in combination with VR are a popular tool not only in aerospace training scenarios. However, options such as additional assessments including workload experiments and stress tests with combined setups such as EEG provide opportunities for gaining additional results from the training scenario [16].

Teleoperation, Remote Operation

The operation with remote machines can often be unintuitive and cumbersome, as users need to interact with a 3D space through a 2D input (keyboard, mouse, and screen). This often requires specific training with the software and allows only experts to interact with the environment. VR can provide a more user-friendly and intuitive way for remote operations. This includes, for instance, astronauts remotely operating droids [17], remote control of sample-return missions [18], or a teleoperation of the lunar rover [19]. Compared to traditional video streams, VR allows the operator more viewing and operating freedom. Additionally, with controllers providing feedback, the operator can also feel force feedback, for example, when interacting with robot arms.

In [20], [21], the authors describe how to operate a collaborative robot with two HTC Vive controllers. In [22], the authors present a comparison of the control of a humanoid robot system in VR versus with a 2D interface. They argue for the more intuitive interaction with a three-dimensional room. Also, in [23], the authors describe the benefits of VR during robotic operations for enhancing the 3D situational awareness in these procedures.

One issue in remote operation is often the time delay due to the distances (e.g. between Earth and the Moon) or reduced bandwidth. In [24], the authors describe a teleportation system and propose a predictive system to overcome delays. Also, in [19], the authors present a VR technique to teleoperate the lunar rover, considering the communication delay between Moon and Earth.

Additional hardware, such as a DLR bimanual haptic interface (two light-weight robot arms), can be used to improve the interaction and give realistic haptic feedback to the operator [25], [26].

Virtual Testbeds, Verification and Testing

The virtual reconstruction of systems and processes also enables the testing and verification of tools and processes cost-effectively and safely with reduced complexity and effort. Because of the intuitive nature and the possibility for visualizing and simulating systems, virtual VR testbed systems are a powerful tool that supports planning, decision-making, and testing already in the early phases of a project.

[27] describes a VR solution to test camera systems which are not available as hardware systems (e.g., to combine different optical systems). In [28], the authors describe a VR testbed as decision support for scenarios such as rendezvous and docking, planetary landing, and exploration. In [29], the authors describe a virtual space robotics testbed for optical sensors. [30] describe a VR experience to integrate, validate and test use cases in the field of satellite integration and verification process. In [31], a virtual testbed for planning planetary swarm-based exploration missions is introduced to allow users to interact with simulated sensor output for a swarm of different spacecraft.

Remote Assistance, Remote Collaboration and Co-Location

Many inflight situations such as maintenance procedures require feedback and communication with various experts who might not be available on-site. VR enables new forms of virtual co-location, remote assistance, and remote collaboration scenarios.

In [32], the authors describe a system in which the remote expert uses a VR HMD in order to be a direct participant in the situation, and the astronaut would wear an augmented reality HMD for receiving instructions. The authors describe a remote assistance scenario for inflight maintenance in ground training for space missions in their scenario. Also, asymmetric collaboration can be an essential method to accelerate collaboration between locations. In [33], the authors describe the case of aerospace, industrial designs, in which experts discuss options in a meeting room. At the same time, a technician is immersed in VR scenarios to test the possibilities. Also, remote collaboration between humans and a human-robot collaboration can be facilitated through VR. In [34], the authors describe a collaborative human-robot task for building small, complex aerospace parts.

Collaborative Workspace

Virtual reality also allows users to share a virtual space to collaborate on various topics of interest. In [35], the authors present their work on a collaborative workspace focused on the data analysis and operations of planetary missions to bring together multi-disciplinary teams of researchers. This space is designed to help the teams work together in an international and interdisciplinary setting.

Designing Systems

VR can be a valuable tool to design or redesign (and evaluate) processes and designs in a cost-effective way. In [36], the authors, for instance, describe how they test different HUD designs with VR. In [37], the authors describe the use of VR for aerospace design (e.g., component aerodynamic design process by visualizing performance and geometry).

Mission Planning

Mission planning, such as planning the paths of the Mars rover, is often a complex process and needs the visualization and consideration of different elements such as topography, surface imagery, or orbital imagery. In [38], the authors described how VR could help to plan such operations with a focus on terrain inspection. In [39], the authors describe a representation for the Martian surface.

User Studies and Evaluations

Virtual reality can be used to evaluate and assess user behavior in a safe and cost-effective setting. This includes, for instance, behavior and risk analysis in the case of an emergency situation [15]. The behavior of the users can be observed, different scenarios can be triggered, and the preparedness and reactions can be evaluated.

VR can also be used to evaluate the design and workflow of existing systems. In combination with eye-tracking hardware as part of the VR head-mounted display, details about the user experience and how they use the system, what they observe and what they might miss. As an example, in [36], the authors use VR in combination with eye-tracking to evaluate the reaction of pilots on HUD interactions.

Therapy

Studies have shown that virtual reality exposure is as effective as actual training flight exposure in the case of treating such as, for example, flight-related anxieties. [40] present a review article showing discussing different forms of layperson anxieties in aerospace environments and touch the topic of VR.

Virtual Reality for Digital Twins

Digital twins represent real assets and offer a vast potential for interacting with, and learning about systems, and also trying out new settings and processes in a safe and cost-effective environment. VR can provide a valuable technique to visualize the digital twins. In [41], a digital twin of aero-engines is presented and visualized in VR to support intuitive interaction. It is used to assess and visualize the performance of a fleet of aircraft engines.

5. Virtual Reconstruction

While many virtual replicas and simulations in VR focus on the experience of current or future systems, the authors in [42] describe the use of VR experiences to reconstruct and investigate the history of Soviet human-crewed spaced flights based on 3D computer reconstructions and documents.

Virtual Reality in Software Development

In the development of software relevant to aerospace, VR also offers many different possibilities for enhancing existing processes. Visualizations and visual metaphors allow the experiencing of software design in a new way. Examples from the literature include, for instance, the visualization of software components and dependency graphs [43], the visualization of software architectures [44], or the design of software [45].

Virtual Reality for Education and to Raise Awareness

VR allows users to be part of an experience which are usually not visible, hard to reach, or too expensive. Space exploration is a typical experience, which attracts many but is not accessible to the general public. It is crucial to raise awareness of the importance of space missions, their impact, and potential problems.

In [46], the authors describe an educational VR experience to raise awareness about the problem of space debris, intending to bring the topic to a broad audience (citizens of all ages). Another use case is also to create enthusiasm in children about these issues by enabling them to immerse into a space station through VR[47]. In [48], a VR installation is presented, which allows participants to experience a situation as an astronaut outside the ISS to learn about the differences of interaction in microgravity and on Earth.

Corner Cases: Engineering Education

Another relevant topic is engaging and creating enthusiasm in students about STEM, an essential gateway to aerospace studies. Many STEM fields can benefit from VR experiences to create learning environments that teach STEM fields in an innovative, visual, and tangible way. It allows the teaching of topics, which are often difficult to understand, such as engineering statics [49] or physics [50] in a more visual and hands-on approach and makes phenomena visible, which usually go unseen.

6. Advantages

Throughout the presented use cases, various main advantages and chances of virtual reality have been described.

Immersive Visualizations and Simulations—The freedom of view supported by VR allows a more realistic and intuitive observation of the scene [18]. VR offers the possibility to create realistic digital mock-ups [39] and allows for an immersive viewpoint that also enhances situational awareness [22]. It make possible the simulation of critical operations (e.g. ground and flight operations) [39] and supports real-time interaction [39]. Existing systems can be recreated and visualized, but elements that are usually unseen or not yet integrated can be simulated and visualized. VR provides the possibility to visualize real scenarios and use metaphors and other visual representations to explain complex topics.

Cost-efficiency, Time-efficiency, Flexibility—VR allows creation, re-creation, and simulation to be taken care of in a very time- and cost-effective way [39]. Operations and virtual training become easier to repeat, costs are reduced, and also dangerous scenarios can be safely integrated [14]. Cost, time, and risks can be minimized [26]. VR is also supporting a high level of flexibility, such as training from home [9].

Accessibility, Natural and intuitive Interaction—The three-dimensional space allows a more intuitive interaction with the 3D data compared to traditional 2D interfaces [22]. Navigation and interaction are possible through natural movements [22]. This also allows non-experts to understand and interact with the systems [30] and is less workload on operator [22]. It also provides for an intuitive collaboration environment for multidisciplinary teams [39]. Controllers and input devices can also support force feedback to allow e.g. more realistic remote operation, and training scenarios [18].

7. Future Research Challenges

The literature reviewed has demonstrated the potential of virtual reality for a wide variety of areas in the aerospace domain. However, we are only at the beginning, and there are still many challenges, interesting unexplored areas, and opportunities in a wide variety of fields. This chapter will discuss a wide variety of challenges and future research and development areas to present an outlook and a possible roadmap.

Visualizations and Simulations—A range of different visualization forms have been discussed in the literature. While the visualizations and simulations bring various chances, there are still many open challenges, such as the representation of complex structures or the use of metaphors [31]. Issues such as the missing personal situational awareness [22] also pose interesting research venues.

Remote Communication—Real-time simulation and also remote communication are still major challenges. A particularly significant area to be dealt with here is distance (e.g. between Earth and the Moon), and bridge this can be far more formidable than the problems to be face in other areas. Interesting first concepts such as predictive operations [24] have been discussed and give an indication of the many research challenges that lie ahead in the future.

Interaction and Locomotion— The right design of natural and intuitive interactions with the virtual environment still poses a challenge. Controllers are not an intuitive device for everyone, and future challenges and chances will also be likely to arise in the interaction with different forms of input controllers and also haptic feedback of these devices [12]. In-world locomotion is also a topic which is often discussed in the literature and needs to be considered based on the application and use case.

Hardware and Virtual Reality Design— The current nature of virtual reality still poses challenges since it is often very hardware intensive [22]. For some setups, users need the HMD connected to external sensors, and a PC with a capable graphics card. This is not only a cumbersome setup, but challenges in the area of cable management are also often mentioned in this context. With the introduction of the Oculus Quest and other new HMDs, many of these problems are already well underway to finding solutions. This said, however, these developments are also bringing in new challenges, because they do not yet have the same computing power. Further to all of this, another important element that is still frequently mentioned is motion sickness [22], which is also related to VR design guidelines.

Evaluations—Many reviewed papers have reported pilot studies and mentioned missing evaluations with a larger user groups [26]. Understanding users and the way how they interact with the virtual realities is a crucial element to improve this field and find new application fields. New forms of user evaluations (e.g. data point tracking and analysis) can also represent an interesting way ahead for a better understanding of this field.

Collaborative and Multi-User Experiences—Remote but also virtual on-site collaboration have been described as important use cases for VR. This is a relevant future use case, not only for improving the technical capabilities and the in-world processes for collaborating, but also to support collaboration across different platforms and to integrate various collaboration techniques.

Use Cases and Scenarios— This paper only gives a first overview of the manifold use cases in this field. In the reviewed works, many authors have already discussed relevant potential use cases for VR in the aerospace field, which have not yet been explored [26]. This includes, for instance, other training scenarios (e.g., sensory illusion [51]). The potential of VR for treating flight-related anxieties has also been demonstrated. [40] present a review article discussing different forms of layperson anxieties in aerospace environments, and point out that only a few of these have as yet been explored through VR exposure yet. The potential for various educational fields has also been shown. In [52], the authors discuss the possibility of virtual worlds for aerospace engineering courses and display in a first study the potential these worlds will have for education. Environments of this kind, however, have not yet been explored in VR. A further interesting potential open use case was reported by [53]. They found that VR might be a countermeasure for microgravity-related motion sickness. Their paper describes an experiment during a parabolic flight, where a tester experiences a reduction of microgravity-related motion sickness while experiencing a VR simulation compared to a parabolic flight without VR. This can also be an exciting starting point for future explorations.

8. Conclusions

In this paper, 36 publications on VR experiences in the field of aerospace were identified and reviewed. Based on this search, we found the following relevant application fields: virtual training and simulation, teleoperation, virtual testbeds, remote assistance and co-location, collaborative workspaces, design systems, mission planning, user studies and evaluations, therapy, and digital twins. Significantly, the field of teleoperation has been explored by many researchers and developers in the past.

The authors report similar advantages of VR compared to traditional setups, such as the potential of immersive environments, the intuitive nature of virtual reality interactions, the cost and time efficiency, the accessibility, and the various benefits remote visualizations and simulations provide.

It was in the field of aerospace in particular that the first successful attempts with virtual reality were made at a very early stage, and various use cases were already demonstrated in the past. The new technologies now available, with their improved flexibility and better results in the context of immersion, are bringing many new possibilities and challenges. In this paper, we have pointed out various future challenges and potential research paths. Included in this are the challenges that lie ahead in the design of visualization and simulation in VR, remote communication, interaction and locomotion design, hardware, user evaluations, the design of collaborative experience, and the potential through new use cases and scenarios.

In summary, research and development in the field of aerospace have always shaped virtual reality and with the exciting challenges this field is bringing to the technology, the potential for innovative VR experiences in the future is assured.

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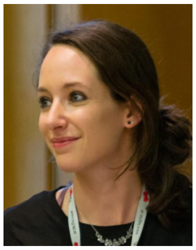
Biography



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