Augmented and Virtual Reality Simulation in Industry

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Simulators have been used for a long time in industry. We identify three categories of use: training, design, and testing. We underline that for these three categories of uses, the two major areas of improvement are a better use of haptic devices but also of artificial intelligence.

Virtual reality (VR) refers to the technological systems with which the user is immersed in a virtual world based on 3D objects.[1] With augmented reality (AR), one or more virtual objects are superimposed on a real environment, registered in 3D space with real-time interactions between the physical environment and virtual objects.[1] Mixed reality (MR) is based on the mapping of the user's space, positioning virtual objects in relation to the real environment and the user and offering to the user natural and immediate interactions.[2] In the present article, we use *immersive technologies* to refer to VR, AR, or MR.

INTRODUCTION

Simulation for industry is the subject of a relatively detailed literature (see, for example, Ören et al.[3]), while research on immersive technologies for industry seems rarer. Yet the development of immersive technologies makes it possible to simulate more situations in a satisfactory and relevant way by providing a feeling of presence to the users.[4]

Simulation in industry refers, in fact, to the three main categories of uses that have been described by Posada et al.[5]: training, designing, and testing (in virtual worlds before deploying in the real world). The aim of this article is to present these main uses of AR and VR that are developing in industry. We also want to analyze the state of research on this subject and the questions that remain unanswered but also to identify the common issues among the different use cases. The examples we have been able to identify were more often from VR than from AR, probably because AR is at a slightly lower level of technological maturity.[6]

SIMULATE FOR TRAINING

A systematic review of the literature was published in 2021[7] in regard to experiments on learning based on VR tools. Some studies show a positive effect of VR on learning (compared to other media), and some show no difference, while others, more rarely, show a negative effect. This first observation should be put into perspective with the well-known publication bias, which leads studies showing positive results to have a much greater chance of being published than those that show no significant difference among several experimental conditions. The authors of the review also take a critical look at the methodology of the studies conducted. Many of them are based on interviews in which students are asked whether they feel that VR helps them learn, which does not prove that learning was actually better. It is also noted that some studies do not have a control group but make a comparison of knowledge before learning and after learning. For example, one of the studies in the article mentions as a positive result a 14% gain on a knowledge test after learning in VR. However, 14% as a difference in knowledge on a specific subject between before and after a course (in VR or not) can also be considered a very low result. Since some studies show the positive effects of VR on learning (although some are methodologically questionable) and others show negative or neutral effects, it is necessary to understand what differentiates them to identify the situations in which this type of medium is relevant.

Immersive technologies appear to have potential whenever training requires users to feel a sense of social presence, that is, the feeling of "being there" with a "real" person.[4] This feeling is supported by stereoscopic 3D, immersion, and the consistent representation of the people we are with. When faced with VR avatars, individuals' emotional responses, particularly in terms of anxiety, are similar to those measured in real-life situations, including responses to negative audience feedback. Increasing social presence is not in itself a benefit to learning. The visual representation of the teacher can also constitute an interference, a piece of competing information that is useless to the task and therefore potentially detrimental.

VR also has the capacity to generate a feeling of physical presence. A visually realistic environment is an effective way to provide a believable virtual experience. This means that VR can also familiarize the learners with a specific workplace. For instance,

FIGURE 1. A realistic representation of an industrial workshop.

Figure 1 shows a realistic representation of an existing industrial workshop that allows learners to see the layout of the machines so that they are comfortable working in the real workshop.

Through headset and gamepad position tracking and through tracking other parts of the body when adequate devices are used, VR is a medium that can lead users to adopt postures that are more or less equivalent to those they would adopt when carrying out a similar activity in a real situation. It is therefore particularly suitable for learning technical gestures or procedures. The level of the precision of the gesture required in the activity being learned should be related to the possibilities of the technology used. For example, learning a procedure on an electrical system or even interacting with a billet in a forge (see Figure 2) can be carried out with the usual VR controllers because it is not the fine motor gesture that will be trained but rather the understanding of the actions to be carried out. On the other hand, learning the precise gesture of a surgeon, if it is possible in VR, would be carried out with an effort feedback device, such as a haptic pen, for example.

There can be several gains in terms of learning regarding the use of haptic systems, but to be widely used, it has to be realistic, usable, and affordable to open a lot of new usages of VR for learning. VR is often used to learn safety behaviors. Obviously, carrying out this learning with a digital simulator rather than in a real situation allows learners to go as far as the accident without taking any risks. VR makes it possible to experience the accident more realistically than a non-immersive device.

In cases where users have to coreference physical elements with virtual elements, AR makes this integration possible. It can be used, for example, to make explanations written on an industrial machine appear in an integrated way, with each piece of content appearing directly near the part of the machine corresponding to what this content refers to. This integration of real elements, such as a machine and pedagogical highlight or visualization, can also be reproduced in VR (see, for example, Figure 3).

Finally, many studies show that course sequences based on immersive technologies often improve course attractiveness and learner satisfaction. For example, a VR anatomy course by Stepan et al.[8] does not make any difference to the traditional course regarding anatomy knowledge, but it is considered more engaging, enjoyable, useful, and motivating for students. Immersive technologies can therefore be a way to make some learning more

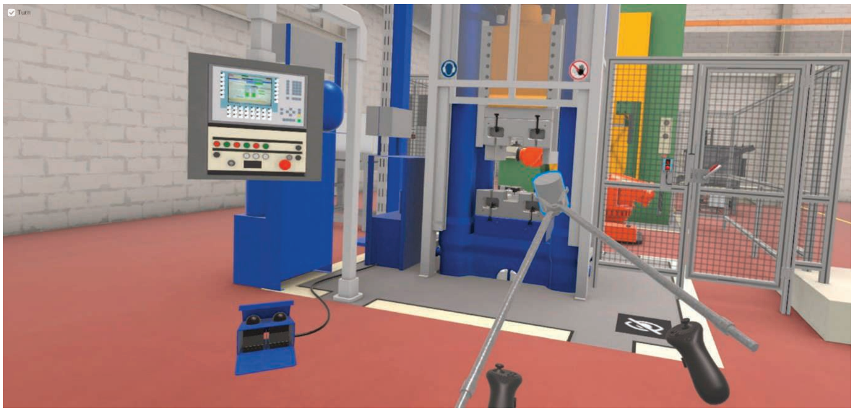


FIGURE 2. An interaction with a billet in a forge.

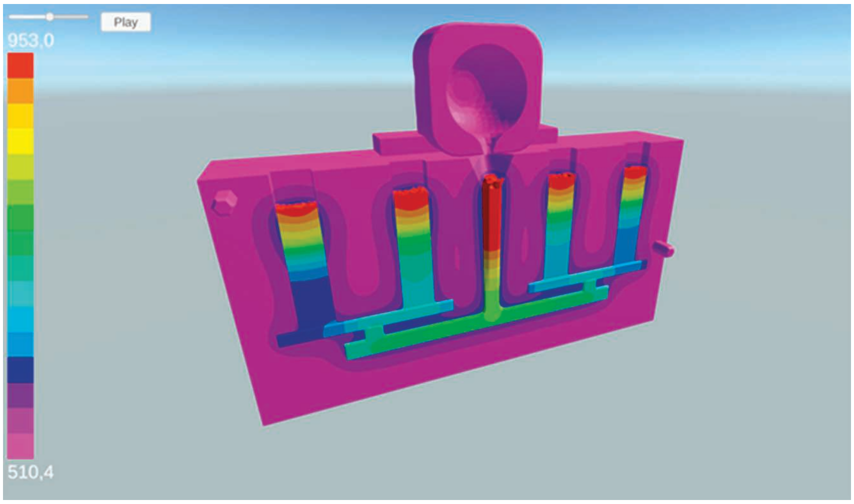


FIGURE 3. The visualization of physical phenomena.

attractive. In some cases, satisfaction and institutional image are issues for trainer. The positive effects of immersive technologies on the pleasurable and motivating nature of the activity also offer a potential that can be interesting for independent learning and revision. In cases where learners have the freedom to do exercises for practice or to not do so, having access to an attractive practice tool can make a difference to the amount of practice done.

SIMULATE FOR DESIGNING PRODUCTS

Simulators based on immersive technologies are identified to be relevant tools to support the design process for three main types of simulations: environments, intermediate objects of design, and co-designers. Immersing the designers in the right environment allows them to consider the characteristics of the place, such as its dimensions. The advantage of the modeled environment is that it can be used even if the real equivalent does not exist yet. When the environment already exists, the simpler and faster process is to acquire its volumes using 3D scanning, which captures all the details in the room that may be useful for the designers.

VR is relevant for the creation of intermediate design objects, particularly during the early stages that necessitate creativity, because it stimulates users and allows them to sketch using natural gestures that facilitate the expression of ideas. Cocreation in VR can be based on a metaphor of painting, sculpting, or 3D modeling to make the activity stimulating and easy to overcome. Figure 4 shows examples of VR sketching activity immersed in a scanned environment. The activity of sketching is in some cases part of ideation as sketching can be the means of representing the ideas generated. Sketching activity leads to generating more ideas than quick and dirty prototyping with tangible materials and leads to exploring more design spaces. VR as a tool for creativity is generally considered to be beneficial for creative activities. VR sketching software would be more effective than tablets for creative sketching as VR would support more flow and task motivation for the users.

VR is also superior to pen and paper for creative sketching because it leads to a satisfying level of efficiency, effectiveness, ease of use, and enjoyment and because it generates more extension of solution space, the enhancement of idea transformation, and inducement to a more holistic design approach for idea generation.[9] Some research has also been conducted on the uses of artificial intelligence (AI) to support the design process, for example, to automatically generate shapes to inspire designers.[10] This type of system could have great potential if integrated into a VR creative design environment.

VR is increasingly used in engineering for visualization but also for interaction with 3D models. In the study by Feeman et al.,[11] the participants had to model a chair. In one experimental condition, they used desktop CAD software, and in the other condition, they used the same software with a VR headset. The chairs modeled with desktop software were simplistic. It seems that the participants considered the task as finished as soon as the model looked like a chair. In comparison, the chairs modeled with headsets were more complex and more creative, as if the participants were more comfortable with this activity and continued longer to improve their model. Figure 5 shows three examples of furniture design made entirely in VR.

Finally, VR allows users to visualize at scale the intermediary design objects they work on to immediately identify corrections or improvements to be made. The integration of an intermediate object of design in a virtual environment of its future context is a means of identifying corrections that need to be made. It is also possible to integrate into AR a model in a real environment to visualize it and verify its adequacy. In a study by Fleury et al.,[12] students had to model furniture to refurbish a break room. The participants modeled the first version of their furniture using desktop 3D software. Then,

(a) (b)

FIGURE 4. (a) A seated user sketching a 3D table in VR, immersed in a 3D scanned virtual environment. (b) A quick and dirty immersed sketch of furniture in a scanned kitchen (on the right).

(a) (b) (c)

FIGURE 5. (a)–(c) Some examples of furniture models generated directly in VR.

they visualized their furniture in VR, immersed in a model of the room, with the possibility to position themselves in a specific posture to test the layout (see Figure 6). This study revealed that the participants were satisfied with their production before the VR step, but they all immediately identified several problems to be corrected (inadequacy between the furniture and the environment) when they were immersed. It is also possible for the designer or the future user to test the physical contact with a future product, for instance, the texture of a seat or a car's dashboard, using intermittent haptic interfaces based on a robotic arm (for example, Mugisha et al.[13])

SIMULATE FOR TESTING A PROCESS

This kind of simulation allows an engineer to have an overview of a process or an organization. This category does not impact only a product, as mentioned in the previous section, but how this product can be used and manipulated in a specific context. The notion of simulation has been addressed several times in the literature, often following needs arising from practical cases in the aeronautical, nuclear, or automotive industries. Simulation for testing a process has a double challenge: anticipating future activity in the design phase and training/educating the operator for a new workstation. In both cases, the simulation must bring sufficient knowledge to the designer and/or the operator so that they appropriate the future environment to discern all the subtleties of the potential interaction among humans, the system, the position, the tool, and the environment. The designers will then have the possibility of "designing": modifying their architectures to adapt them to the characteristics and expectations of people. As for the operators, they will be able to know the strategies to adopt and the essential knowledge to memorize and train their reflexes to carry out their activities as well as possible in safety.

Beyond training, simulation also makes it possible to anticipate "human errors," particularly in the nuclear sector or even aeronautics. Indeed, we propose to use digital simulation tools such as VR to study, understand, and anticipate the behavior of users. By implementing numerous simulations testing users under different conditions, it becomes possible to observe recurring errors that can be corrected by improving the systems or the physical environment or even by better training users. The simulation is distinguished by three objectives, which were defined by Béguin and Weill-Fassina[14] and which we detail here in the context of analysis carried out in the design office.

- knowing a work situation whose real observation is impossible
- acting as early as possible in the design process so that modifications are made
- interacting around the social concept means; that is, each professional actor in the design office

(a) (b)

FIGURE 6. (a) and (b) A user testing the view of a 3D modeled environment, reproducing a realistic position using a simple tangible chair.

working on a system must know and understand the simulated situations and their conclusions for the purposes of homogeneity of the final technical data.

These three objectives are part of a more global approach in which simulation is the pivot. Figure 7 shows the formalization of the approach to conducting a simulation project in ergonomics. Before any simulation, it is first necessary to analyze the current context and, of course, the future context in which the product or system under development will be used. It is then necessary (to prepare the simulation) to carry out a study by analogy to similar or even existing systems. There are often work and usage contexts that are close to the situation that needs to be simulated. It is therefore essential to carry out a prospective analysis of existing processes to foresee the possible similarities with the future process or procedures in the work environment in design. This preparation also aims to ensure a strong ecological validity of the future simulation and, hence, to ensure the smallest difference between what is simulated and what will happen in a real situation.

In the second step, it is necessary to design around the simulation. Thus, in this phase, the future process has to be simulated considering the characteristics of the future user. The last step, "to formalize," is perhaps one of the most important in a design office. Indeed, most of the population composing a design office and testing a process is specialized in mechanical engineering, not in human factors. These stakeholders lack knowledge of the human factors, and this formalization stage aims above all to communicate with all the departments of the design office working on the studied and simulated system. A good formalization of the simulation and the associated conclusions leads to recommendations that will have to be challenged against the mechanical criteria.

Many industries now develop and use digital simulation tools like VR and AR to assess a process. We can take some examples from the aviation industry, which has developed many uses of digital simulation tools over the last 20 years. More particularly, in maintainability, a department of the design office, which anticipates the future maintenance of aircraft, is currently in development. This department must anticipate human errors during the maintenance activity and make relevant recommendations to all design stakeholders to improve the global aircraft design, maintenance tools, and procedures. During the maintenance, there are multiple physical contacts that are important to simulate through

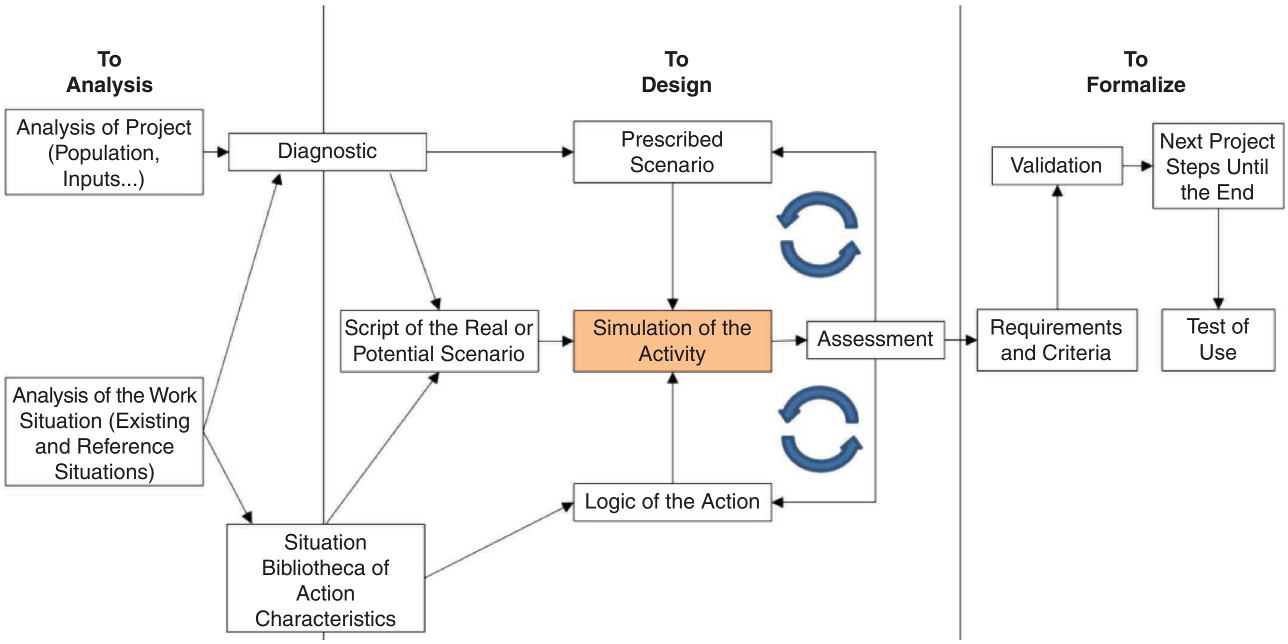


FIGURE 7. The human factors approach during a simulation process. (Source: Based on Van Belleghem and Guerry.[15])

VR. Indeed, the human factors analysis must take into consideration the three dimensions as physical, organization, and cognitive. The engine maintenance through the VR based on physical-sensory feedback has been tested.

The haptic system studied proved to be effective on the entire workstation represented by the engine. Indeed, this system follows the operators in their movements and has made it possible to ensure the diagnosis of different postures. This system, dedicated to a specific engine, has therefore made it possible to study certain criteria of the physical component of the ergonomics of the simulated tasks. Haptic systems are a real development issue and should lead to an optimal evaluation since they go beyond visual and sound immersion. Figure 8 shows a haptic system used during VR simulation, essential to assess human factors dimensions.

However, the cost of development and operation remains high, while many work situations cannot be studied. Indeed, the device remains bulky and complex in its implementation, not allowing adaptability to all work situations. In the context of aviation maintenance, many situations occur in a very constrained environment due to the very architecture of the aircraft. The haptic system is still not the most adequate tool, and other alternatives exist, sometimes simpler and cheaper.

More recently, in the context of a European helicopter manufacturer, a study has been performed to better know the complementarity among existing simulation tools in the maintainability department.[16] The use of VR to assess the three dimensions of human factors has highlighted the need to add some physical part to the environment. The need for motion in the work environment does not allow haptic system integration. However, a modular tangible interface system has been developed to provide adjustable rest and force feedback to various work situations in VR to ensure the consistency and representativeness of the simulation without the need to build a complete wood mockup. Before each VR simulation, an assessment of the tangible interface or force feedback is done to prepare the required material that could need 3D printing. The addition of the physical elements as well as their synchronization between the real and virtual world is less expensive than the haptic system, and it appears to be efficient at assessing human factors criteria.

The maintainability department of this industry is equipped with 3D printers to provide fast solutions for real part dimensions that can be easily merged into the VR simulation thanks to the motion tracker installed on the parts. To ensure representativeness, weight can be added to the 3D-printed parts, and a connection with the tangible interface can be made to reproduce, for example, a torque check. Such a protocol can be set up in a couple of days, whereas building a fully representative mockup would take weeks. Figures 9 and 10 show an example of

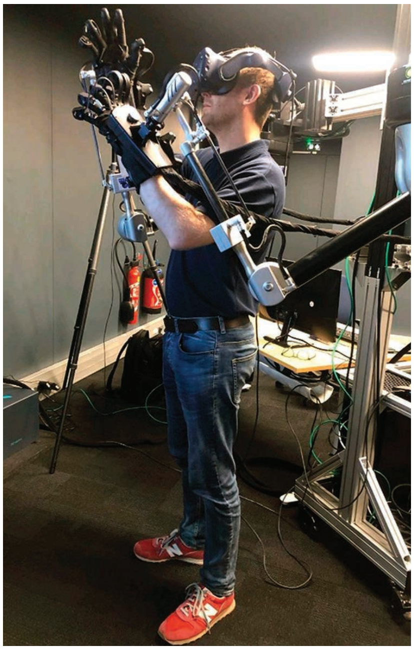
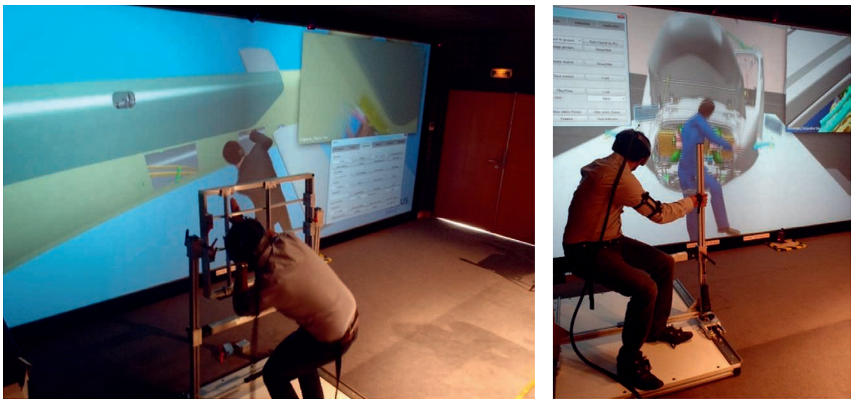


FIGURE 8. A haptic system used during a VR simulation.



(a) (b)

FIGURE 9. (a) and (b) A 2015 simulation in VR during the predesign phase of H160 to assess the ergonomic criteria for maintenance tasks such as the replacement of the flight control actuator inside the tail boom through a hatch or cleaning of the air conditioning filter in the nose avionic bay.

the digital system deployed for the last 10 years.

However, VR is not adapted to virtually perform all kinds of maintenance tasks. To compensate, AR is also developed and used. For example, AR has been used to specify, during the design process, the location and sizing of the handles and footstep on the helicopter fuselage.[17] Thanks to a simplified wood mockup, these authors have assessed the value of the AR to complete the simulation with all the details of the digital mockup. Two AR devices used allow a collaborative session among operators, human factors specialists, and designers, allowing them to validate the design and to identify potential risk and mitigation with higher accuracy, reducing lead time and cost with better confidence with each stakeholder.

ADDING AI TO IMMERSIVE SIMULATORS IS LIKELY TO SIGNIFICANTLY IMPROVE THEIR EFFECTIVENESS.

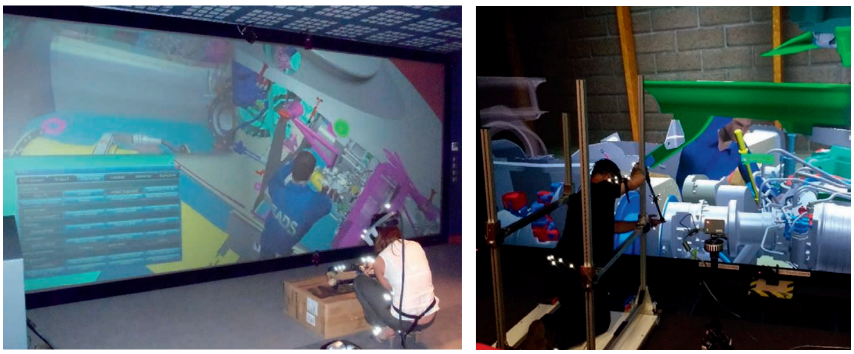
AR and VR allow one to visualize and interact with information or things in an immersive way, providing a feeling of presence to the users. This allows one to test situations in virtual worlds rather than in the tangible world, which has several virtues.

- save time and resources by testing something before deploying it
- improve safety by exposing the users only to virtual dangers
- allow an optimized information presentation format to guide attention and facilitate understanding.

The motivation for the present article was to describe and discuss the main uses of immersive technologies that are developing in industry. The aim was to analyze the state of research on this subject and the main issues that need to be addressed for future research.

We distinguished three main fields of use: training, designing products, and testing a process. Immersive technologies are used when people need to interact in a natural way (gesturally or posturally) with something that does not yet exist (a digital representation of a product being designed) or to interact with devices that are expensive (resources are saved by using the simulator rather than the real device) or dangerous (it is possible to go as far as an accident without danger). They are also used when it is necessary to visualize things as if you were facing them: to learn about them, test them, or consider them for reflection.

Among the avenues for the development of immersive simulators for industry, haptics seems particularly promising. *Haptics* refers to the notion of both force feedback and tactile perception. Realistic force feedback makes some training use cases possible when this feedback is necessary information to adjust a gesture, mainly for motor training. This can be useful for a lot of training, for instance, in the medical field (for example, surgery and dentistry) or for musical instruments. Tactile perception can be useful when texture must be simulated (for example, to test the interior of a car prototype[13]) Today, the use of haptic devices is limited because the equipment is relatively expensive and complex to implement. In addition, this involves specific



(a) (b)

FIGURE 10. (a) and (b) 2011 and 2017 simulations in VR during the predesign phase of H160 to assess force feedback and operator loads for the engine transmission shaft or torque check of the transmission system.

software developments to manage the haptic aspects in an immersive application. We believe there is a strong case for developing research to make haptic devices simpler and more accessible to develop new uses.

The collaborative dimension also appears as an important element in the three categories of uses mentioned in this article. Learning situations in immersive environments are almost always considered in research as individual situations with a user learning content by using an application. However, real training situations, whether vocational or educational, are usually collective. They bring together several learners, but they also involve the presence of a teacher or trainer. Similarly, immersive tools used in product or process design research are mostly individual and focused either on the designer (as in VR drawing tools) or on the tester (as in maintenance simulations). Nevertheless, the design process is often collective, involving several professionals (designers, engineers, etc.) and future potential users as testers. This is the second area of research that we feel is insufficiently developed today. There is a need for work that considers the role of teachers in immersive training and the specific interfaces that they could use to monitor and run training courses. There is also a need for research based on collaborative tools for product and process design, reflecting the collective aspect of design and the variety of roles of the stakeholders.

Adding AI to immersive simulators is likely to significantly improve their effectiveness. It can be used to analyze gestures to "guess the user's intentions" and propose corrections (for example, see Xu et al.[18]) or to evaluate production and provide detailed feedback based on model gestures, as it is used in training with other technologies (for example, see Bonneton-Botté et al.[19]) Another use of AI for immersive applications is to take over some of the work that needs to be done, for example, generative design, which automatically generates content based on specific constraints.[20] Clearly, AI is likely to become increasingly important in digital applications. This raises many new research topics that need to be addressed. Task sharing between AI and users needs to be done in a meaningful way, but more importantly, the issue of AI representation in immersive environments needs to be explored and characterized. Depending on the type of task being performed, it is necessary to know how the AI should be represented in the environment to facilitate interaction, trust, and the efficiency of the activity. For example, in VR or AR, one could imagine representing the AI by a character, humanoid or not, or evaluating innovative modes of dynamic data visualization in immersion. ■

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