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A Conceptual Training Simulator for the Assembly of Electric Vehicle Batteries in Virtual Reality

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Abstract

The growth of vehicle electrification is posing an increasing demand for electric batteries in the automotive industry. To respond to this growing demand, the automotive industry is starting to venture into the process of battery assembly. Multiple challenges arise from the complexities and the risks associated with these type of assembly processes. In this paper, the concept for a gamified virtual reality training system for battery assembly operators with the virtual representation of the risks is presented. A manual assembly process with automated assistance is considered. The results highlight the main aspects to consider for modeling a battery assembly process in a virtual environment. These aspects cover the areas of accurate modeling of risks, general user experience factors, and potential applications of the virtual reality training system.

Keywords: Virtual Reality; Training; Electric Vehicle Battery; Risks; Gamification

1. Introduction

As climate action, the 13th Sustainability Goal (United Nations), is becoming an increasingly urgent matter worldwide, the European Union is targeting a 55% reduction of greenhouse gas emissions by 2030 as part of the plan for achieving climate neutrality by 2050 (European Commission). For the automotive industry, the current trends to achieve this goal include vehicle electrification. To increase Electric Vehicle (EV) adoption, EV batteries (EVBs) are drifting towards higher voltages to increase their performance and reduce charging times (Aghabali et al., 2021).

Traditionally, the automotive industry has not been involved in the process of assembling batteries for EVs, so it now faces the challenges of finding productive, efficient, safe, and sustainable approaches for incorporating these new components into its production system. The growing connections between automotive and battery manufacturing industries offer possibilities for knowledge exchange and innovation (Ustabaş and Döner, 2021), however, the adaptation of battery assembly processes with the rest of assembly processes needed for car manufacturing constitutes a new field open for exploration within the automotive industry.

EVB manufacturing comprises multiple design decisions that are not only affected by performance requirements, there is also a need to address mechanical, thermal, electrical, and metallurgical challenges. These decisions affect the processes and technologies needed for EVB manufacturing and assembling. For example, it was observed that for welding different battery cell types (pouch, cylindrical or prismatic cells) inside a battery, the suitability of diverse welding technologies can differ (Zwicker et al., 2020). The design of EVBs is closely linked to the manufacturing process. Battery packs include multiple flexible elements whose assembly and fitting present difficulties for automation. Hybrid manufacturing systems that combine manual and automated processes can have benefits for these and other types of tasks, such as time savings in part feeding (Krüger et al., 2009). When facing the possibility of implementing automated assisted processes, the Level of Automation (LoA) needs to be decided according to the characteristics of the application at hand. For instance, Goh et al. (2020) proposes a LoA taxonomy that encompasses the variability in the inputs, outputs, strategies to apply, time demands, and other requirements. Once a suitable LoA is decided for a process, task allocation between human and robot needs to be contemplated. Different methods based on hierarchical task analysis and task decomposition have been developed to allocate tasks between humans and robots based on their strengths and the desired outputs. Examples of these methods include the adjustment to dynamic changes in the process by reallocating tasks in real-time when changes are detected (Bruno and Antonelli, 2018) or the definition of different workstation design variables for multiple scenario evaluation (Ore et al., 2020).

Assigning tasks to human operators in the EVB production process entails risks associated with the dangerous nature of managing stored energy. The risks of handling lithium-ion batteries include electrical, fire and explosion, and chemical hazards, which interact between each other. For example, the occurrence of an electrical short circuit can increase temperature, inducing a chemical reaction that results on the combustion of materials and the apparition of flames (Diekmann et al., 2018). External short circuits of batteries present the risk of direct current electric shocks, which can paralyze muscles, cause blood electrolysis, burns, heat, and even death, even without the interaction with other fire, explosion, and chemical hazards intrinsic to the batteries (Diekmann et al., 2018). Multiple safety standards exist to ensure that batteries perform as expected, with the quality and safety requirements needed for their application (Chen et al., 2021). However, compliance with standards does not necessarily mean that risks can be ignored or eliminated.

The steps in EVB assembly that need human participation introduce big risks for the operator's safety due to the voltages involved. One of these risks, which can present dangers for the operator's health, is that of short circuits. For this reason, preventive safety measures, such as implementing standardized assembly sequences, using insulated equipment, and providing rigorous training, need to be taken (Jooma, 2013). Simulation and digital tools are some of the allies that the current industry has for evaluating alternatives and making decisions, and they can play an important role in finding and improving solutions for these challenges.

Human-Robot Collaboration (HRC) is currently still in need of improvement in safety considerations, intuitive interactions, and safe operator training (Arents et al., 2021). Digital training, utilizing technologies such as Virtual Reality (VR), can be viewed as a way to increase hazard awareness for the real-world task in a safe environment (Arents et al., 2021) and to facilitate assembly and disassembly verification of complex three-dimensional systems (Wolfartsberger et al., 2019). Training can be considered an important factor in HRC (Gervasi et al., 2020).

This paper attempts to contribute in the direction of exploring how a virtual system for training operators, known as a Virtual Reality Operator Training Simulator (VR-OTS) (Patle et al., 2019), with a focus on electrical risk representation, can enable the operator's skill acquisition needed for the automated assisted assembly of EVBs in the automotive industry. Previous work on related fields has presented positive learning and technology acceptance results from the use of virtual tools for learning about electricity on academic settings (Ogbuanya and Onele, 2018; Nuanmeesri and Poomhiran, 2019), and for learning about electrical safety in industrial scenarios such as electrical installations (Blackledge and Barrett, 2012) and electrical substations (Castañeda-Mancillas et al., 2022). However, no work has been found on training for manual battery assembly, which differ from electrical installations in that they require live working while presenting a complex mixture of risks due to the materials and power involved and the possibility of interacting with assistive automation. Moreover, the found VR-OTS tend to give feedback to the users as values (such as the number of amperes circulating through a circuit), not addressing how implementing more gamification elements to this feedback could have an impact on learning.

The novelty of this paper is the research on how to apply virtual tools and a gamified approach to risk representation for training in the developing field of EVB assembly. The risk representation intents to make the user more aware of the risks by experiencing impactful virtual consequences that have a lasting learning effect in the real world. A conceptual VR-OTS for EVB assembly is developed through an iterative dialog with automotive companies and, as a result, the main aspects considered for the development and implementation of a EVB assembly VR-OTS are listed and categorized, in an effort to work towards the creation of a framework that guides the development of this type of VR-OTS.

2. State of the art

The industry is experiencing an important change that includes the introduction of multiple Industry 4.0 technologies and the rise of automation. For the industry to be able to adapt to the current market and environmental demands, including short product life cycles, a high level of customization, and reduced emissions, system flexibility becomes of great importance (Johansen et al., 2021b). Humans have a key role in achieving this flexibility in manufacturing settings while incorporating some level of automation for increased performance, repeatability, and accuracy (Gopinath and Johansen, 2019). Multiple internal, external, and technological reasons are driving the integration of human and robot collaboration (Correia Simões et al., 2020). The risks associated with combining operators and automated systems need to be addressed and controlled in order to implement safe and sustainable production systems. Safe assembly process design and operator training become important factors for minimizing risks and increasing the operator's understanding of the hazards associated with the task (Nielsen et al., 2022; Diego-Mas et al., 2020).

2.1. Electrification in the automotive industry

EVBs are the aggregation of battery packs, power electronics, a mechanical structure, a cooling system, and a managing system (Sharma et al., 2019). EVB packs are composed of multiple battery modules, which are built from joining the basic electrochemical units; the battery cells. This hierarchical assembly allows to build up the necessary voltage and capacity from the lower values of the battery cells. Individual cells provide a certain amount of energy between its terminals, which can be increased by joining the terminals of multiple cells with module busbars to create battery modules, which are completed with module controllers. Battery modules are then joined with pack busbars, creating the battery packs (Zwicker et al., 2020; Sharma et al., 2019).

In the EVB assembly process, the steps that involve the tight-fitting of flexible components, such as cables, or managing heavy parts, can become complex for automation, making the process rely on some level of manual assembly (Sharma et al., 2019). Implementing manual assembly steps in the assembly of EVBs, however, introduces important safety issues even if the tools and work environment are insulated following the IEC 60900 standard (IEC 60900) for live working settings of up to 1kV a.c. and 1.5kV d.c., as operators are managing increasingly higher voltages. A step moving in the direction of automation is the introduction of automated assisted processes, in which operators closely collaborate with robots. This combination, while potentially benefiting production, introduces additional risks to consider for the operator.

The prospect of fast changes in battery design to meet the evolving demand also introduces new challenges for the design and implementation of assembly processes (Aghabali et al., 2021). Therefore, assembly processes with increasing levels of automation, need to be able to adapt to changes in the near future to secure the viability and sustainability of their implementation (Johansen et al., 2021a).

2.2. Virtual Reality in industry

Extended Reality (XR) technologies, including VR, Augmented Reality (AR), and Mixed Reality (MR), are expanding the possibilities of the present and future Industry 4.0. The main industrial applications of VR present in literature in recent years focus on virtual manufacturing for planning and simulation (Chandra Sekaran et al., 2021), which includes assembly evaluation and ergonomic assessment of workstations (Peruzzini et al., 2021; Reinhard et al., 2020; Garcia Rivera et al., 2020) and human-robot interactions (Ottogalli et al., 2021), factory layout planning with the use of virtual twins (Pérez et al., 2020; Havard et al., 2019; Gong et al., 2019), product prototyping (Wolfartsberger, 2019; Berg and Vance, 2017), robot path planning and teleoperation (González et al., 2021; Arnarson et al., 2021), and training (Schwarz et al., 2020). The results from the academic research on industrial application use cases tend to indicate that VR can be an adequate option for achieving interactive and immersive visualizations but that it still needs to be considered as a complementary tool, as it requires the integration with other tools and methods for all-rounded successful outcomes (Chandra Sekaran et al., 2021; Wolfartsberger, 2019).

Some VR assembly training study cases suggest that training time can be reduced in comparison to traditional training methods while maintaining similar learning rates (Hoedt et al., 2017) and even increasing operator's performance (Kalkan et al., 2021). Key elements for VR training systems success seem to include realistic interactions with objects, immersive features, a reduced break of presence, virtual body ownership, and the inclusion of gamification (Radhakrishnan et al., 2021).

VR-OTS for automated assisted tasks introduces the possibility of training the operator in an environment with controlled risks. In the case of tasks that involve exposure to energy sources, as with EVBs, training in a safe environment becomes of great importance. This importance is strengthened by the introduction of automated assistance for task completion, as the increased complexity of the system can result in increased difficulty for the operator to maintain awareness of the dangers present at each moment in the process.

2.3. Gamification

Gamification has shown potential for learning outcomes (Palmas et al., 2019), with multiple studies showing how it can affect on cognitive, motivational, and behavioral learning outcomes (Sailer and Homner, 2020) and on different educational levels, from school to university education, and different contexts, such as learning physics or physical education (Manzano-León et al., 2021).

Different theoretical principles from learning theories, motivational and affective theories, and behavioral theories have been linked to elements present in gamification (Krath et al., 2021). This theoretical view helps understand the reasons behind the effects that gamification can have on shaping learning and, therefore, could be used as a guide for aspects to consider when developing a gamified learning system. According to this theoretical view presented by Krath et al. (2021), the achievement of the desired user behavior is rooted in the presentation of clear and prioritized goals as manageable tasks, providing immediate user feedback, positive reinforcement, and guidance. To make the learning experience personally relevant to the individual, goal customization, adaptation to skills' level, and multiple path choices should be allowed. Finally, permitting collaboration and results comparison between users are regarded as having positive social effects.

2.4. Research purpose

The concept for a gamified VR-OTS for EVB automated assisted assembly is presented in this paper, together with the methodology followed for its initial development. This system includes the virtual representation of short circuits and ergonomic risks created by the operator's actions during assembly. This representation is proposed with the aim of helping operators visualize and internalize how these risks could be materialized in the real world, and therefore, increase awareness of how incidents can be prevented. With the introduction of a collaborative system between operator and automation, awareness becomes of even greater importance, as not only the battery risk needs to be considered, but also the risks presented by the interaction with an automated robot.

Risk prevention and reduction in the context of operations that concern electricity is a joined effort between designing standardized assembly processes and assembly parts, safety protocols, insulated parts, protection equipment, insulated tools readily available from the market or in-house designed, and continuous workforce training, as required by the European Standard for the operation of electrical installations (EN 50110-1:2013). For the mixture of automated assisted assemblies and EVBs, providing operators with adequate training for both types of risks and the new ones generated by their combination becomes crucial for risk prevention.

This paper aims to answer the questions of (1) how to develop a gamified VR training system for a high electrical risk automated assisted assembly process, with enhanced risk representation, and (2) how can this VR training system be used as a tool for assisting on learning and skill development in the fast-evolving environment of EVBs. To achieve this, a VR-OTS for the automated assisted assembly of EVBs in a demonstrator case assembly is developed, following the methodology described in section 3.

3. Materials and Methods

A design and creation methodology (Oates, 2006) was used as the frame for guiding the development of a conceptual VR-OTS. The steps followed, as depicted in Figure 1, include an initial identification and definition of the problem, followed by the suggestion of a solution, the development of given suggestion, its evaluation, and the extraction of conclusions. A prototyping approach is followed, with the aim of iterating in the process to define the problem in more detail. The limited scope of this paper signifies that the artifact that is designed at this stage is the concept for a VR-OTS in line with the identified needs and the method to develop it. The steps followed aim to allow the extension of the research to a design methodology that has the creation of the VR-OTS as the produced artifact.

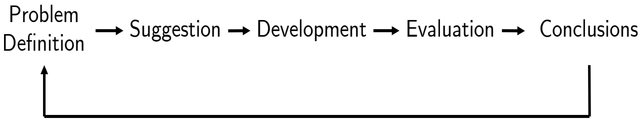


Figure 1. Iterative design and creation methodology

In the first stage, knowledge is acquired for understanding the problems to be addressed. Current challenges faced by the automotive industry concerning the EVB assembly process were identified by combining information collected from academic literature and unstructured interviews with companies from the automotive industry. Raising awareness of the latent risks that EVB can present to operators is identified as a factor that can contribute to reducing the probability of their materialization. To achieve this, VR is proposed as the main technological tool, in combination with a gamification approach for optimizing its performance.

3.1. Problem definition and Concept suggestion

Through the study of the EVB assembly process several challenges are identified and selected to be addressed :

- Adaptation to quickly evolving designs and assembly processes.
- Increasing risks for operators with EVB raising voltages.
- Design of safe and effective training for operators.
- Complexities derived from the collaboration with robots.
- Task design with HRC.

Once the challenges and technological approaches are defined, a first conceptual idea is developed to illustrate the capabilities of the VR-OTS. The concept of a VR training experience with the representation of electrical hazards is suggested as a way to reduce the possibility of risk materialization through operator awareness of the dangers associated with the EVB assembly tasks. A gamification approach is taken to design the type feedback given by the system. The idea for the VR-OTS is evaluated in dialogue with automotive companies and feedback is gathered about their perspectives on how it could be developed and applied in a valuable manner and on what benefits it could bring. The industry evaluation is utilized as a guide for defining the future steps to take in the development of the VR-OTS.

3.2. Concept development

A VR environment is developed to give shape to the suggested concept. The steps followed for the development of the VR-OTS are summarized in Table 1.

The game engine Unity 3D (Unity Technologies, 2022),

Table 1. VR-OTS development method

Implementation steps	Description
1. Defining the assembly operations	The simplified process of assembling three busbars and six screws to connect four battery modules, and the placement of a battery pack cover is defined as the main task to complete in the VR-OTS. The parts are designed and the assembly steps are specified.
2. Designing the layout and building the workstation	A fixed station is designed based on the defined assembly process. The assembly takes place on a table where the battery modules are located. The busbars, screws, and a screwdriver are located on a shelf next to the table. A collaborative robot is included in the scene and placed on the assembly table. A battery pack cover arrives from a conveyor belt that ends at the workstation, and a screen displays information related to the conveyor process (see Figure 2 for the designed layout).
3. Implementing the assembly operations	The assembly parts and assembly steps are introduced and defined in the VR environment (see Figure 3 for the implemented assembly).
4. Implementing the electrical and ergonomic risks representation	In the case of an operator making a mistake during the assembly process, electrical and ergonomic risks may materialize. The triggering actions for the risks and their representation are included in the simulator. The short-circuiting of a battery module is represented with the apparition of a lightning bolt (see Figure 4a) and the manual lifting of heavy objects is represented with a change to red color in the avatar's body (see Figure 4c). Both occurrences are accompanied by alert messages that explain the situation.
5. Including the possibility for different assemblies	A menu to choose from different assemblies that represent different EVB models is incorporated.

in combination with the Oculus Integration package, was used for the development of the VR system, which is developed for the Oculus Quest headset (Meta Platforms, Inc., 2022). An overview of the elements included in the developed VR workstation can be seen in Figure 2. The 3D models used were obtained from four different types of sources: the operator's avatar was outsourced from a Unity Store Asset (Banana Yellow Games, 2021), the lightning bolt was also obtained from a Unity Store Asset (Digital Ruby, 2017), the plant layout elements were obtained from the libraries in the manufacturing simulation software Visual Components Premium Version 4.4 (Visual Components Oy, 2022), the screwdriver and screen were obtained from the online catalog of the manufacturing company Atlas Copco (Atlas Copco Group, 2022), and the assembly parts were modeled for this project. The battery pack cover was modeled in Unity 3D, given the simple geometry that was used for its representation, and the rest of the parts were modeled in SolidWorks 2020 (Dassault Systèmes SE, 2022), based on the basic appearance of battery modules, busbars, and screws. Inverse kinematics is used for the basic avatar's control, based on the VR controllers and headset tracking.

The user, who in this case is the assembly operator, is presented with four unconnected battery modules (Figure 3a) and the assembly parts next to them (Figure 3b). The busbars and screws are assembled manually in the positions indicated by dynamic assembly instructions (Figure 3c). A screwdriver is then used to tighten the screws (Figure 3d). Visual and auditory positive feedback is given after task completion.

In the case that the terminals of a battery module are short-circuited by the operator's hands, the electrical shock risk is represented with the apparition of a lightning bolt (Figure 4a), accompanied by a lightning sound and VR controller vibration feedback. An alert message is also displayed in front of the operator. A battery pack cover is delivered to the workstation by a conveyor belt. A beeping sound signals the arrival of the cover, and a screen displays a message informing the operator that the part is ready for assembly (Figure 4b). Due to the dimensions and weight of the cover, it is considered unsuitable for ergonomically safe manual lifting. In case the operator lifts the cover manually, the operator's avatar color changes to red, and an alert message explaining the situation is shown (Figure 4c). The ergonomically safe lifting operation with robot assistance prevents the apparition of the ergonomic alert (Figure 4d).

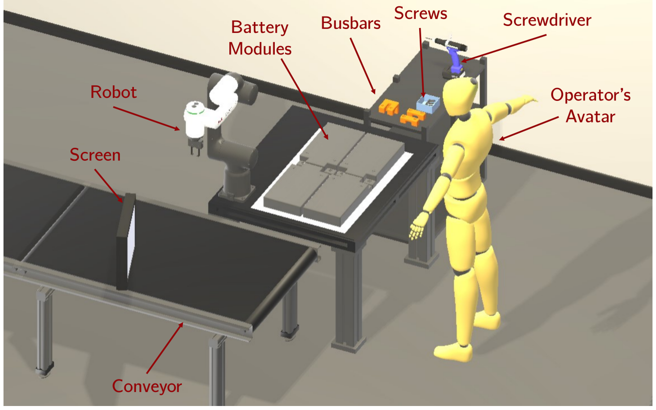


Figure 2. Overview of the developed VR-OTS layout

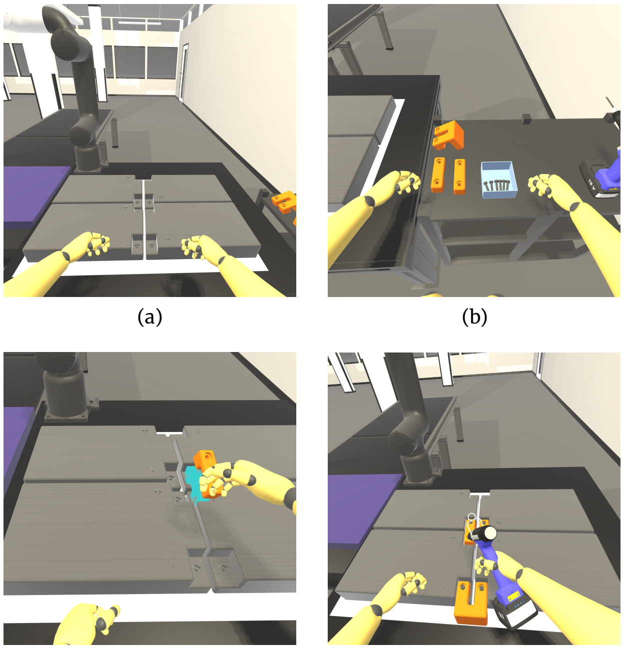
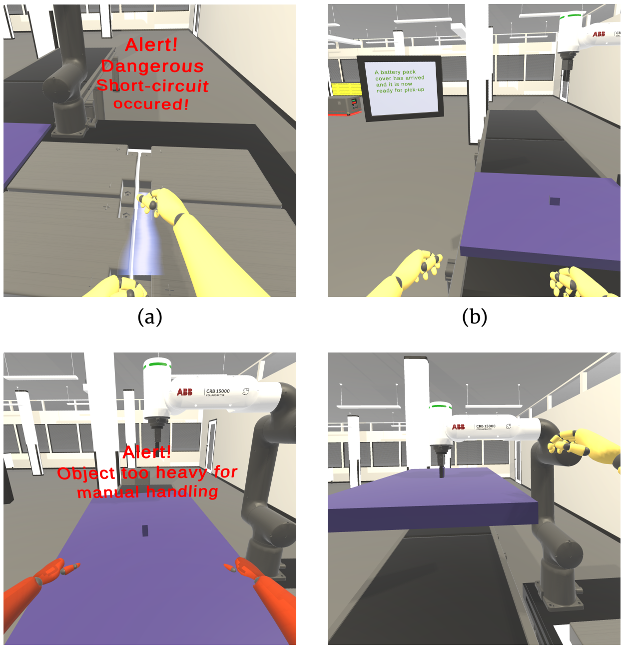

(a) (b) (c) (d)

Figure 3. Busbar assembly of EVB pack from the operator's point of view: (a) Unconnected grey battery modules on assembly table, on top of a white surface representing the limits of the battery pack housing, (b) busbars and box with screws placed on a shelf next to the assembly table, (c) busbar assembly process with a blue shadow indicating the busbar position, and (d) busbar scrweing with an electric screwdriver.



(a) (b) (c) (d)

Figure 4. Electric and ergonomic risk representation from the operator's point of view: (a) Short circuit caused by touching the terminals of a battery module with bare hands. A lightning-bolt is created and an alert message appears, (b) Battery pack cover arrives in a conveyor belt and a message on the screen informs the operator, (c) the heavy cover is picked up by hand, triggering an ergonomic alert. The avatar turns red and a message appears, (d) the part is picked up with a robotic arm and no ergonomic alerts appear.

Weight simulation in VR has been explored in the literature with the use of hardware and software tools (Ye, 2021). The use of external hardware that provides haptic feedback proportional to the weight of the handled object is ruled out for this application, as the trade-off between hardware simplification and accurate weight representation is considered acceptable at this stage. In the implemented representation emphasis is put on conveying the message of which parts surpass the threshold for safe manual lifting. Software-based methods rely on introducing a discrepancy between the expected and experienced movement of heavy objects, introducing a delay in their movement or a difference in the controller-object control ratio. These options are not introduced in this VR-OTS, as the aim is set to create an interaction paradigm that mimics reality. To increase the perceived weight with the limitations of the chosen implementation, a dark color is selected for the battery pack cover, as darker colors have been suggested to produce a heavier feeling than lighter colors (Maehigashi et al., 2021). Low brightness is selected for the cover's material, as it is also indicated that it can convey a heavier feeling than high brightness (Ban et al., 2013). A menu is also included as part of the VR-OTS user interface to allow the selection between different assembly training options for the multiple EVB models that could be produced in the assembly station.

3.3. Concept evaluation

The implemented version of the conceptual VR system is developed through an iterative process following the steps pictured in Figure 5.

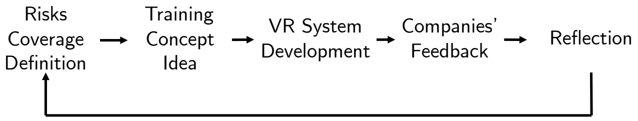


Figure 5. Iterative concept evaluation process based on the design and creation methodology followed.

In this study, the iterative loop is completed three times, starting with the definition of the types of risks covered in the VR-OTS and how they are presented to the operator. Next, a conceptual virtual training experience is designed, defining the operations, workstation elements, and interaction paradigms. Following the requirements of this conceptual training experience, a new version of the VR-OTS is implemented. Each version is used by the research team and video recordings are presented to the involved automotive companies involved in this research project in order to evaluate its design and implementation. Feedback is gathered from their perspectives on what aspects of the assembly process should be highlighted to the operator and on which areas they have faced more difficulties during training. The results from the feedback are used to reflect on how to further develop the VR-OTS by guiding

Table 2. Results overview. Development and implementation aspects to consider for a battery assembly VR-OTS, classified in three areas.

Virtual Modeling of Risks	General VR User Experience	VR-OTS Applications
Introducing the correct assembly sequence and specifications, including metrology operations.	Incorporating an intuitive setup process for new product variants.	Providing continuous training in a safe environment.
Representing the automated assisted operations in the workstation.	Providing feedback proportional to real-life consequences.	Providing initial assembly training in a safe environment.
Considering the participation of multiple operators.	Facilitating an intuitive use of the system for operators.	Allowing the introduction of different battery models in the assembly training system.
Modeling the different insulation layers for protection and the physical properties of the conductive objects in the environment.	Providing an intuitive process for updating the system when changes occur in the real environment.	Representation of different scenarios and risks based on environmental and individual factors (such as the type of protective equipment used).
Represent the main range of battery assembly specific risks (arcs, burns, high temperature, short circuits, explosions, and ergonomics).		
Adherence to the laws and safety standards followed in real-life assembly operations.		

the definition of the latent risks in the assembly process and how to successfully convey them to the operators.

4. Results and Discussion

The results from the iterative evaluation of the conceptual VR-OTS have been classified into three main categories, including the considerations for building the virtual physics and interaction paradigms that model the risks in the virtual environment, the general considerations for creating a basic satisfactory VR user experience, and the application cases towards which the VR-OTS should be designed for. These results can be found in Table 2.

The general VR user experience aspects observed are in line with the general guidelines for VR development that can be found in the literature (Regazzoni et al., 2018; O'Connor and Domingo, 2017), which focus on creating a experience in which the technology does not create a barrier in the learning process.

The work of Garcia Fracaro et al. (2021) presents a framework for the development of VR-OTS with gamification elements for a chemical reaction in the chemical industry, which similarly with the EVB assembly, is a high-risk task with multiple environmental factors involved and in which operator errors can have dangerous consequences. For the implementation of the chemical risks involved in the task, an interdisciplinary approach, including chemistry, engineering, and computer science experts, is applied for designing the VR-OTS. In the case of the EVB assembly VR-OTS, the participation of experts in EVBs is needed.

Exploring alternatives for electrical battery assembly and its LoA, adapting to new battery designs and voltage changes, and training operators on new battery assembly skills while assuring their safety, are all part of the challenges that the automotive industry is currently facing. Finding solutions for these issues is of complex nature. Selecting VR as a tool for facilitating training for the automated assisted assembly of EVBs by addressing the risks associated with the process introduces a new set of challenges that need to be addressed. These challenges include the implementation of a model of the risks and environment that represents reality with the fidelity needed for the learning outcomes to be accurate, the limitations of the VR technology, and the cost-benefit evaluation for the development and implementation of the VR-OTS. Previous studies conclude that the use of VR technology for training does not assure successful outcomes (Diego-Mas et al., 2020; Checa and Bustillo, 2020). The work of Grassini et al. (2020) highlights that enhancing the sense of presence in the virtual environment is a key factor for VR training. There is a need for the design of the physics that govern the virtual world and to include the mechanisms that trigger the battery-related hazards in different scenarios in a realistic manner, which would contribute to the sense of presence, but it also increases the complexity of the system.

5. Conclusions and Future work

In this paper, the concept of a gamified VR-OTS for EVB automated assisted assembly with a focus on risk representation is presented. The method followed for the development of the conceptual VR system is described and the preliminary evaluation of a concept is included as a guide for the future development and industrial application of such a system. The results obtained from this study point to the importance of creating representative models of the risks involved in the operations covered in a VR-OTS, to the underlying need for a user experience that allows the operator to focus on the content of the VR-OTS, and to the definition of the suitable use applications for this technology.

The early stages of the definition and design of the VR-OTS limit the readiness level of the system and the outcomes of this study. Future work in the implementation of a wide range of dangers and the elements needed for measuring, triggering, and representing them would be needed. In addition, the system, together with different interaction interfaces, should be tested by operators for evaluating its effectiveness and the outcomes of its use.

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References

Aghabali, I., Bauman, J., Kollmeyer, P. J., Wang, Y., Bilgin, B., and Emadi, A. (2021). 800-V electric vehicle powertrains: Review and analysis of benefits, challenges, and future trends. *IEEE Transactions on Transportation Electrification*, 7(3):927–948. https://doi.org/10.1109/TTE.2020.3044938.

Arents, J., Abolins, V., Judvaitis, J., Vismanis, O., Oraby, A., and Ozols, K. (2021). Human–robot collaboration trends and safety aspects: A systematic review. *Journal of Sensor and Actuator Networks*, 10(3):48. https://doi.org/10.3390/jsan10030048.

Arnarson, H., Solvang, B., and Shu, B. (2021). The application of virtual reality in programming of a manufacturing cell. In *2021 IEEE/SICE International Symposium on System Integration (SII)*, pages 213–218. ISSN: 2474-2325. https://doi.org/10.1109/IEEECONF49454.2021.9382657.

Atlas Copco Group (2022). Dimensional Drawings [Database]. https://webbox.atlascopco.com/webbox/dimdrw/.

Ban, Y., Narumi, T., Fujii, T., Sakurai, S., Imura, J., Tanikawa, T., and Hirose, M. (2013). Augmented endurance: controlling fatigue while handling objects by affecting weight perception using augmented reality. In *Proceedings of the SIGCHI Conference on Human Factors in Computing Systems*, CHI '13, pages 69–78. Association for Computing Machinery. https://doi.org/10.1145/2470654.2470665.

Banana Yellow Games (2021). Banana Man | 3D Humanoids | Unity Asset Store (Version 1.1). https://assetstore.unity.com/packages/3d/characters/humanoids/banana-man-196830.

Berg, L. P. and Vance, J. M. (2017). An industry case study: Investigating early design decision making in virtual reality. *Journal of Computing and Information Science in Engineering*, 17(1):011001. https://doi.org/10.1115/1.4034267.

Blackledge, J. and Barrett, M. (2012). Development and evaluation of a desktop VR system for electrical services engineers. *International Association of Engineers: ICEEE12, London*. https://doi.org/10.21427/D7D05T.

Bruno, G. and Antonelli, D. (2018). Dynamic task classification and assignment for the management of human-robot collaborative teams in workcells. *The International Journal of Advanced Manufacturing Technology*, 98(9):2415–2427. https://doi.org/10.1007/s00170-018-2400-4.

Castañeda-Mancillas, E. E., Sanchez-Rentería, E., Torres-Guerreo, F., and Buń, P. (2022). A design proposal: Virtual reality environment for safety training in electrical substations. In Trojanowska, J., Kujawińska, A., Machado, J., and Pavlenko, I., editors, *Advances in Manufacturing III*, Lecture Notes in Mechanical Engineering, pages 278–291. Springer International Publishing. https://doi.org/10.1007/978-3-030-99310-8_22.

Chandra Sekaran, S., Yap, H. J., Musa, S. N., Liew, K. E., Tan, C. H., and Aman, A. (2021). The implementation of virtual reality in digital factory—a comprehensive review. *The International Journal of Advanced Manufacturing Technology*, 115(5):1349–1366. https://doi.org/10.1007/s00170-021-07240-x.

Checa, D. and Bustillo, A. (2020). A review of immersive virtual reality serious games to enhance learning and training. *Multimedia Tools and Applications*, 79(9):5501–5527. https://doi.org/10.1007/s11042-019-08348-9.

Chen, Y., Kang, Y., Zhao, Y., Wang, L., Liu, J., Li, Y., Liang, Z., He, X., Li, X., Tavajohi, N., and Li, B. (2021). A review of lithium-ion battery safety concerns: The issues, strategies, and testing standards. *Journal of Energy Chemistry*, 59:83–99. https://doi.org/10.1016/j.jechem.2020.10.017.

Correia Simões, A., Lucas Soares, A., and Barros, A. C. (2020). Factors influencing the intention of managers to adopt collaborative robots (cobots) in manufacturing organizations. *Journal of Engineering and Technology Management*, 57:101574. https://doi.org/10.1016/j.jengtecman.2020.101574.

Dassault Systèmes SE (2022). SolidWorks (Version 2020) [Computer software]. https://www.solidworks.com.

Diego-Mas, J. A., Alcaide-Marzal, J., and Poveda-Bautista, R. (2020). Effects of using immersive media on the effectiveness of training to prevent ergonomics risks. *International Journal of Environmental Research and Public Health*, 17(7):E2592. https://doi.org/10.3390/ijerph17072592.

Diekmann, J., Grützke, M., Loellhoeffel, T., Petermann, M., Rothermel, S., Winter, M., Nowak, S., and Kwade, A. (2018). Potential dangers during the handling of lithium-ion batteries. In Kwade, A. and Diekmann, J., editors, *Recycling of Lithium-Ion Batteries: The LithoRec Way*, Sustainable Production, Life Cycle Engineering and Management, pages 39–51. Springer International Publishing. https://doi.org/10.1007/978-3-319-70572-9_3.

Digital Ruby (2017). Lightning Bolt Effect for Unity | Particles/Effects | Unity Asset Store (Version 1.0.1). https://assetstore.unity.com/packages/tools/particles-effects/lightning-bolt-effect-for-unity-59471.

EN 50110-1:2013. Operation of electrical installations - Part 1: General requirements. Standard, European Standard.

European Commission. 2030 climate target plan. https://ec.europa.eu/clima/eu-action/european-green-deal/2030-climate-target-plan_en. Accessed: 2022-02-14.

Garcia Fracaro, S., Chan, P., Gallagher, T., Tehreem, Y., Toyoda, R., Bernaerts, K., Glassey, J., Pfeiffer, T., Slof, B., Wachsmuth, S., and Wilk, M. (2021). Towards design guidelines for virtual reality training for the chemical industry. *Education for Chemical Engineers*, 36:12–23. https://doi.org/10.1016/j.ece.2021.01.014.

Garcia Rivera, F., Brolin, E., Syberfeldt, A., Högberg, D., Iriondo Pascual, A., and Perez Luque, E. (2020). Using virtual reality and smart textiles to assess the design of workstations. *SPS2020*, pages 145–154. Publisher: IOS Press. https://doi.org/10.3233/ATDE200152.

Gervasi, R., Mastrogiacomo, L., and Franceschini, F. (2020). A conceptual framework to evaluate human-robot collaboration. *The International Journal of Advanced Manufacturing Technology*, 108(3):841–865. https://doi.org/10.1007/s00170-020-05363-1.

Goh, Y. M., Micheler, S., Sanchez-Salas, A., Case, K., Bumblauskas, D., and Monfared, R. (2020). A variability taxonomy to support automation decision-making for manufacturing processes. *Production Planning & Control*, 31(5):383–399. https://doi.org/10.1080/09537287.2019.1639840.

Gong, L., Berglund, J., Fast-Berglund, A., Johansson, B., Wang, Z., and Börjesson, T. (2019). Development of virtual reality support to factory layout planning. *International Journal on Interactive Design and Manufacturing (IJIDeM)*, 13(3):935–945. https://doi.org/10.1007/s12008-019-00538-x.

González, C., Solanes, J. E., Muñoz, A., Gracia, L., Girbés-Juan, V., and Tornero, J. (2021). Advanced teleoperation and control system for industrial robots based on augmented virtuality and haptic feedback. *Journal of Manufacturing Systems*, 59:283–298. https://doi.org/10.1016/j.jmsy.2021.02.013.

Gopinath, V. and Johansen, K. (2019). Understanding situational and mode awareness for safe human-robot collaboration: case studies on assembly applications. *Production Engineering*, 13:1–9. https://doi.org/10.1007/s11740-018-0868-2.

Grassini, S., Laumann, K., and Rasmussen Skogstad, M. (2020). The use of virtual reality alone does not promote training performance (but sense of presence does). *Frontiers in Psychology*, 11. https://doi.org/10.3389/fpsyg.2020.01743.

Havard, V., Jeanne, B., Lacomblez, M., and Baudry, D. (2019). Digital twin and virtual reality: a co-simulation environment for design and assessment of industrial workstations. *Production & Manufacturing Research*, 7(1):472–489. Publisher: Taylor & Francis. https://doi.org/10.1080/21693277.2019.1660283.

Hoedt, S., Claeys, A., Van Landeghem, H., and Cottyn, J. (2017). The evaluation of an elementary virtual training system for manual assembly. *International Journal of Production Research*, 55(24):7496–7508. Number: 24. https://doi.org/10.1080/00207543.2017.1374572.

IEC 60900. Live working - Hand tools for use up to 1 000 V a.c. and 1 500 V d.c. Standard, International Electrotechnical Commission.

Johansen, K., Ashourpour, M., and Rao, S. (2021a). Positioning sustainable automation in production of customized products. *Procedia Manufacturing*, 55:358–364. https://doi.org/10.1016/j.promfg.2021.10.050.

Johansen, K., Rao, S., and Ashourpour, M. (2021b). The role of automation in complexities of high-mix in low-volume production – a literature review. *Procedia CIRP*, 104:1452–1457. https://doi.org/10.1016/j.procir.2021.11.245.

Jooma, Z. (2013). Electrical workplace safety - seven electrical safety habits. In *2013 Electrical Arc Flash Conference - IDC Technologies*, pages 1–14. Retrieved from https://api.semanticscholar.org/CorpusID:111158196.

Kalkan, O. K., Karabulut, S., and Höke, G. (2021). Effect of virtual reality-based training on complex industrial assembly task performance. *Arabian Journal for Science and Engineering*, 46(12):12697–12708. https://doi.org/10.1007/s13369-021-06138-w.

Krath, J., Schürmann, L., and von Korflesch, H. F. O. (2021). Revealing the theoretical basis of gamification: A systematic review and analysis of theory in research on gamification, serious games and game-based learning. *Computers in Human Behavior*, 125:106963. https://doi.org/10.1016/j.chb.2021.106963.

Krüger, J., Lien, T., and Verl, A. (2009). Cooperation of human and machines in assembly lines. *CIRP Annals*, 58(2):628–646. https://doi.org/10.1016/j.cirp.2009.09.009.

Maehigashi, A., Sasada, A., Matsumuro, M., Shibata, F., Kimura, A., and Niida, S. (2021). Virtual weight illusion: Weight perception of virtual objects using weight illusions. In *Extended Abstracts of the 2021 CHI Conference on Human Factors in Computing Systems*, pages 1–6. ACM. https://doi.org/10.1145/3411763.3451842.

Manzano-León, A., Camacho-Lazarraga, P., Guerrero, M. A., Guerrero-Puerta, L., Aguilar-Parra, J. M., Trigueros, R., and Alias, A. (2021). Between level up and game over: A systematic literature review of gamification in education. *Sustainability*, 13(4):2247. https://doi.org/10.3390/su13042247.

Meta Platforms, Inc. (2022). Explore Oculus Quest. https://www.oculus.com/quest/features/.

Nielsen, K., Ng, K., Guglielmi, D., Lorente, L., Pătraş, L., and Vignoli, M. (2022). The importance of training transfer of non-technical skills safety training of construction workers. *International Journal of Occupational Safety and Ergonomics*, pages 1–9. https://doi.org/10.1080/10803548.2022.2052624.

Nuanmeesri, S. and Poomhiran, L. (2019). Perspective electrical circuit simulation with virtual reality. *International Journal of Online and Biomedical Engineering (iJOE)*, 15(5):28–37. Number: 05. https://doi.org/10.3991/ijoe.v15i05.9653.

Oates, B. J. (2006). *Researching Information Systems and Computing*. Sage Publications Ltd.

Ogbuanya, T. C. and Onele, N. O. (2018). Investigating the effectiveness of desktop virtual reality for teaching and learning of electrical/electronics technology in universities. *Computers in the Schools*, 35(3):226–248. Publisher: Routledge. https://doi.org/10.1080/07380569.2018.1492283.

Ore, F., Jiménez Sánchez, J. L., Wiktorsson, M., and Hanson, L. (2020). Design method of human–industrial robot collaborative workstation with industrial application. *International Journal of Computer Integrated Manufacturing*, 33(9):911–924. https://doi.org/10.1080/0951192X.2020.1815844.

Ottogalli, K., Rosquete, D., Rojo, J., Amundarain, A., María Rodríguez, J., and Borro, D. (2021). Virtual reality simulation of human-robot coexistence for an aircraft final assembly line: process evaluation and ergonomics assessment. *International Journal of Computer Integrated Manufacturing*, 34(9):975–995. https://doi.org/10.1080/0951192X.2021.1946855.

O'Connor, E. A. and Domingo, J. (2017). A practical guide, with theoretical underpinnings, for creating effective virtual reality learning environments. *Journal of Educational Technology Systems*, 45(3):343–364. Publisher: SAGE Publications Inc. https://doi.org/10.1177/0047239516673361.

Palmas, F., Labode, D., Plecher, D. A., and Klinker, G. (2019). Comparison of a gamified and non-gamified virtual reality training assembly task. In *2019 11th International Conference on Virtual Worlds and Games for Serious Applications (VS-Games)*, pages 1–8. IEEE. https://doi.org/10.1109/VS-Games.2019.8864583.

Patle, D. S., Manca, D., Nazir, S., and Sharma, S. (2019). Operator training simulators in virtual reality environment for process operators: a review. *Virtual Reality*, 23(3):293–311. https://doi.org/10.1007/s10055-018-0354-3.

Peruzzini, M., Grandi, F., Cavallaro, S., and Pellicciari, M. (2021). Using virtual manufacturing to design human-centric factories: an industrial case. *The International Journal of Advanced Manufacturing Technology*, 115(3):873–887. https://doi.org/10.1007/s00170-020-06229-2.

Pérez, L., Rodríguez-Jiménez, S., Rodríguez, N., Usamentiaga, R., and García, D. F. (2020). Digital twin and virtual reality based methodology for multi-robot manufacturing cell commissioning. *Applied Sciences*, 10(10):3633. https://doi.org/10.3390/app10103633.

Radhakrishnan, U., Koumaditis, K., and Chinello, F. (2021). A systematic review of immersive virtual reality for industrial skills training. *Behaviour & Information Technology*, 40(12):1310–1339. https://doi.org/10.1080/0144929X.2021.1954693.

Regazzoni, D., Rizzi, C., and Vitali, A. (2018). Virtual reality applications: Guidelines to design natural user interface. *Proceedings of the ASME 2018 International Design Engineering Technical Conferences and Computers and Information in Engineering Conference*. https://doi.org/10.1115/DETC2018-85867.

Reinhard, R., Mårdberg, P., García Rivera, F., Forsberg, T., a Rivera, F., Berce, A., Fang, M., and Högberg, D. (2020). The use and usage of virtual reality technologies in planning and implementing new workstations. *DHM2020*, pages 388–397. Publisher: IOS Press. https://doi.org/10.3233/ATDE200047.

Sailer, M. and Homner, L. (2020). The gamification of learning: a meta-analysis. *Educational Psychology Review*, 32(1):77–112. https://doi.org/10.1007/s10648-019-09498-w.

Schwarz, S., Regal, G., Kempf, M., and Schatz, R. (2020). Learning success in immersive virtual reality training environments: Practical evidence from automotive assembly. In *Proceedings of the 11th Nordic Conference on Human-Computer Interaction: Shaping Experiences, Shaping Society*, pages 1–11. ACM. https://doi.org/10.1145/3419249.3420182.

Sharma, A., Zanotti, P., and Musunur, L. P. (2019). Enabling the electric future of mobility: Robotic automation for electric vehicle battery assembly. *IEEE Access*, 7:170961–170991. https://doi.org/10.1109/ACCESS.2019.2953712.

United Nations. Goal 13 | department of economic and social affairs. https://sdgs.un.org/goals/goal13. Accessed: 2022-02-17.

Unity Technologies (2022). Unity (Version 2020.3.27f1) [Computer software]. https://unity.com/.

Ustabaş, A. and Döner, A. (2021). Inter-firm relations between battery suppliers and electrical vehicles manufacturers: A network analysis. *Atatürk Üniversitesi İktisadi ve İdari Bilimler Dergisi*, 24:527–551. Retrieved from https://dergipark.org.tr/en/pub/ataunisosbil/issue/55053/683305.

Visual Components Oy (2022). Visual Components Premium (Version 4.4) [Computer software]. https://www.visualcomponents.com.

Wolfartsberger, J. (2019). Analyzing the potential of virtual reality for engineering design review. *Automation in Construction*, 104:27–37. https://doi.org/10.1016/j.autcon.2019.03.018.

Wolfartsberger, J., Haslwanter, J., and Lindorfer, R. (2019). Perspectives on assistive systems for manual assembly tasks in industry. *Technologies*, 7(1):12. https://doi.org/10.3390/technologies7010012.

Ye, X. (2021). A survey on simulation for weight perception in virtual reality. *Journal of Computer and Communications*, 09(9):1–24. https://doi.org/10.4236/jcc.2021.99001.

Zwicker, M. F. R., Moghadam, M., Zhang, W., and Nielsen, C. V. (2020). Automotive battery pack manufacturing – a review of battery to tab joining. *Journal of Advanced Joining Processes*, 1:100017. https://doi.org/10.1016/j.jajp.2020.100017.