Batteries & Supercaps

Concept
doi.org/10.1002/batt.202400042

Chemistry Europe
European Chemical Societies Publishing

www.batteries-supercaps.org

Breaking Down the Barriers between the Digital and the Real: Mixed Reality Applied to Battery Manufacturing R&D and Training

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In a scenario in which the manufacturing of high-performance, safe batteries on an unprecedented large scale is crucial for the energy transition and fight against climate change, research laboratories and cell production industries are facing challenges due to the lack of efficient data management and training tools. In this context, the use of intelligent devices plays an important role on the path towards the optimization of the manufacturing process and the enhancement of the battery performance while reducing production costs. In this Concept, we present an innovative Mixed Reality tool for efficient data collection and training in real-time in battery research laboratories and battery manufacturing pilot lines, which runs on Microsoft HoloLens 2 glasses. We report a deep analysis on its ergonomic and usability aspects, and describe how we solved the problems found during its development. Thanks to this tool, users can collect data while keeping their hands free and receive advice in real time to design and build batteries with tailored properties. This optimizes data management in battery manufacturing environments. Now, thanks to our Mixed Reality application, users can collect data in the place of work, save this data automatically on a server and exploit it to receive advice and feedback to support their decision-making and learning of the manufacturing process.

1. Introduction

The ongoing global energy transition is driving an unprecedented increase in the demand for rechargeable batteries, with lithium-ion batteries (LIBs) emerging as the cornerstone technology. The establishment of new gigafactories is essential to support the production scale-up required for widespread adoption of electric vehicles. In this scenario, the European Union, and France in particular, have taken on board the strategic importance of batteries in the energy transition and in reducing greenhouse gas emissions. In this direction, initiatives are underway to strengthen Europe's independence in the battery sector, create jobs and stimulate innovation.[1] For example, with the Battery 2030+ research initiative, Europe has put together a global roadmap to push battery research for a safer, more sustainable and more competitive future.[2] Within this framework, several research themes have been identified, including Artificial Intelligence (AI)-driven accelerated discovery of battery interfaces and materials, and the integration of smart sensing and self-healing functionalities into the battery cells. This ambitious international initiative unfolds a comprehensive global roadmap, steering battery research toward transformative goals, and promotes the use of new technologies to stimulate and accelerate battery research and development.

The integration of smart digital technologies and data management tools into industrial processes is the main pillar of the Industry 4.0 concept, which promotes the use of new technologies such as big data analytics, blockchain and the Internet of Things (IoT), as well as Virtual Reality (VR), Augmented Reality (AR) and Mixed Reality (MR). VR, AR and MR are immersive technologies, since they create a simulated environment that the user can interact with in a way that feels

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Supporting information for this article is available on the WWW under https://doi.org/10.1002/batt.202400042

real. VR is fully immersive, creates a 3D computer-generated environment and generally uses a headset, thus making it a compelling alternative for gaming and training applications.[3] On the other hand, AR allows users to keep seeing the real environment, but overlies virtual elements, and MR combines and allows real and virtual environments to coexist, with the user interacting with both of them at the same time.[4] MR offers spatial flexibility for interacting with virtual objects in real time in a more natural way, and is a technology that frees up hands, which can be particularly useful in situations where users need to keep their hands free for other tasks.[5,6]

Thanks to their unique properties, immersive technologies have an outstanding potential for a wide range of applications: manufacturing and assembly tasks, where they can be used to improve the efficiency and accuracy of processes with real-time guidance and assistance; customer service and sales, since they can provide customers with product information and support in real time to increase sales; or education and training, since they can provide a more engaging and effective learning experience than traditional methods.[7] Additionally, thanks to the development of new generations of advanced hardware such as MR glasses with increased data processing power, new digital applications are made possible. Furthermore, interconnected computers, smart devices and intelligent machines communicate with each other and can reduce human activity while automating and facilitating data flow management.[8] This revolution is also changing the way we work by redefining tasks. Digitalization is speeding up research, increasing efficiency and productivity, as well as quality and customization.[9] In battery cell manufacturing, integrating some of these technologies and AI has the potential to facilitate predictive maintenance and the optimization of production processes. Overall, Industry 4.0 promises to revolutionize the way battery cells are produced and used, leading to a more sustainable and efficient energy future, but several challenges still remain.

In order to seamlessly incorporate immersive technologies in battery research and production, it is essential to have a profound understanding of the battery manufacturing process. Battery cell manufacturing is a challenging and complex process, with strict safety and environmental requirements, which involves a sequence of steps.[8] The manufacturing process of LIB cells is highly sensitive to numerous process parameters, for instance to small variations in temperature, composition, pressure, humidity and other conditions that have a strong impact on the battery cell performance and lifespan, thus making it crucial to optimize them.[10] LIBs are the dominant battery technology today due to their relatively high energy density, long lifespan, low maintenance and low cost, but there is still room to improve their performance. The LIB cell manufacturing process (Figure 1) begins with the selection of the formulation and premixing of the active material, conductive additives and binder powders. Next, the liquid


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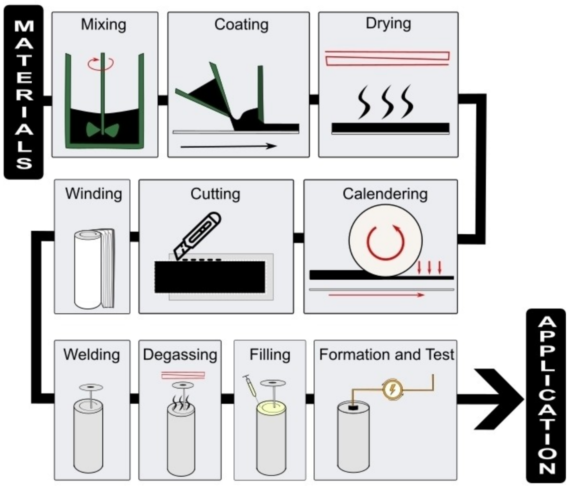

Figure 1. Scheme of the battery manufacturing process. Figure adapted from our previous publication, Denisart et al.[11]

solvent is added to obtain a liquid, viscous ink, and, after mixing, the resulting slurry is coated on the current collector and dried in an oven to evaporate the solvent. Afterwards, the resulting electrode is calendered between two rollers that apply uniform pressure to the strip to increase the electrical conductivity by reducing its thickness and its porosity. The process must be repeated to obtain the second electrode, thus producing a LIB cell consisting of an anode (negative electrode), a porous separator and a cathode (positive electrode). The two electrodes are cut according to the battery cell format required and assembled, involving either the stacking (*e.g.* pouch cell format) or winding (cylindrical format) of the components. Next, the terminals are welded and the cell is inserted into a partially sealed capsule. The battery cell is then degassed and filled with the liquid electrolyte, before it is completely sealed. Next, the solid electrolyte interphase (SEI) formation step is performed, and finally, the cell is ready to be used for its application.

This manufacturing process for LIB cells is highly complex, with many interdependencies and a high degree of sensitivity to numerous parameters and a large number of different parameter combinations and work conditions.[10] Therefore, in order to accelerate research and development strategies, it is essential to create a systemic understanding to identify and understand the correlations between the different parameters (*e.g.* formulation, mixing speed, comma gap, temperature, etc.) and the electrode and cell properties (*e.g.* electrode conductivity or cell energy density). A better understanding of these interdependencies in the manufacturing process is essential, but having tools for efficient manufacturing data management and training is also critical. The right data management policies are necessary to post-process and exploit the manufacturing data correctly, and training is important to guarantee efficiency, productivity and data quality: the realization of both aspects through immersive technologies, as proposed by us in this Concept, arises as a promising approach to automate and accelerate battery manufacturing optimization.

Data management has been proven to be essential for accelerating research and development, and has been increasingly explored in recent years.[12] Data management is the process of collecting, storing, organizing and preserving the data created and collected by an individual, a research group or a company,[13] and can be divided into three stages: quick and easy data capture, data storage and preservation, and data analysis for reuse to accelerate research. When data is poorly managed, it can be inaccurate, incomplete or inconsistent, thus making it difficult for researchers or engineers to draw meaningful conclusions from it and leading to wasted resources and time.[14] This can lead to a significant number of lost opportunities for better science and engineering. Thus, data governance and data quality have become top priorities and, for this, it is important to dispose of efficient data management processes and the right technology.

When LIB cells are manufactured, a large amount of data is generated (*i.e.* input parameters such as formulation, coating speed, drying rate, calendering degree, and output parameters such as electrode porosity, cell energy density), and, therefore, it is essential to have tools that facilitate data collection and improve the understanding of the data while highlighting avenues for exploring data analysis. Several tools have already been described, although there are no common standards or policies widely accepted for data management in the battery field.[15] Optimized data management has the potential to reduce scrap rates, improve battery quality and identify the process stages or materials that cause failures. Ultimately, this will enable a large number of still unexplored avenues of research to be explored more quickly and clearly. In the study presented in this Concept, we elucidate how MR can be used for data collection in the battery manufacturing. By seamlessly blending the physical and virtual realms, MR tools enhance safety and efficiency, providing an innovative solution for navigating and gathering crucial data in lab and industrial environments and optimizing the data management process as a whole. Several studies have examined the contribution of immersive technologies as training and activity support tools,[16,17] with excellent results in other applications, including gaming, healthcare, training and automotive manufacturing.[18]

Through our previous works which pioneered the use of VR and MR in the battery field, we have shown that these technologies have many advantages, in particular for education purposes, because they allow users to enjoy a unique real-time immersive and interactive experience.[19–21] We believe that MR, in particular, has the potential to revolutionize the battery manufacturing process by improving worker training, inspection and assembly tasks. This is because, through the use of MR headsets and holographic displays, workers can access data and instructions in real time, improving efficiency and reducing the risk of error.[22] MR can also facilitate maintenance and remote assistance, allowing experts to guide and troubleshoot manufacturing processes remotely.[23,24] It has already been shown in other application contexts that MR is a suitable technology for making decisions and carrying out certain tasks, such as the design review process.[25] Finally, a study in the field of architecture shows that users seem convinced that using MR increases their personal satisfaction, particularly in collaborative situations.[25]

The construction of several gigafactories in Europe requires a workforce trained in many aspects such as understanding battery electrochemistry, safety protocols, quality control and production processes.[26] In recent years, training in other fields has made increasing use of digital technologies such as VR, but it is still essential to adapt them to training activities which are relevant to the real gigafactories' needs, to enable them to produce high-quality batteries and achieve their production targets. The training process is highly complex and time-consuming, and must include the technical skills needed to manufacture battery cells properly (*i.e.* safe handling of chemicals and operating machinery) and understand the correlations between the manufacturing parameters and the properties of the produced electrodes and cells.[10,27] The use of immersive technologies such as VR for professional training has become widespread in other disciplines, with demonstrated improved efficiency and quality of procedural tasks in several fields such as healthcare, medicine, engineering, linguistics, education or the automotive industry.[28–31] Due to total immersion, and therefore the impossibility of perceiving the outside environment, the main disadvantage of VR is that it has to be used in rooms with a large amount of space, and is therefore impossible to use in real workspaces (like a battery manufacturing pilot line or a battery factory), which might be cluttered and which are subject to strict safety regulations.[11] MR, which lets users see both digital information and the external environment, is therefore a step forward and offers the possibility of being assisted and trained at their own workstations.

In this Concept, we introduce a transformative MR application on Microsoft HoloLens 2 glasses that presents a groundbreaking solution to data collection and training challenges in the field of battery manufacturing. By enabling users to see both digital information and their external environment, our MR application fosters a hands-free approach, allowing users to collect data seamlessly and receive real-time guidance during battery design and manufacturing, and addresses the complexities of data management by automatically saving collected data on a server, overcoming the hurdles associated with dangerous workspaces. This innovative MR solution not only enhances safety and efficiency but also facilitates experiential learning in the experimental setting, marking a significant stride in advancing battery manufacturing processes. In Section 2, we describe the main characteristics of our MR solution and how it was developed and tested, while the description of the studies carried out which led to different versions of our prototypes are discussed in Section 3. In Section 4 we conclude and indicate future directions for our work.

Method

Description of the Tool

The infrastructure of our MR application was designed to assist in the data collection, decision-making and training of battery scientists, engineers and operators while they are working in electrode formulation and battery cell manufacturing in laboratories, prototyping, pilot or production lines. This innovative technology promises to improve the quality and safety of battery production, ultimately benefiting consumers and the environment, and emerges as a fascinating tool with a high potential to break down the barriers between the real and the virtual battery manufacturing worlds. Our tool is a novel and secured software usable from MR glasses (HoloLens 2) by hand gestures. By wearing the MR glasses, the user can see holographic objects overlaid in the real environment with which they can interact (Figure 2a). These objects contain either instructions and advice in the form of panels or 3D objects on how to reproduce an experiment carried out by someone else or learn how to perform a manufacturing process, either a holographic notebook for data collection and providing assistance for decision-making to the users to achieve their desired electrodes or cell properties. By simply using the MR interface and without the need for programming skills, users can also update databases in real time from the data they are acquiring from their

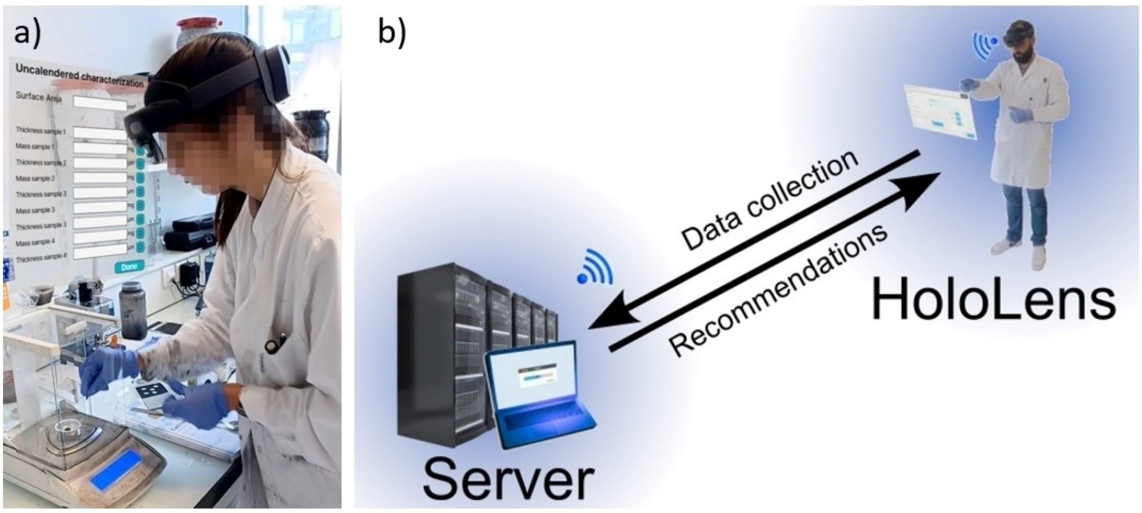

Figure 2. a) User wearing HoloLens during battery manufacturing. b) Data is collected through the HoloLens and sent to the server for storage. The server provides feedback to the user in the form of training or decision-making recommendations.

ongoing experiments (*e.g.* battery electrode porosity measurement).

Our MR tool was implemented through the Unity platform, specifically tailored for Microsoft HoloLens 2 glasses. The software development phase involved coding in Unity, followed by extensive testing at the user level. Noteworthy emphasis was placed on seamless integration with the HoloLens 2 platform, ensuring optimal performance and a cohesive user experience. We made the necessary code development to ensure that our software in the MR glasses was in continuous communication with a server storing the collected data and/or providing feedback to the MR user, such as recommendations on the training recipe or the manufacturing parameter values to adopt to achieve the desired electrode or cell property (Figure 2b). This raised the training and R&D efficiency because there is no need to expend time in compiling spreadsheet files on computers or taking notes in hard notepads: our MR infrastructure enables users to visualize explanatory models and access formulation guidance in real-time while running experiments in a lab or battery manufacturing pilot line.

The development of the final version of our solution took two years. Three generations of our MR infrastructure were developed in the context of the STARS (Smart Augmented Reality Training Assistant for Battery Scientists) and SMARTISTIC (Smart Battery Manufacturing Research and Development Assistant based on Augmented Reality Technology and powered with the ARTISTIC project) research projects, running in parallel and led by Prof. Alejandro A. Franco at Université de Picardie Jules Verne, Amiens, France. The aim of the STARS project was to build a MR software to train students, scientists, engineers and operators on the formulation and manufacturing of battery cells, while the SMARTISTIC project aimed to develop a MR software to support decision-making by scientists, engineers and battery operators when they are working on the electrode formulation and battery cell manufacturing in laboratories, pilot lines or factories. In order to maximize the usefulness and minimize user experience concerns and health impacts, we conducted extensive and rigorous ergonomic studies of these experiences.

In our software development, we recognized the significance of ergonomics and we performed various studies to improve our MR tool ergonomic design. Ergonomics is the scientific discipline concerned with the understanding of interactions among humans and other elements of a system, and the profession that applies theory, principles, data, and design methods to optimize human well-being and overall system performance.[32] Ergonomics helps make human-machine interaction more intuitive by keeping the human in the center,[32,33] and provides a batch of efficient methods to analyze the real activity of the users and highlight the needs and constraints they face during their activities. Subsequently, ergonomics allowed us to include future users in the design process of our MR infrastructure, in order to understand user scenarios, their tasks and their working environment and then build an optimal and comfortable user experience that corresponds to their real needs.[34] These studies led to interventions tailored to enhance user experience and minimize the risk of discomfort or injury.

Our study was conducted with profiles with different levels of experience (Professor > Supervisor > PhD student > Master student) and designed with careful consideration of the available resources, aimed to maximize the validity and reliability of the findings within these constraints. Additionally, the user group in our study consisted of individuals with prior experience. While there may be variability in the level of experience within this group, the inclusion of individuals with real-world expertise added credibility to our findings and offered valuable insights into the practical applications of our software. Furthermore, our study employed rigorous methodologies, including thorough data collection and analysis techniques, to ensure the accuracy and integrity of the results obtained. By focusing on the specific objectives and parameters outlined in our research, we aimed to provide meaningful contributions to the field based on this group of users. Details of the specific ergonomic studies and interventions undertaken are provided in the following.

Observations

Several sequences of observations were carried out to capture the actual activity of LIB manufacturing. In order to collect the most reliable data, we asked a well-experienced post-doctoral researcher of our research group to manufacture a battery cell in the pilot line of our laboratory, and filmed all her communications, movements and tasks. We recorded this activity twice, one month apart, to identify possible variations in the conditions under which the task was performed. The data collected was used to describe and explain how the experiments were performed. We also saved information about the sequences of tasks performed, the distribution of functions between individuals and machines, the layout of the workplace and identified training needs. Each stage of the battery cell manufacturing was recorded and then analyzed with the Boris software.[35] Boris, the acronym for Behavioral Observation Research Interactive Software, is a free and open-source software to create activity chronograms. It allows analyzing different types of human behaviors observed in video recordings, and is known for its flexibility, ease of use and compatibility with different video formats.

To enrich these observations, we conducted a self-confrontation interview with the postdoctoral researcher, asking her to provide feedback on her actions. During this interview, she explained her intentions (what she did or what she might or might not have done when she saw herself on the screen). These analyses provided us with valuable insights into the activity.

We precise that our procedures performed by studying human behavior were in accordance with the ethical standards of the institutional and/or national research committee and with the 1964 Declaration of Helsinki and its later amendments or comparable ethical standards, similarly to the works that we already reported in this journal.[19–21] Informed consent was obtained from all individual participants included in our study.

Interviews with Professionals

We also supplemented our observations with interviews with battery researchers from various research laboratories and battery companies (PhD students, post-doctoral researchers, engineers and professors, for a total of 10 hours of interviews). The interviewees were volunteers, and the interviews took place by Zoom or face-to-face in a meeting room in our laboratory. Several topics were addressed, including training needs, descriptions of activity in their organizations with different production scales, and their opinion about possible applications of MR in their activity. These interviews were an opportunity for professionals to project themselves into the future, imagine useful functionalities compatible with real needs and help generate optimal lab experiences. We aimed to provide a better user experience to guarantee satisfaction. In highly competitive sectors like the one of batteries, this satisfaction could be turned into higher sales growth, greater loyalty and a greater tendency to recommend the service.[36,37]

All the interviewees' responses were transcribed and analyzed using Nvivo 11 software.[38] After analysis of the needs and constraints, a new version of the prototype was designed.

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doi.org/10.1002/batt.202400042

Usability Testing

We tested our tool in a real battery manufacturing situation. We asked four experimentalists from our laboratory with diverse profiles (experience, gender, level of education, frequency of use of the pilot line) to make an electrode assisted by the first version of our tool (V.1, see Section 3). Previously, the participants filled in several questionnaires on their socio-demographic data, their tendency towards technophilia and technophobia[39] and their level of simulation sickness.[40] Each step of the HoloLens 2-assisted manufacturing process was filmed and lasted around 3 hours and 30 minutes. After use, the participants completed several questionnaires to measure cognitive load,[41] level of simulation sickness (compared with pre-use score) and perception of the device.[42] Additional tests were performed with the second and third generations of our tool (V.2 and V.3, see below). Table 1 indicates the new features integrated after each new release of our tool.

2. Results

The first version (V.1) of our MR tool (Figure 3a) was designed in 2021 with limited information about the real needs and constraints of target users and the way how they would operate with the MR glasses on. This information was obtained after first interactions and tests. Wearing a HoloLens 2 headset, the user had to first stand in front of a QR code in order to start using the application. The QR codes had to be strategically placed in front of each workstation (near each manufacturing process machine – mixer, coater, calender – and characterization spot – weigh scale of the electrode before and after calendering, the thickness gauges of the electrode before and after calendering) within our battery manufacturing pilot line so that the user could easily read and interact with the corresponding holographic panel (see video in Supplementary Material). Then, the headset brought up the holographic interactive panel corresponding to the associated QR code. Each panel showed the instructions to assist users and display input parameters for obtaining an electrode with the desired properties. To use this technology, users had to reproduce the electrode of their choice and enter the numeric data using a numeric keypad. All the data entered by the user was automatically stored in the data server in real-time (cf. Figure 2b). Table 2 shows the variables that the user can collect at each manufacturing step with our MR tool for their storage in the database. The detailed data workflow is not provided because of the ongoing transfer of our technology to a startup under creation.

On this first version of our MR solution, we carried out a heuristic analysis to optimize its usability by minimizing design flaws before presenting the prototype to the first users. We asked four experimentalists (2 PhD students, 1 engineer and 1 researcher who had all experience in battery manufacturing in the pilot line of our lab) to use our tool in real electrode manufacturing conditions. We observed a number of difficulties in terms of legibility, arm and neck pain during use, mental workload and visual fatigue. We used Jakob Nielsen's 10 heuristics and Bastien and Scapin's criteria.[43,44] This enabled us to modify the positions of the buttons within the panels, and

Table 1. Evolution of our Mixed Reality tool resulting from the identified ergonomics problems.

	Version 1 (V.1.) 2021	Version 2 (V.2.) 2022	Version 3 (V.3.) 2023
Description	• First version of the MR application. • Users can follow instructions to produce an electrode through the different manufacturing steps.	• Users can collect experimental data directly in the lab. • Experimental data is transferred in real-time from the HoloLens 2 to the server.	• Users can manufacture an electrode and learn the process. • Users are assisted by the Hololens during the manufacturing process: they receive feedback and comments depending on the process variables used.
New features and changes	• Voice recognition function to search for recipes, i.e., instructions to manufacture electrodes with tailored final properties. • Holographic panels attached to QR codes.	• Labels from previous completed steps do not show up anymore to facilitate usage. • Missing information about machine type or solvent mass is now displayed. • The position of the holographic panels followed can be set. • More attractive and user-friendly frontend.	• New training mode added to provide support and feedback in real-time. • Error messages are displayed if wrong input values are used. • The numeric keypad has been improved to make it easier to enter data. • Electrode porosity, mass loading, density and active mass are now calculated and displayed in real time.
Ergonomic problems detected	• Arm and neck pain during use. • Cognitive overload and fatigue after use. • Safety in the laboratory can be compromised due to the poor posture the user is forced to adopt. • Recurring bugs that force the user to relaunch the application. • In the case of critical bugs, the application shuts down automatically.	• The user has to relaunch the application in case of bugs. • Difficulties adjusting panels when the user enters a lot of data.	

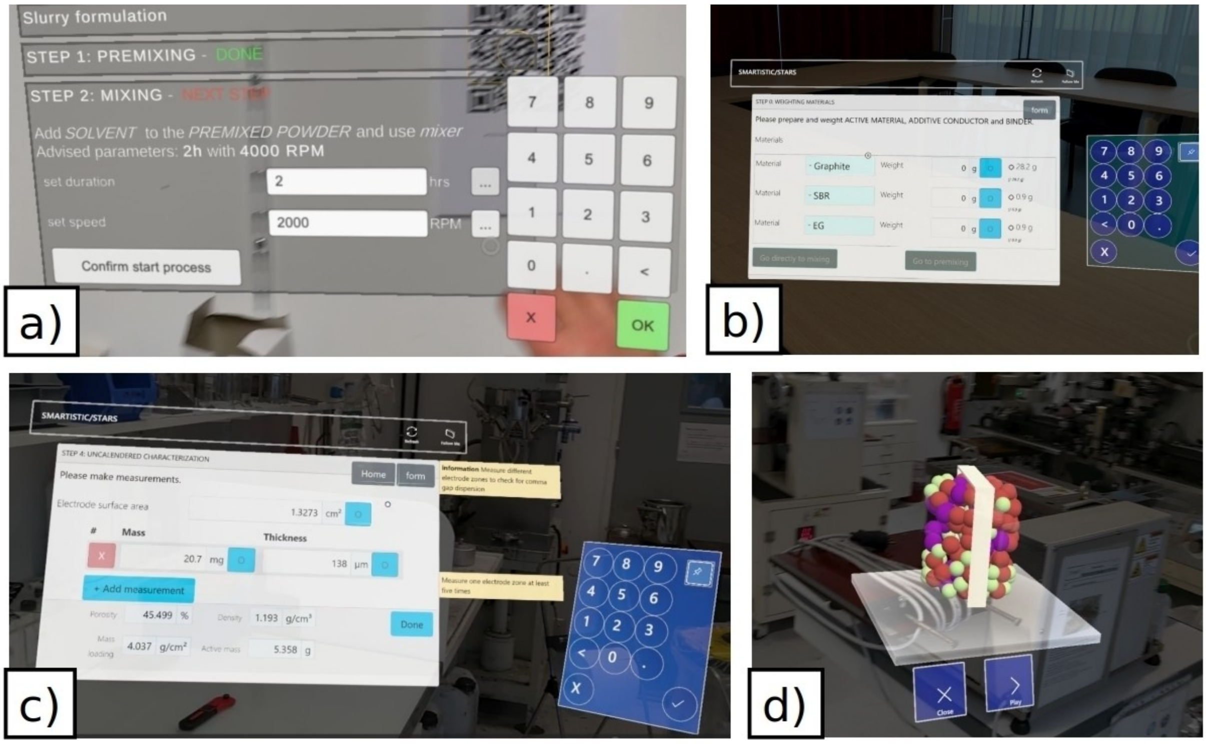

Figure 3. a) V.1 of our tool (snapshot of the holographic interface for the slurry mixing step); b) V.2 of our tool (snapshot of the holographic interface for the slurry mixing step); c) V.3 of our tool (snapshot of the holographic interface for the training in the electrode calendering step); d) V.3. of our tool (snapshot of the holographic animation of the slurry mixing process in the training mode).

reduce the workload by eliminating certain information that was unnecessary for the user or by reducing the number of actions required for each step. The NASA TLX enabled us to identify mental and physical demands as the main source of cognitive load. In other words, the task was perceived as arduous and demanding, both mentally and physically. In particular, users highlighted the lack of fluency and responsiveness when interacting with the holograms. In fact, users spent several minutes with their arms outstretched, creating muscle pain in the shoulder area, as we can see in Figure 4. Indeed, when a user has his arm stretched out in front of him and maintains this position, shoulder pain can appear and intensify, resulting in a lower willingness to use it in the future. To alleviate this problem, we worked on the fluidity of the tool and adjusted the panel's position according to the user's needs. To reduce mental demands during use, we worked on the structure of the holograms and the ease of understanding the instructions. For example, we have standardized all hologram structures and icons. We also worked to guarantee the safety of MR users in our pilot line, which constitutes, as any chemistry laboratory, an environment where one must work with caution. In this work, we closely collaborated with the lab safety engineers of CNRS and Université de Picardie Jules Verne. Usually, experimenters have to wear personal protective equipment (PPE) such as a gown, gloves, goggles or a mask to avoid breathing in solvent vapor or powders, and we found out that the fixed position of the V.1 holographic panels could be dangerous, so we worked to minimize the interference with the user's field of vision. We also moved the QR codes so that the holographic panels were in front of the eyes and above the lab benches, but it turned out that this position was inconvenient because the users had to stretch their arms out in front of them, and dangerous because they were leaning over the bench, and there was a risk of spilling a chemical product. This

Table 2. Input parameters that can be collected through our MR tool for the different battery electrode manufacturing steps.

Manufacturing Step	Input Variables
Formulation	• Active material mass (g) • Carbon additive mass (g) • Binder mass (g) • Solid Content (%)
Premixing	• Machine Type • Mixing Time (hh:mm:ss) • Rotation Speed (rpm)
Mixing	• Machine Type • Mixing Time (hh:mm:ss) • Rotation Speed (rpm) • Solvent Mass (g)
Coating & Drying	• Comma Gap (μm) • Coating Speed (m/min) • Coating Temperature (°C)
Calendering	• Rolls Gap (μm) • Rolls Speed (m/min) • Rolls Temperature (°C) • Mass of final product (mg) • Thickness of final product (μm).

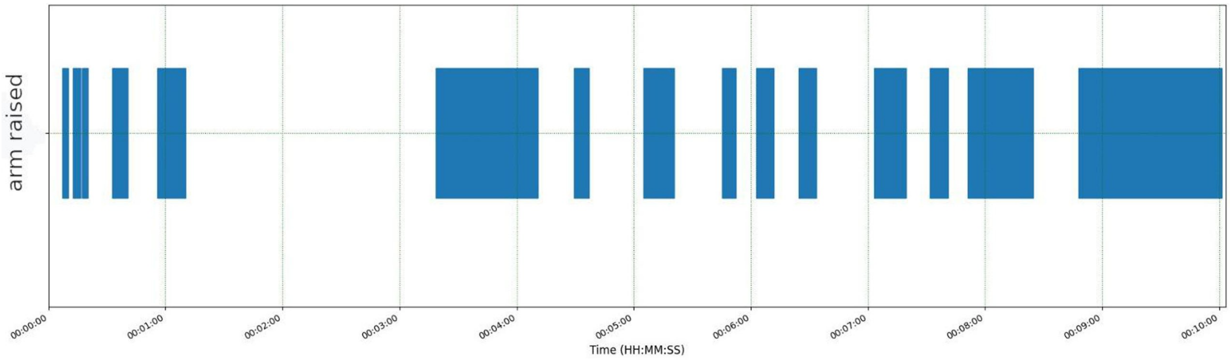

Figure 4. Chronogram representing how long the user had his arm raised in front of him to interact with the holograms of V.2. The wider the bar, the longer the user held his arm out in front of him.

was unacceptable, so we felt that it would be better to leave users free to choose the position according to their preference and the characteristics of the situation. Furthermore, the use of MR made it easier and quicker to manufacture the electrodes, as users no longer had to search for information in their notes or laboratory notebooks or enter their data in spreadsheet files on computers, as all the necessary information and data collection functionalities were presented right in front of their eyes. We also observed that users had very positive impressions of the device after use, particularly in terms of its usefulness and attractiveness.[45]

To improve the ergonomics of the tool, we worked on human-machine interaction by improving fluidity during use. In particular, the error rate, the number of clicks and the physical reactions of users were indicators. For example, we transformed the search functionality from a very unresponsive search bar to a filter-based search mode. We also eliminated the voice command functionality because of the interference from machine noise. We also worked on the design, adapting the colorimetry and aesthetics of the tool (redesigning the buttons). Finally, we worked on matching functionalities to the real needs of future users. In this context, we worked on customizing the display (choice of modules displayed) and homogenizing the positioning of recurring actions.

In order to fix the problems detected in the first version, we designed a second version (V.2) of our MR tool, based on users' feedback from usability testing and input from future users at several stages of the MR design process (Figure 3.2). The V.2 was finalized in October 2022. V.2 was brighter, and the vocabulary was adapted to the language used by experimentalists (*e.g.* from "weight" to "mass"). We also added some missing information, such as the possibility of inputting the thickness and mass of samples to characterize the electrode after calendering. V.2. enabled data to be entered quickly and easily and stored on a dedicated server, so that the users can also retrieve the information from their office computer. To make data entry easier, we added a panel tracking feature to give users the option of positioning the panel where they want it and tracking it in real time. We also enhanced the interface quality and system responsiveness to deliver an improved, more memorable customer experience. We had seen from the user tests carried out in the previous version that responsiveness was an essential element, and that a lack of responsiveness could be a hindrance. We therefore tested the prototype on the battery manufacturing prototyping line 3 times with our group's ergonomics specialist and battery research people new to MR. After each test, we provided feedback to the developers for them to work on the enhancement of the user experience. Thanks to the comments and experience of the experimenters involved in this work, we were able to validate the usability and effectiveness of the system. We did not carry out user tests on this version because we wanted to test the coordination between the experiment assistant and training modes in our MR tool. With this V.2 of our tool, users could create their experiments of interest while saving data to our database (experiment assistant mode of our tool), but also run new experiments following the advice and feedback provided by our tool (training mode of our tool), and we analyzed if the realization of experiments with each mode resulted in successful experimental manufacturing of the electrodes in both cases, with satisfactory results.

V.3 of our MR tool was finalized in May 2023 and combined in a more advanced fashion the management of battery manufacturing data and a training functionality for this process in the same system (Figure 3.c and see video provided in the Supplementary Information). The manufacturing assistant has been made more intuitive. The biggest change was the addition of a tutorial mode, allowing users to learn in a real manufacturing situation by following the instructions and advice available at each stage. The V.3 of our tool features videos, audio and animations to help the user understand the manufacturing process and the interaction between the input parameters and the final characteristics of a battery electrode in the experimentation or pilot line room (Figure 3.d). To define the subjects and the format that might be appropriate, and to design a useful and effective training course, we drew our inspiration from the needs expressed during interviews. Indeed, professionals told us that it is essential to understand the manufacturing process before being able to apply the methods. To this end, while the trainees are making an electrode, they can benefit from advice on setting up the machines or on the elements to which attention must be paid. All the advice has been written by an experimentalist from our research group who regularly trains newcomers, so she has the necessary experience to identify the blocking or difficult points for trainees, who, for example, eventually could get stuck due to the lack of knowledge about the battery manufacturing process, get lost in calculations or use the machines improperly. The aim of this advice is to help users apply the theoretical principles during the manufacturing process. At the end of each manufacturing sequence, the user has a summary of the parameters and the formulation, and can compare them with the objectives they were supposed to achieve (for example in terms of electrode thickness and porosity). Errors are therefore part of the learning process, and each difference between the objectives and what has been achieved is accompanied by advice or assistance.

Finally, depending on the user's success and errors, a subsequent training session is proposed for the user to match their needs.

3. Conclusions

In this Concept, we showed a novel MR tool to support decision-making and training in battery manufacturing. Our tool offers a significant number of benefits, including increased working efficiency due to real-time data capture, reduced errors and accelerated skills gains. In particular, our solution can be used to optimize battery manufacturing processes, thanks to intuitive manufacturing and properties data collection and the ability to retrieve data effortlessly. As a complement, we are also building a computer-based tool to help users analyze the data collected by using our MR solution. Our MR tool has tremendous potential to significantly support battery labs and companies to improve their manufacturing processes and accelerate research and development in the field, while reducing costs and guaranteeing high-quality battery electrodes and cells.

We believe that MR is a valuable technology to support the battery manufacturing sector. In the coming months, we intend to extend the use of MR to other applications, notably other types of battery chemistries and technologies. Our MR solution allows bringing digital twins, data and computer simulations directly in the place of experimentation: it can be seen then as a fantastic enabler of the removal of the frontier between the real and the digital environments, therefore maximizing the impact of digitalization in battery manufacturing.

4. Supplementary Material

We include videos as supplementary material showing the use of the different versions from an external point of view and from a user's perspective.

Acknowledgements

We deeply acknowledge Dr. Ziana Zapata-Dominguez, from Prof. Alejandro A. Franco's group at LRCS Amiens, for her valuable contributions to the definition and selection of input variables for the holographic MR panels of our tool. We also acknowledge the testers of our solution (researchers from our laboratory and the startup Tiamat Energy). We deeply acknowledge Romain Lelong from Reviatech SAS for the implementation of the holographic panels in the HoloLens 2, subcontracted with the funding support of the SMARTISTIC and STARS projects. A. A. F. deeply acknowledges the support of the Institut Universitaire de France and the European Union's Horizon 2020 research and innovation program for the funding support through the European Research Council (grant agreement 772873-ARTISTIC project–). A. A. F., L. D. and J. F. T. deeply acknowledge the European Union's Horizon 2020 research and innovation program for funding support through the European Research Council (grant agreement 101069244-SMARTISTIC project). A. A. F. and L. D. deeply acknowledge the Programme Maturation of CNRS and CNRS Innovation for the funding support of the STARS project.

Conflict of Interests

The authors declare no conflict of interest.

Keywords: Keywords: mixed reality, rechargeable batteries, manufacturing, digital twins

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Manuscript received: January 22, 2024
Revised manuscript received: April 5, 2024
Accepted manuscript online: April 5, 2024
Version of record online: June 10, 2024