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A Scoping Review and Expert Recommendations for Immersive Solutions towards Predictive Maintenance

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ABSTRACT

Under an industrial-academic partnership project, the present work aims to map and catalog the different applications of Augmented and Virtual Reality in predictive maintenance (PdM) practices. Through a preliminary scoping review, we targeted two main digital libraries in computing and engineering. Thus, we address the key attributes regarding the types of immersive technologies and the solutions used in several industries for PdM. By categorizing the surveyed prototypes according to 10 parameters in their interaction, visualization, and research methods, we expose the state-of-the-art and valuable knowledge gaps within immersive PdM. After this analysis, we conducted a workshop with 3 manufacturing experts discussing the future of maintenance interfaces, bringing forth their feedback in the shape of recommendations for what to further explore within immersive PdM.

Index Terms: Predictive maintenance, augmented and mixed reality, virtual reality, situated visualization, collaborative interfaces.

1 INTRODUCTION AND BACKGROUND

Predictive maintenance (PdM) anticipates machine failures through an evaluation of a machine's current condition and historical data to optimize the timing of maintenance activities [53]. PdM is therefore a sophisticated maintenance approach in many engineering fields, playing a crucial role in ensuring structural safety, and decreasing maintenance cost and time [22]. To be more specific, PdM is comprised of two aspects: the 'prediction' aspect focuses on forecasting machine failure and evaluating its remaining useful life [36, 37], while the 'maintenance' aspect includes the decision-making strategy [50] and the actual maintenance operations carried out by operators and technicians.

Augmented and Virtual Reality (AR/VR) technologies have been widely used in many engineering fields, due to their significant advantages in visualization [43, 17]. A recent review indicated that AR/VR technologies have been one of the four most employed maintenance solutions in industrial settings since 2019 [1], along with PdM, Artificial Intelligence (AI) methods, and Digital Twinning. By integrating the prognostic results and maintenance strategies into visualization models, a virtual replica of the physical assets can be created, namely a Digital Twin [2, 65, 35]. As a consequence, maintenance operations – which are vital for PdM – can be significantly streamlined and enhanced [17]. This improvement is evident from three perspectives: remote training, on-site operations, and cross-reality collaboration.

For remote training, VR-based training modules can provide maintenance staff with realistic simulations of equipment and scenarios, improving their skills and readiness for actual maintenance activities [20, 27]. During on-site operations, one clear advantage for AR solutions is that maintainers are enabled to see machinery data spatially situated where it is most relevant on the factory floor, with the implementation of situated visualization [47, 24]. Finally, combining these technologies can facilitate remote assistance by enabling experts (immersed in a VR digital twin) to guide on-site technicians (using a situated AR visualization) through complex maintenance procedures under cross-reality collaboration [13, 34], reducing the need for physical presence and travel costs.

The use of AR/VR applications in maintenance and manufacturing has been extensively studied and implemented across various industrial fields, and substantial reviews on these broader topics have been published [43, 17]. Under a narrower context, the present work intends to offer an updated overview of the intersection of AR/VR and PdM research, focusing our efforts on the solutions presented in the last 5 years, filling the gap left since these publications [43, 17]. By surveying and cataloging papers that demonstrate or analyze implemented systems and prototypes within this specific community, we aim to offer a typology of its state-of-the-art, exposing possible research gaps.

This work is conducted under a project entitled "Smart Predictive Maintenance for the Pharmaceutical Industry"[1]. This is an industrial-academic partnership between KTH (Royal Institute Of Technology), Digital Futures, and AstraZeneca. This scoping review serves as a stepping stone toward one of the three pillars of this project: exploring interactive, immersive, and contextual visualizations, which has been deemed increasingly beneficial as a maintenance strategy over the last 5 years [1].

After the review, we conducted a workshop with 3 experts in manufacturing, each under a different role. We believe their iterative feedback to be imperative for our research to impact the future industrial outcomes of this project.

2 REVIEW METHODOLOGY

Based on the PRISMA [42] systematic review method, we begin with an exploratory search of the last five years (2019 – 2024), complementing the gap left since the publication of similar reviews [43, 17], which explored the use of AR/VR applications in maintenance and manufacturing. Under a narrower context, our work offers an updated overview of the intersection of immersive technologies and Predictive Maintenance research.

The following search term was used to retrieve the initial records: *"predictive maintenance"* AND (*"augmented reality"* OR *"virtual reality"*).

Given this research's interest in systems and prototypes, as opposed to purely theoretical works, the focus of our search was on engineering and computing venues, being constrained to the IEEE-

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[1] digitalfutures.kth.se/research/industrial-postdoc-projects/smart-smart-predictive-maintenance-for-the-pharmaceutical-industry/

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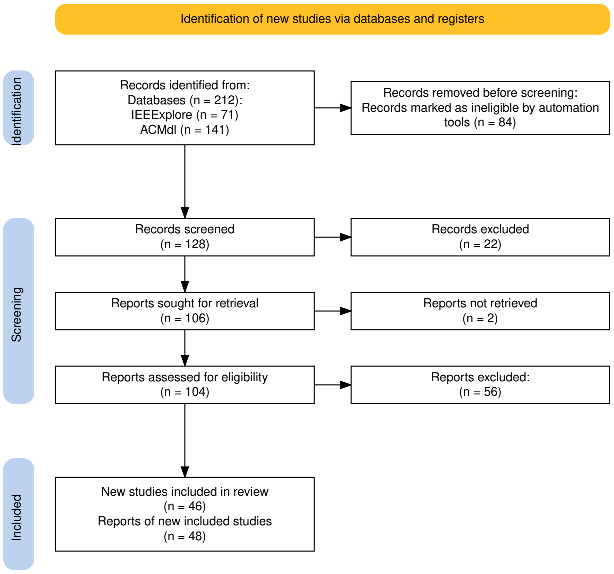

Figure 1: PRISMA 2020-compliant flow diagram describing the search methods [26]. More details about each phase can be found in Section 2.

Xplore[2] and ACM digital library[3] search engines.

In order to ascertain the relevancy of our results, the content of each work was validated regarding a few conditions, and excluded from the scope in case it met either one of them. These were: **a)** conference proceedings in their integrity - removed during the identification phase; **b)** literature reviews or surveys - excluded in the first step of the screening phase, by assessing the title of the articles; **c)** not being centered around AR or VR technologies, and **d)** not discussing predictive maintenance in some sense, both excluded in the last step of the screening phase, by assessing the abstract of the articles. Each of these exclusion conditions is mapped onto the flow diagram available in Fig. 1. After they passed the screening, each article would be categorized according to a set of attributes, further discussed in the next section.

3 RESULTS

By following the aforementioned research methods, we gathered a sizeable sample of highly relevant and recent works, including 42 conference papers and 6 journal articles. To provide a relevant map of the available literature on the current topic, we will categorize the reports regarding the following attributes:

Country: The set of countries in which the affiliations of the multiple authors of each paper are located. In summary, these can be grouped into Europe - 29 papers (60%); East Asia - 12 (25%); North America - 5 (10%); South Asia - 3 (6%); South East Asia - 3 (6%); and Latin America, Middle East and Oceania, all with 1 paper each (2%).

Year: The distribution per year in which the papers were published, which is available in Fig. 2. A notable increase trend can be noticed along the years, except for the year 2021, which may arguably be explained by the COVID-19 pandemic and its effects on user studies [19]. Notably, the latest year available (2024) is still ongoing during the publication of this study, which explains its numbers being lower than the previous two years.

Paradigm: The immersive interface paradigms that the papers address (AR, VR, or both), which is available in Fig. 2 and Table 2. Notably, the amount of AR papers has always been higher than VR, which is arguably understandable due to its *in situ* use. The trend, however, seems to indicate that the amount of VR papers might surpass its counterpart in the future.

Industry: The specific industries the papers intend to contribute to with their proposed prototypes, which is available in Table 1. The industries that stand out the most are Construction and Urban Development, Transportation (including car and rail manufacturers), and Information Technology (IT), likely due to their higher investments in high-tech solutions.

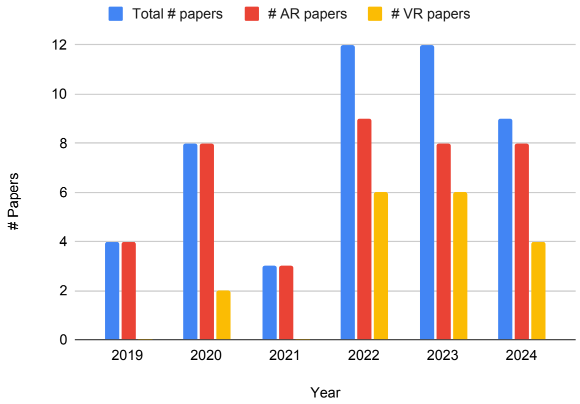

Figure 2: Number of papers published from 2019–2024. Notably, *T#p* does not represent a sum of *#AR* and *#VR*, as some works refer to both platforms.

Prototype platform: Which type of device the prototypes are meant for – e.g. Head-Mounted (HMD) or Handheld devices –, which is available in Table 2. Out of the papers that specify a device, the amount of prototypes using handheld platforms (e.g. smartphones and tablets - 31%) is less than half of its HMD counterpart (e.g. AR and VR headsets - 69%). This trend in hands-free interaction is expected due to the recent improvements in see-through and pass-through devices (e.g. the HoloLens 2[4], and the Meta Quest[5] series, respectively). In the cases where no prototype was implemented in the study, the analysis for that paper ends here.

Cardinality and symmetry: Whether the prototypes are meant for a single user, in a single platform, or for multiple users in collaboration (single-user/platform, multi-user/platform). If multi-user, following Ruddle's [49] definition (symmetric: different users access the system from the same, or equivalent, platforms or paradigms; asymmetric: different users access the system from different, or not equivalent, platforms or paradigms), we also catalog the symmetry of the collaboration between users. These are available in Table 2. The majority of the prototypes only allowed a single user and a unique platform (61%), with the remainder (39%) using multiple platforms, and a few allowing multiple users to interact with one another via these different platforms (22%). Interestingly, only two studies implemented a symmetric collaboration scenario [56, 57], with most of the asymmetric implementations only allowing a remote person to call-in via voice or video [6, 7, 33, 34, 63],

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[2] ieeexplore.ieee.org
[3] dl.acm.org
[4] microsoft.com/en-us/hololens/
[5] meta.com/se/en/quest/

rather than providing a remote digital twin in VR. Given the benefits of cross-reality and remote collaboration in industrial practices [13], this indicates a highly valuable gap left unexplored.

Industry	Keywords	References
Transportation	“Electric monorail”, “Automotive”, “Metal stamping”, “Vehicle air compressor”, “Hyperloop”, “Railway Infrastructure”	[2, 3] [10, 27] [30, 33]
IT	“Data center”, “Telecom”, “5G”, “EMC”, “RFID”, “IOT”	[6, 7] [12, 24] [39, 60]
Construction and Urban Development	“Public lighting”, “Smart Cities”, “HVAC”, “Elevator”, “Road Infrastructure”, “Drone”, “Building Management”	[28, 31] [46, 47] [48, 56] [58]
Aerospace	“Defense”, “Military”	[4, 9] [52, 59]
Energy	“Wind turbine”, “Geothermal”, “Steam jet ejector”	[8, 11]
Mining	“Coal”, ”Electromechanical”, “Shearer”, “Mineral”	[21, 34] [65]
Additive Manufacturing	“3D printing”	[44, 51]
Paper	“Tissue converting”	[14, 40]
Food	“Dairy”	[32]
Logistics	“Warehouse”, “Robots”	[38]
Retail	“Inventory management”	[15]
Generic or multi-use	“Bearings”, “Cobots”, “Digital Assistant”, “Digital Twin”, “Electric motor test bench”, “Industry 4.0 / 5.0 compliant machinery”, “Production Scheduling”, “Robot arm”, “Sorting Line”, “Teleoperation”, “Turning machine”, “Welding”	[18, 23] [29, 41] [45, 54] [57, 55] [61, 62] [63, 64] [66]

Table 1: Industries referred to in the collected papers.

Liveness of the scenario: Whether the prototypes are meant to be used in live operation scenarios (real-time data) or for training/education purposes (data is not necessarily live), which is available in Table 3. A considerable amount of the prototypes focused exclusively on live operation scenarios (47%), with only a few exclusively pursuing training or education purposes (19%), while the remainder encompassed both scenarios (33%).

Access location: Whether the prototypes are meant to be operated exclusively *in situ* (local only), or from anywhere (remote), which is available in Table 3. The majority of the prototypes exclusively aimed for the systems to run locally at their facilities (58%), as opposed to also including remote access (42%). This is expected since workers usually need to perform physical maintenance in the machines. Notably, remote access does not imply the absence of local access, so this can be seen as an extra feature.

Multimodal feedback: Besides visual, which modalities of feedback the prototypes are able to output to the users (e.g. audio and/or haptics), which is available in Table 3. Only four of the papers surveyed (8%) offered some sort of audio output integrated into their immersive experience, usually as part of their video content. No sonification or haptic feedback has been found, suggesting these systems have very low accessibility to visually impaired users [16, 25].

Category	Value	References
Paradigm	Augmented Reality	[2, 3, 4, 6] [6, 7, 9, 10] [11, 14, 21, 23] [27, 44, 15, 29] [46, 40, 63, 54] [33, 45, 38, 55] [56, 41, 28] [39, 34, 24, 61]
	Virtual Reality	[48, 64, 57, 32] [65, 52, 8, 59]
	Both	[47, 66, 62, 58] [18, 30, 31] [12, 51, 60]
Prototype Platform	Head-Mounted Device	[3, 10, 6, 7] [8, 11, 18, 21] [23, 24, 33, 41] [47, 46, 48, 54] [56, 55, 63, 65]
	Handheld Device	[14, 45, 38, 34] [27, 44, 29, 40]
	PC simulation or Unspecified	[2, 39, 51, 57] [58, 62, 64, 66]
	Not implemented (proposal only)	[4, 9, 12] [15, 28, 30] [31, 32, 52] [59, 60, 61]
Cardinality and symmetry	Single-user Single-platform	[2, 8, 14, 23] [24, 27, 29, 38] [40, 41, 44] [45, 46, 48, 51] [54, 55, 58, 62] [64, 65, 66]
	Single-user Multi-platform	[10, 11, 18] [21, 47]
	Symmetric Collaboration	[56, 57]
	Asymmetric Collaboration	[6, 7, 33] [34, 63]

Table 2: Categorization of the papers analyzed in this scoping review, part I

Input modes available: Which modalities of interaction the prototypes are implemented to accept as user input (e.g. gaze, gestures, voice, VR controllers, and/or touch), which is available in Table 3. Out of the 23 papers that specified the input modes available, 28% made use of gaze interaction, 38% included gestures, 28% included voice commands, 14% included VR controllers, and 43% used regular touchscreen interaction.

Situated Content: Whether the augmented contents in the prototypes are presented in a situated form [24], and if so, which form of content (e.g. animation and/or data), which is available in Table 3. Out of the papers that disclosed their visualization methods, 31% made use of situated animations (3D models or videos), 42% included some sort of situated data visualization, and 16% had both. Given the benefits of situated visualization in industrial practices [24], this indicates a valuable gap to be further explored.

Use of AI methods: Whether the prototypes made use of any AI methods, which is available in Table 3. In total, 10 papers (21%) disclosed making use of some AI model, although most of these did not specify what algorithms were used. This lack of clarity demonstrates a need for more reproducible studies to be conducted in this community.

User study: Whether the papers included results from a user study, which is available in Table 3. The majority of the papers surveyed (77%) did not present any results at all. Out of the 11 papers that reported results, 7 reported results from their performed user experiments, with the 4 remaining focusing on system performance results. This lack of result analyses demonstrates a need for further experiments to be conducted within the AR/VR and predictive maintenance intersection.

Category	Value	References
Liveness of the Scenario	Live Operation	[2, 3, 6, 7] [8, 10, 14, 18] [21, 23, 24, 29] [33, 34, 38, 40] [41, 44, 45, 46] [47, 48, 51] [56, 55, 58, 62] [63, 64, 65, 66]
	Education or training	[3, 6, 7, 10] [11, 18, 21, 23] [27, 32, 33] [38, 56, 57, 63]
Access Location	Local only	[3, 7, 6, 10] [14, 18, 21, 23] [24, 29, 33, 34] [38, 40, 41, 45] [47, 56, 63, 65]
	Remote	[2, 8, 11, 18] [27, 44, 46, 47] [48, 51, 57, 55] [58, 62, 64, 66]
Multimodal Feedback	Audio	[21, 23, 33] [34, 57, 60]
	Haptics	[23, 41, 47]
Input Modes Available	Gaze	[3, 10, 24] [41, 55, 63]
	Gestures	[3, 10, 18, 24] [41, 46, 47] [55, 56, 63]
	Voice	[3, 10, 33] [56, 63]
	VR controllers	[8, 47, 48]
	Touchscreen	[11, 14, 21, 27] [29, 34, 38] [40, 44, 45]
Situated Content	Animation	[2, 3, 10, 14] [18, 21, 29, 34] [38, 45, 47, 54] [58, 65, 66]
	Data	[6, 8, 14, 18] [21, 24, 29, 33] [34, 38, 40] [47, 65]
Use of AI Methods		[3, 7, 8, 10] [14, 18, 34, 41] [45, 46, 51, 54] [62, 63, 64, 65, 66]
User Study		[3, 10, 11, 21] [24, 27, 34, 44] [47, 56, 57]

Table 3: Categorization of the papers analyzed in this scoping review, part II

4 REVIEW DISCUSSION

Throughout the surveyed results, we notice a geographical distribution highlighting Europe as a leading contributor with over half of the total papers, followed by East Asia and North America. The temporal analysis indicated a growing interest in the subject over time, with AR consistently being more focused in predictive maintenance immersive applications, though the balance could be shifting in favor of VR. Further insights revealed trends regarding platform usage, with HMDs having dominated over traditional handheld devices in the last 5 years, attributed to the recent advancements in AR/VR hardware.

The industry focus shows a strong presence in sectors like construction, transportation, and IT, possibly due to high-tech investments in these fields. The lack of previous efforts within the pharmaceutical industry is rather surprising. This is either representative of a major research gap or confidentiality protocols within these companies. Regardless of the reason, we believe our project's focus on this type of research is rather pertinent and timely.

The collaborative setups explored suggest a gap in the exploration of multi-user environments, especially in symmetric scenarios, which are sparsely implemented despite the potential benefits for remote and cross-reality collaboration in industrial contexts. The current low adoption rates of single-user environments in the industry are likely the cause of this. This is likely to change in the near future, with the expected trend for current smartphones to be replaced with immersive and wearable interfaces. This underexplored area presents an opportunity for future research.

Most of the prototypes were designed for live operational scenarios, with a third including to that a support to educational contexts, reflecting a significant interest in real-time applications. Additionally, a majority of the prototypes were designed for local, on-site use, emphasizing the practical need for workers to interact with physical machines, though close to half incorporated remote access as an extra feature. Regarding multimodal feedback, the lack of non-visual outputs like audio or haptic feedback indicates limited accessibility for users with visual impairments, a gap that future research should address.

In terms of user interaction, touchscreens were the most commonly used input mode, with novel alternatives, considered more natural – e.g. gestures and gaze – being underrepresented, highlighting a minimal diversity in interface design. Situated virtual content appears frequently, though there is room for more integration of both data and animation to enhance industrial applications. AI was incorporated into some of the prototypes, though details on the algorithms used were often vague, indicating a need for more transparent and reproducible research. Notably, user studies were conducted in some of the papers, but the majority lacked any type of result analyses, pointing to a broader need for more experimental validation in this field.

5 EXPERT FEEDBACK

Subsequently, we conducted a workshop by presenting a summary of the scoping review to 3 experts in manufacturing, each person was invited specifically because they perform complementing roles with one another, in the field of manufacturing. In addition to the conducted academic research, we believe consulting and collaborating with industrial experts is vital for society to fully benefit from research. As the review did not show enough evidence that the surveyed prototypes successfully scale into real-world manufacturing scenarios, we believe more focus needs to be put into translating the results into applied solutions.

5.1 Workshop

Within the context of AstraZeneca, the invited manufacturing experts hold the following roles:

E1: Senior Business Developer in Technical Development and Innovation (1 year). Formerly an IT Project Manager / Business Analyst (2 years), a System Maintenance Manager (3 years), a Service Engineer (3 years), and a Line Technician (5 years).

E2: Machine Operator (7 years) and Instructor for the Good Manufacturing Practice (GMP) [5] program (2 years). Formerly a first-line manager (1 year).

E3: Trainer in the Total Productive Maintenance (TPM) [1] academy (1 year). Formerly a Production Support Manager (2 years), a first-line manager (5 years), Business Developer and Production Technician (2 years), and a Machine Operator (7 years).

During the workshop with all experts present, we introduced them to the goals of our Predictive Maintenance project, and presented them with a summary of the findings of this scoping review. Finally, we conducted a semi-structured interview with each one, asking for their feedback on which scenarios of their current work could make better use of these technologies.

Operator Assistant: Expert E1 suggested the training of new operators can be highly accelerated by using AI-powered Conversational Agents. They motivated this by describing the large number of documents describing maintenance procedures they need to read through and memorize. One example they provided was a changeover (the process of converting a line or machine from running one product to a new one), which had over 600 steps. They suggested that a context-aware or conversational assistant could parse the procedure information and describe it to the worker when it is relevant.

Remote Training: Experts E1 and E3 valued the aspect of game-like environments for the training of maintenance procedures, such as troubleshooting. In their opinion, machine breakdowns are often caused by humans due to inexperience. By using VR, E1 said users should experience dismantling a machine into its small unique pieces, which would be unrealistic with the physical machines, due to time and cost. E3 believed this sort of remote gamified experience to be the ideal setting to explore within the TPM academy [1], which serves to train the staff to perform operator and specialist maintenance activities collectively. According to E3, TPM focuses on building a collaborative work mindset between different types of manufacturing professionals.

They believed using this between classes could highly shorten the time it takes to qualify these professionals, especially by allowing remote and local people to collaborate synchronously, under cross-reality collaboration [13].

Multimodal Interface: Expert E1 suggested the need to focus on multimodal interfaces, especially audio and vibrotactile feedback [23], to represent what you hear and feel coming from the physical machines. When working as a line technician, they heavily relied on these senses while troubleshooting, since mechanical problems are often caught early with unexpected noise and vibration, under predictive maintenance. By replicating these problems during training, under multimodal feedback, E1 believes workers are likely to develop these sensing skills and start creating production value much earlier in their training.

Situated Interface: E1 and E2 had previously explored the integration of video instructions in a Heads-Up Display RealWear[6] headset, as a substitute for the current paper-based documentation on maintenance procedures. At the time, videos were chosen as they did not have access to any spatially aware hardware. By focusing on the list of competencies a worker needs to have in order to be fully certified to handle a machine, they found it much more valuable to train new workers using videos due to their visual and motion description, and capacity to control their own learning. Especially since their synchronous time with instructors is very limited, and their access to certain restricted areas is not possible prior to acquiring the necessary certifications, due to safety, health, and environmental awareness reasons. E2 clarified that the older hardware they used did not offer the immersion and fidelity levels they were looking for, so the efforts for live AR instructions were discontinued then. Given our presentation, however, all 3 experts reported foreseeing much value in situated visualization through AR, both for training, such as during the GMP program [5], and in live operation scenarios as well, such as a changeover, due to its spatial awareness, but especially since the user is free to use both hands at all times. E1 pointed out that their major concern was with how cumbersome current AR devices are, which could affect the willingness of people to wear them during their tasks. They added that this would be highly alleviated once slim and lighter devices such as the Meta Orion glasses[7] were commercially released.

5.2 Future Work

Considering the summary of the lessons learned during our workshop, we aim to put into action the integrated development of the 4 interface topics that were mainly discussed (Operator Assistant, Remote Training, Multimodal and Situated Interfaces). Aligned with the other members of the predictive maintenance project, who are currently using sensor fusion to develop a 3D reconstructed digital twin of a manufacturing line, our proposal is to integrate these interface paradigms into their work. By allowing workers to visualize and interact with a VR Digital Twin of a manufacturing line, as well as its augmented Physical Twin *in situ*, we believe we can enable instructors and trainees to have a more integrated and satisfactory teaching/learning experience.

6 LIMITATIONS AND CONCLUSION

As a preliminary step into a comprehensive scoping review, the main limitation of this paper is the fact that most of the results treated predictive maintenance in a very broad aspect, often focusing on maintenance as a whole, and maintenance training, which is common in non-academic works. This is likely due to the results being extracted from only two digital libraries. Although the focus on the biggest engineering and computing libraries (IEEE and ACM) is arguably a solid stepping stone, more academic sources are required to perform an exhaustive state-of-the-art review, such as ScienceDirect[8], SpringerLink[9], and Frontiers[10]. This slightly skewed our findings and subsequent discussions during the workshop, although every expert acknowledged the value of learning and training for better results in predictive maintenance. Regarding the time frame assessed (last five years), the current year of this publication (2024) is still ongoing, which hinders the yearly numerical analysis. The focus on the most recent works, however, proved valuable due to how much the state-of-the-art has changed for the available AR/VR devices in that time frame.

Overall, we performed a preliminary scoping review of 48 papers at the intersection of immersive technologies and predictive maintenance research. We cataloged the surveyed papers and their prototypes according to several parameters in their interaction, visualization, and research methods, presenting a typology of the state-of-the-art covering ten main topics and exposing valuable gaps in the literature. Current AR/VR applications within predictive maintenance mainly focus on single-user and single-platform experiences, rarely exploring cross-reality collaboration despite being highly promising [13]. Although demonstrably beneficial to simulated industry practices in controlled environments [21, 24, 34], even situated visualization remains underrepresented in the current scope, likely due to the reasons discussed with the experts. Furthermore, there is a lack of evidence that the prototypes successfully scale into productionized systems deployed in real-world settings - such as a live manufacturing plant running 24/7 under industrial good practice requirements [5]. For society to fully benefit from the research, more focus needs to be put into translating the results into applied solutions.

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