ARBoard: Augmented Reality for PCB Operations in Industry 5.0

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***Abstract*—Industry 5.0 represents the next evolution in manufacturing, emphasizing human-centric approaches while leveraging advanced technologies to create sustainable, resilient, and personalized production systems. Recent advancements in the Internet of Things, Cloud Computing, Machine Learning, Artificial Intelligence and Augmented Reality are starting to have significant effects in the manufacturing lifecycle thanks to the increase in the efficiency and productivity through automation and optimization while maintaining human expertise at the center of operations.**

Focusing on the electronic manufacturing world, these pervasive new technologies continue to improve, and together with automation play a fundamental role in today's industrial production. Nevertheless, manual activities remain essential in the development lifecycle of electronic products and of their PCBs. Manual labor is necessary especially during the prototyping phase to debug the design and validate its correct behavior. For this purpose, test engineers have to constantly switch between PCB schematic and layout files in a process that is slow, error-prone and stressful. The inefficiency of this process leads to a bigger time-to-market and a cost increase as well as potentially impacting the final quality of the products. This paper presents ARBoard, an innovative smart glasses-ready Augmented Reality (AR) application to bring manual PCB operations to the Industry 5.0 era. In AR, the user visualizes useful information about the board under test such as datasheet, schematic and markers projected on the physical board. The markers are placed by the user that directly points at the schematics and chooses the components that they want to locate on the board. This feature eliminates the need for cross-referencing between multiple documents and the successive localization of the components on the physical board.

The functionalities of the app are expanded by a local and private AI assistant. Users can ask questions about the board, and the AI assistant will answer taking information from the board's datasheet. The AI assistant also automatically highlights the relevant component as it answers to the user.

***Index Terms*—Augmented Reality, AI assistant, PCB debug, PCB validation, PCB assembly, PCB troubleshooting, Smart Glasses**

I. INTRODUCTION

Printed Circuit Boards (PCBs) form the foundation of every electronic device in our modern world, serving as the intricate nervous system that powers our digital age. These sophisticated platforms have evolved into incredibly complex networks of components and connections, with modern PCBs containing thousands of interconnected elements working in perfect harmony.

The complexity of contemporary PCBs presents a significant engineering challenge, both when designing them and when debugging the prototypes. Modern PCBs, in fact, are not simple single-layer boards but rather multi-layered structures that can include up to 12 or more layers, each serving a specific function such as power distribution, signal transmission, or grounding and each needs to be carefully designed [1] [2].

The increasing miniaturization and density of modern PCBs present growing challenges for testing and debugging, with components becoming more tightly packed and test points increasingly difficult to access.

In the prototyping and debugging phases of PCB development, manual operations remain essential despite significant advancements in automation technologies. These manual processes are critical for validating designs, identifying defects, and ensuring product quality before mass production. However, they require engineers and operators to constantly switch between multiple formats and documentation types, including schematic diagrams, layout files, datasheets, and the physical board itself.

This constant context switching creates a workflow that is inherently inefficient and error-prone. The challenge becomes even more pronounced when working with off-the-shelf boards (such as development boards to integrate in their prototypes), where electronic manufacturers may not have access to complete design files yet must still navigate through these complex electronic labyrinths for their prototypes. PCB complexity has reached a point where even identifying and testing individual components has become a significant challenge for skilled engineers.

Industry 5.0 represents the next paradigm shift in manufacturing, building upon Industry 4.0's technological foundations while emphasizing human-centric approaches, sustainability, and resilience [3] [4] [5]. Augmented Reality (AR) is a key enabler of Industry 5.0, with its unique capabilities being increasingly exploited for PCB applications both with complex sensors and projectors [6] and with dedicated AR headset [7] [8] [9].

This paper presents ARBoard, an innovative AR application designed for smart glasses that revolutionizes manual PCB operations by bringing them into the Industry 5.0 era. ARBoard creates an intuitive bridge between digital documentation and physical PCB by overlaying critical information directly onto the board as viewed through AR glasses. The system enables engineers to visualize useful information about the board under test such as datasheets, schematics, and component locations projected directly on the physical board. Users can select components from schematics through intuitive hand tracking gestures and automatically locate them on the physical board through visual markers. Furthermore, ARBoard incorporates a local and private AI assistant that answers queries about the board by referencing component datasheets and automatically highlights relevant components as it responds to queries.

The paper is organized as follows: Section II provides backgrounds about Industry 5.0, challenges in PCB operations and the state-of-the-art PCB debug and validation solutions in general. Section III details the system architecture and implementation of ARBoard. Section IV discusses the use cases of the ARBoard application, such as PCB prototype assembly and debugging, and PCB troubleshooting. Section V provides some final considerations.

II. BACKGROUND

This section gives a brief historical context about PCBs and their debug evolution as well as a background on Industry 5.0 main points together with the challenges that the PCB industry faces today, a description of IPC-2581 that is one of the main files used by ARBoard, and an introduction about the world of Augmented Reality.

A. Historical Context and Evolution of PCB Debugging

Printed Circuit Boards (PCBs) have undergone significant evolution from simple single-layer designs to complex multilayer structures with increasingly miniaturized components and intricate signal paths [10] [11]. This transition has introduced substantial challenges in manufacturing and testing processes, particularly in the debugging phase. Modern PCBs represent intricate networks that require engineers to cross-reference multiple information sources simultaneously, creating a cognitively demanding work environment. The traditional approach to PCB debugging involves continuous switching between schematic diagrams, layout files, and the physical board itself, leading to inefficiencies and increased potential for human error [9].

The increasing complexity of contemporary PCBs has exacerbated these challenges, as engineers must navigate densely packed components while maintaining precise correlations between logical connections represented in schematics and their physical implementations on the board. This evolution necessitates more sophisticated approaches to PCB debugging that can address the limitations of conventional methods while accommodating the technical demands of modern electronic systems.

B. Industry 5.0

Industry 5.0 represents the next evolution of Industry 4.0, shifting the focus from pure automation and efficiency to human-centricity, sustainability, and resilience [12] [3]. Its goal is not to replace humans with machines, but to integrate them in a synergistic collaboration that values creativity, intuition, and problem-solving capabilities [4].

Compared to Industry 4.0, which mainly focused on automation, data, and cyber-physical systems, Industry 5.0 emphasizes human-machine cooperation, the circular economy, and production personalization, seeking a balance between advanced technology and human value [13]. Recent works extend this vision by introducing the concept of the industrial metaverse, which bridges physical factories with digital and semantic-enhanced virtual environments, further empowering human augmentation in industrial operations [14].

C. IPC-2581

IPC-2581 is an open, neutral, and standardized file format used for the exchange of PCB (Printed Circuit Board) design data. It is developed and maintained by the IPC organization to facilitate seamless data transfer between design, manufacturing, and assembly processes.

IPC-2581 is encoded in an XML and human-readable format. The content is easy to parse and contains complete information about the board. In particular for this paper, the most important information is:

1) PCB Geometry: full and accurate descriptions of the PCB shape.
2) Components: Fully detailed information about component placement and rotation inside the board.
3) Layers' details: full layer-by-layer information with copper structures and etching information for each layer.

An example of the top layer and the components of a board made by STMicroelectronics is shown in Fig. 1.

D. Current Challenges in PCB Operations

1) Manual Debugging Limitations

The traditional manual approach to PCB debugging involves alternating between various forms of documentation and the physical board, creating a workflow characterized by frequent context switching and high cognitive load [9]. The manual method introduces significant visual fatigue due to constant refocusing between documentation sources and the physical board, leading to increased error rates and extended debugging times.

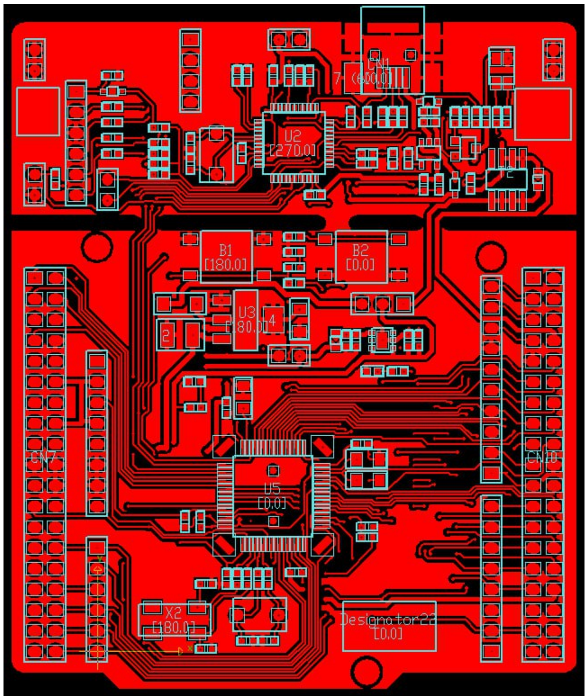

Fig. 1: The top layer and the components of an STMicroelectronics Nucleo board as seen from its IPC2581 files

2) Component Identification Complexity

Component identification represents a particularly challenging aspect of PCB debugging and troubleshooting, especially in densely populated boards with miniaturized components. Engineers must locate specific components of interest in schematic and layout documentation and correlate them with physical on-board identifiers. This process becomes increasingly difficult as component density increases, leading to extended debugging cycles and potential misidentifications.

E. Existing Solutions

1) State-of-the-Art Analysis

Current approaches to manual PCB debugging and troubleshooting can be categorized into three primary methodologies, each with specific technical limitations:

1) **Manual Debugging**: The conventional approach relies on paper or digital schematics and placement files, requiring engineers to manually alternate between documentation and the physical board. This method is characterized by slow processes, high error rates, and substantial mental fatigue [9].
2) **ODB++ Viewers**: Digital visualization tools provide enhanced views of PCB designs requiring an ODB++ file containing the design information of the PCB under analysis [15]. These viewers lack real-time interaction capabilities with physical boards, limiting their practical utility in debugging scenarios.
3) **Current AR Solutions**: Existing Augmented Reality applications for PCB work, such as inspectAR, require complete design files and operate exclusively on computer or smartphone platforms rather than AR headsets [16].

III. Proposed Approach

The proposed approach is an Augmented Reality framework, called ARBoard, that streamlines manual PCB assembly, debugging, and fault isolation by superimposing markers and data directly onto the board through smart glasses. Running on the head-mounted display, the core application employs computer-vision algorithms to lock the PCB's pose with high precision, then renders floating panels that show schematics, layout layers, and contextual menus in the user's natural field of view. Engineers can reach toward these panels, select a component, net, or test pad with a simple pinch or point gesture, and instantly see the corresponding element illuminated on the physical board by dynamic AR markers, eliminating the usual back-and-forth between paper prints and CAD viewers.

Complementing the visual overlay is a locally hosted AI assistant that listens to spoken questions and retrieves knowledge from the project's documentation. When the user asks, for example, which parts share a net with an overheating resistor, the assistant replies audibly while synchronously highlighting every related component on the board.

Together, the head-worn AR interface and the edge-based AI assistant form an integrated architecture that replaces the traditional workflow with a unified experience driven by voice, gestures, and vision. The result is a significant reduction in search time for signals and components, a lower cognitive load on the engineer, and a smoother transition from prototyping to final validation.

A. System Architecture

The ARBoard system architecture consists of two primary components working in conjunction to deliver a seamless Augmented Reality experience.

The high-level flow of these two modules can be seen in Fig. 2. During the first step, when a new PCB needs to be analyzed, the user uses ARBoard PC software to select the board user manual and (optionally) the board design data. The software then prepares a database for the Augmented Reality application. At this point the user wears the AR glasses and use ARBoard to work on the PCB. In particular:

1) **Main ARBoard application**: operates on dedicated AR glasses equipped with built-in displays, image recognition cameras, and portable processing units. The application has been developed to function with specialized augmented reality headsets and glasses with 6 Degrees-of-Freedom (DoF) and with image and hand tracking capabilities.
2) **PC-based software**: a component that acquires and processes PCB information from public documentation (and when available PCB design files), including schematics and placement files. This component performs automated analysis of PCB design data and prepares visual overlay information for transmission to the AR glasses.

The connection between these two components is established through Wi-Fi technology, enabling real-time data exchange between the PC software and AR glasses for transmission of processed schematic data, component positions, and interaction feedback.

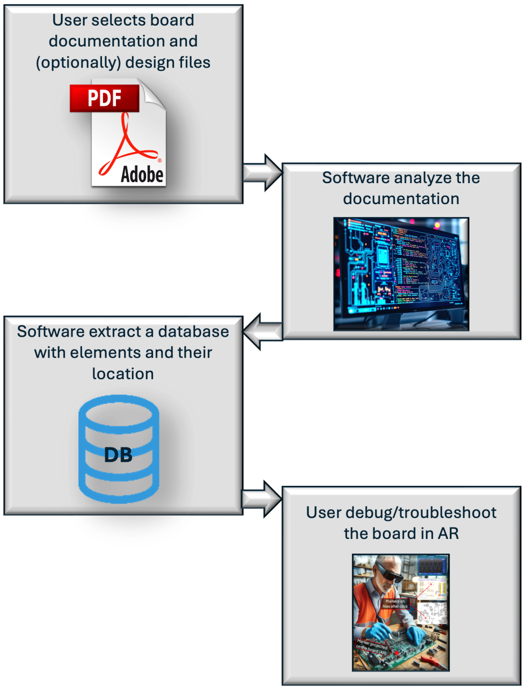

Fig. 2: ARBoard application flow: it starts with a software that extract the necessary data from the board files and culminates with the user debugging the board in Augmented Reality

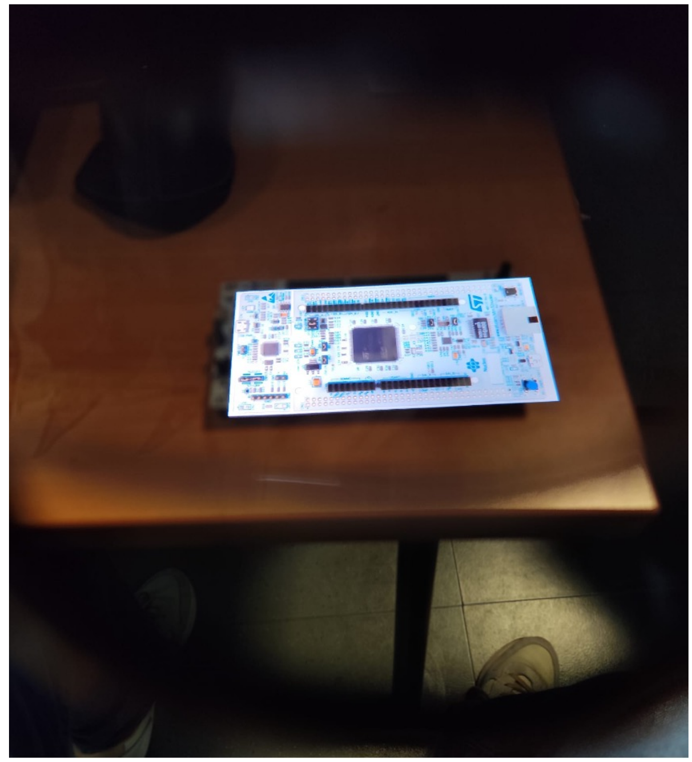

Fig. 3: An example of a Nucleo board tracked by the ARBoard AR application. A digital twin is overlapped to show the tracking in action (the visible misalignment is due to camera perspective, not tracking error)

B. Core Technical Modules

1) PCB Recognition and Tracking Module

ARBoard implements a machine learning-based approach for real-time PCB recognition and tracking. The system automatically recognizes PCB layouts using computer vision algorithms that identify board boundaries, component positioning, and reference markers. Once recognized, the system establishes precise spatial registration between the physical board and its digital representation without requiring manual calibration.

A critical feature of this module is continuous tracking, where the AR glasses constantly monitor the PCB position and orientation in 3D space. This ensures accurate alignment of digital overlays with physical components as the user moves or the board position changes. In particular, to achieve this result, ARBoard uses the tracking capabilities of ARFoundation framework, developed by Unity Technologies. An example is shown in Fig. 3 where ARBoard tracks a Nucleo board from STMicroelectronics. The figure shows an overlaid "digital" twin, used for demo purposes to show the tracking feature of ARBoard.

2) AR Visualization System

The visualization system renders digital information directly in the user's field of view. Selected components are highlighted with colored AR markers that are simultaneously visible on both virtual documentation and the physical board, creating a consistent visual language across different views. The system projects relevant information through floating virtual panels that display datasheets, schematics, and component specifications positioned contextually in relation to the board.

The visualization system also includes context-sensitive menus providing access to system functions and settings through a spatial user interface optimized for AR interaction, with elements positioned to minimize obstruction of the physical workspace.

3) Interaction Module

The hand tracking interface enables users to select components and interact with virtual interfaces through natural gestures, including pointing and pinching motions. An example is shown in Fig. 4 where the user shows the open palm to access the settings menu.

4) AI Assistant

An AI-powered assistant enhances the system's capabilities through contextual understanding of PCB elements and user intent. The assistant operates on a dedicated PC connected to the local network, ensuring privacy and performance even without internet connectivity. This local processing architecture minimizes latency while maintaining user data confidentiality, an important consideration for industrial settings where proprietary designs may be involved. An example of an AI-assisted pins localization is shown in Fig. 5.

Users can query the assistant using natural language about specific components, connections, or board functions. The system processes these requests contextually, automatically highlighting relevant components on the physical board when responding to queries. This spatial contextualization significantly reduces the cognitive load required to correlate verbal explanations with physical elements. The assistant integrates

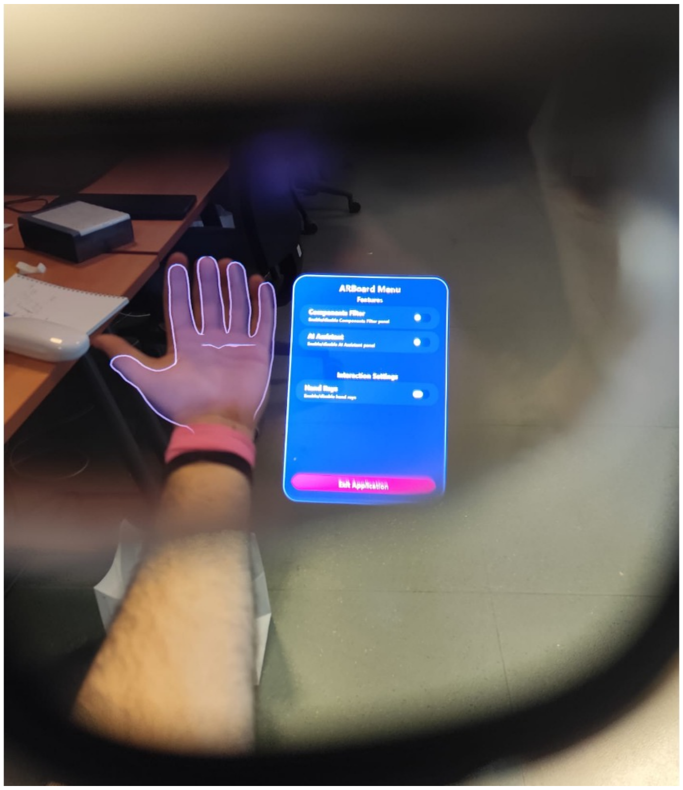

Fig. 4: An example of hand-gesture recognition in the ARBoard application, where showing an open palm triggers the settings menu

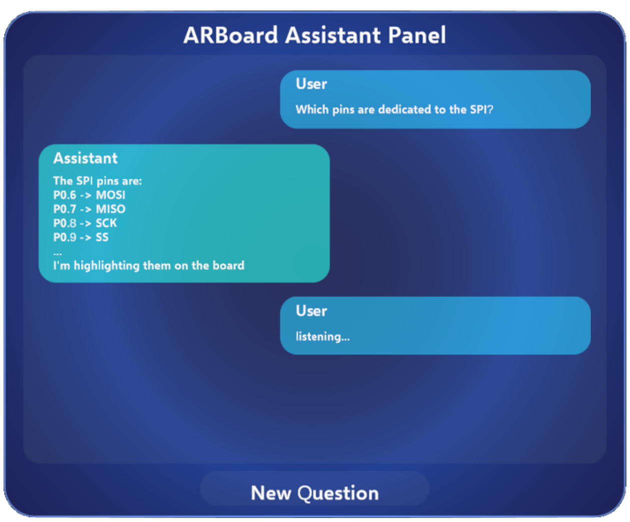

Fig. 5: ARBoard AI assistant answering technical questions and highlighting component on the physical board

comprehensive component datasheet information, allowing it to provide detailed technical specifications, operating parameters, and usage notes on demand without requiring manual document retrieval.

The AI system is developed using open-source software and performs the following three steps (all performed on a local PC):

1) Transcribe the user request into text: The trascription of the user request is performed through the Whisper advanced automatic speech recognition system developed by OpenAI.
2) Answer the user question: after the trancription, the user question is given to the AI assistant based on gpt-oss-20b or other open source LLMs. The LLM answer the user question based on the various board documents such as user manuals and design files.
3) Highlight (if necessary) the relevant components on the board: a part from the textual answer, the agent can automatically highlight components on the board. This behavior is achieved by customized tool calls performed by the LLM model itself.

C. Data Processing Pipeline

ARBoard implements a multi-stage pipeline transforming documentation into AR content.

- Documentation analysis extracts component information from available sources—either public documentation (using computer vision to identify components) or IPC-2581 files (providing enhanced capabilities with precise layouts and connections).
- Computer vision processing tracks PCBs in real-time, while spatial mapping correlates digital and physical coordinates. The render pipeline generates appropriate visual overlays, and interaction processing translates gestures and voice commands into system actions. This creates an intuitive interface between physical PCBs and their digital documentation.

IV. Use Cases

ARBoard has two primary use cases that, although related to PCB laboratory work, address different needs without depending strictly on each other. Fig. 6 shows a rendering of a user wearing the AR-capable glasses XREAL Air 2 Ultra to locate a specific pin on a complex PCB. ARBoard is initially designed and programmed to work on these glasses, but the framework used (OpenXR) allows quick adaptation to other AR-ready headsets.

A. Use Case 1: PCB Prototyping, Debugging and Firmware Validation

During the prototyping phase, engineers must test PCB functionality, validate firmware behavior, and debug hardware-software interactions. ARBoard accelerates these operations by overlaying schematic information, datasheets, and signal paths directly on the physical board and by providing AI-driven assistance for identifying relevant components or nets. This integration reduces the need for constant switching between

Fig. 6: User localizing a pin through ARBoard application running on XREAL Air 2 Ultra

schematic files and the physical board, thereby decreasing cognitive load and error probability.

In-lab evaluations were conducted with 6 graduate students in Electronics Engineering who were asked to perform typical debug tasks, such as identifying microcontroller pins, tracing signal paths, and checking debugging interfaces on an STMicroelectronics Nucleo Board. The experimental setup included a workstation with standard tools (oscilloscope, probes, and the ARBoard system). Results showed an 80–90% reduction in search time for signals and components compared to the standard schematic/layout workflow, and a 30–40% decrease in overall debug and validation time.

An example of this visualization is shown in Fig. 7, where the board view is linked to a digital twin showing the selected pins and nets. Quick access buttons allow engineers to highlight frequent debug connections such as the microcontroller port, SPI or debugger pins.

B. Use Case 2: PCB Assembly and Troubleshooting

Assembly tasks represent a different practical scenario: operators or technicians must mount, identify, or replace components on populated or semi-populated boards. Unlike prototyping/debugging, this workflow does not necessarily involve firmware validation, but requires fast and reliable component recognition, even when only partial documentation (e.g., datasheets or public manuals) is available. Here ARBoard enables operators to locate components quickly, visualize placement details, and query the AI assistant in natural language (for example: "show me the power regulation section" or "highlight the reset pin").

This use case was evaluated with 4 participants with basic PCB assembly experience. Each participant was asked to locate and place selected passive components on prototype PCB boards, first with standard documentation and then using ARBoard. The system reduced assembly-related search time by approximately 60% and minimized misplacement errors. Similar results have been confirmed by 2 experienced engineers who used ARBoard to assemble multiple PCB prototypes for their company.

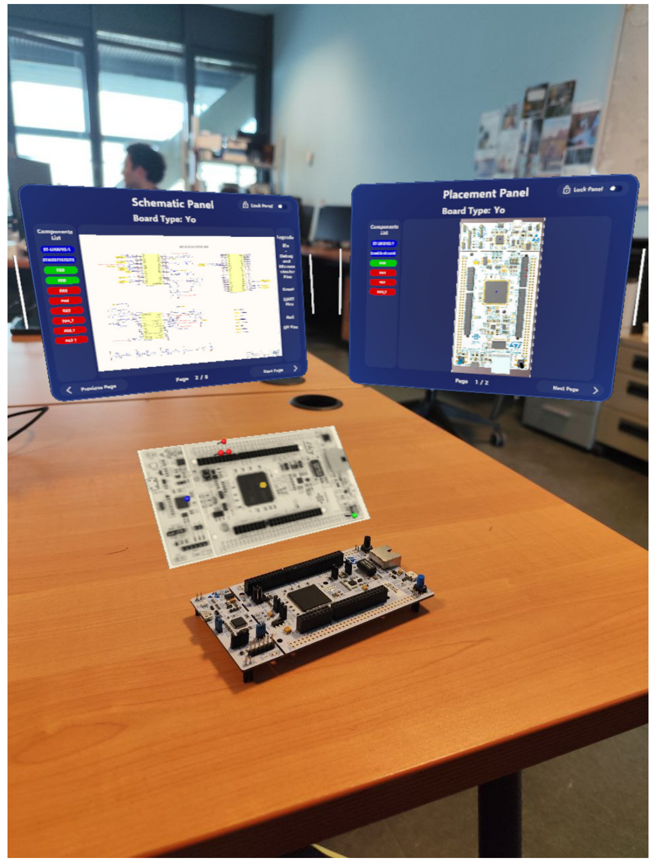

Fig. 7: ARBoard markers visible on a digital twin of the PCB and correlated schematic/layout panels, assisting in debugging and firmware validation

Fig. 8 shows an example where a user selects a component from the schematic panel and the system highlights the corresponding position on the physical board, supporting assembly and troubleshooting procedures.

For the assembling process in particular, the Assembly Mode Panel allows the user to select all the component of a given type (for example all the capacitors or resistors with a certain value and package). Selected components are highlighted with the same color. An example of the Assembly Mode Panel is shown in Fig. 9.

V. Conclusion

ARBoard represents a significant advancement in PCB prototype assembling, debugging and PCB troubleshooting by integrating Augmented Reality visualization with AI-driven analysis capabilities. The system eliminates inefficient context switching between documentation and physical boards or monitors, potentially reducing cognitive load while improving accuracy in component identification and signal tracing. While preliminary in-lab and in-company deployments have shown

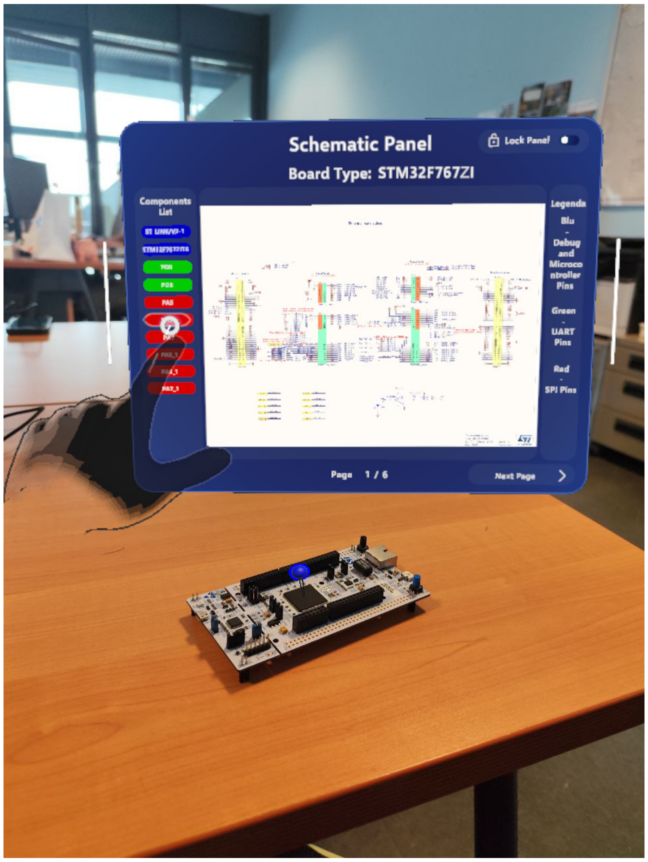

Fig. 8: ARBoard highlighting a PCB component selected from the schematic panel during assembly and troubleshooting

Fig. 9: The Assembly Mode Panel makes it easy to select all the components of the same type

promising efficiency gains (80-90% reduction in signal search time), future work will include comprehensive user studies with quantitative metrics and a larger user base to empirically validate the various data and the cognitive load reduction. As PCB complexity increases with higher component densities and layer counts, ARBoard's architecture supports ongoing enhancement through expanded AI capabilities and hardware integration, positioning it as a foundational technology for next-generation electronic engineering workflows aligned with Industry 5.0 principles.

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