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Enhancing CNC Machine Operator Accessibility through a Multimodal Chatbot

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Abstract: Modern CNC machining presents significant operational complexities and data interaction challenges, often creating accessibility barriers for a diverse operator workforce. This paper details the design, development, and accessibility-focused evaluation of a Flutter-based mobile conversational assistant tailored for CNC machine operators. Developed with industry collaboration, the system aims to bridge the accessibility gap by translating complex, real-time telemetry data (spindle speed, feed rate, alarms) into easily understandable, actionable insights. The architecture leverages IoT data streams, structured storage, efficient querying, and automated data processing. Crucially, it employs a multimodal interface (text and voice), multilingual support, and a conversational interaction model powered by a Large Language Model (LLM) with Retrieval-Augmented Generation (RAG). Specific features like hands-free continuous conversation mode and visual adjustments directly target physical, cognitive, and linguistic accessibility needs. By providing intuitive, context-aware guidance through natural language, the assistant empowers operators with varying technical literacy and language backgrounds, reduces cognitive load, facilitates hands-free information access, and aims to foster a more inclusive and efficient shop floor environment. Initial findings suggest significant potential in reducing task completion times and improving usability compared to traditional interfaces.

Keywords: *CNC Machines, Operator Accessibility, Human-Computer Interaction, Conversational AI, Chatbot, Multimodal Interface, Multilingual Support, Industry 4.0, Flutter, Inclusive Design*

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I. INTRODUCTION

Modern manufacturing is undergoing a transformation under Industry 4.0, where automation, cyber-physical systems, and real-time data integration are redefining production environments. At the heart of this transformation are Computer Numerical Control (CNC) machines, enabling highly accurate, autonomous manufacturing processes. However, these advancements have also introduced complex human-machine interaction challenges. Operators must interpret dense telemetry data, such as spindle speed, feed rate, and alarms, to make split-second decisions often with limited support from outdated Human-Machine Interfaces (HMIs).

The complexity of traditional CNC systems imposes high cognitive demands on the operator. These demands, coupled with the rigid interface paradigms of console-based HMIs, create significant accessibility issues, especially for workers with limited technical training or language barriers. This misalignment between system complexity and operator capability has a measurable impact on efficiency, safety, and job satisfaction.

To address this gap, our work introduces a multimodal, mobile-first conversational assistant designed specifically for CNC environments. The assistant leverages voice and text input, multilingual communication, and contextualized responses to support diverse operator needs. Its design is grounded in survey-informed insights and accessibility-first principles. Operators can interact naturally asking questions about machine status or alarms and receiving actionable responses in real time, even in hands-free scenarios.

This paper focuses on the accessibility gap in CNC interfaces and presents our assistant as a survey-driven solution. By grounding interaction in natural language and deploying the system on mobile platforms, we aim to reduce cognitive load, eliminate physical interaction barriers, and provide inclusive support for a globally diverse workforce. Each feature of the assistant, from voice interaction to real-time telemetry integration, was informed by operator

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feedback and designed to improve accessibility and usability on the shop floor.

II. RELATED WORK

A. Conversational Interfaces and Accessibility in Industry

In recent years, the deployment of conversational interfaces in industrial settings has gained significant traction, largely due to the evolution of smart manufacturing principles under Industry 4.0. One of the key innovations in this space has been the use of digital twins virtual models that mirror real-time shop-floor operations. Tao and Zhang (2017) presented a concept known as the Digital Twin Shop-Floor, which demonstrated how synchronized data exchange between physical equipment and virtual models can enhance predictive maintenance and reduce downtime through early anomaly detection [1]. Similarly, the architecture proposed by Xu et al. (2016) for cyber-physical production systems emphasized how interconnected systems including chatbots can be used to automate decision-making and streamline human-machine interaction in smart factories [4].

More recently, researchers like Ahaneku et al. (2023) introduced AI-driven chatbots into manufacturing for diagnostic purposes. Their implementation, built on advanced natural language processing frameworks like Google Dialogflow and BERT, incorporated self-learning capabilities to continuously improve troubleshooting accuracy [10]. While such solutions have showcased technical promise, they have often been confined to desktop or web environments, lacking the flexibility and mobility required for dynamic, real-world shop-floor scenarios.

In contrast, the system proposed in our work emphasizes a mobile-first design philosophy. It integrates seamlessly within an Industrial IoT (IIoT) ecosystem and supports real-time interaction via smartphones or tablets. This ensures that CNC operators can access system guidance and telemetry feedback without being restricted to fixed locations or desktop systems addressing one of the key accessibility limitations identified in earlier implementations. Furthermore, the design choices in this project were guided by survey responses that consistently highlighted the need for portable, natural language-based tools to assist operators during active machine engagement.

B. CNC Monitoring in the Context of User-Friendly Interfaces

CNC machines, fundamental to precision-driven manufacturing, demand constant oversight to ensure operational reliability and product quality. Several researchers have explored the use of advanced monitoring systems to meet these demands. For instance, the work of Tao, Cheng, and Zhang (2018) on digital twin technologies illustrated how real-time data analytics could be employed to anticipate system failures and optimize machining parameters for performance gains [5]. Likewise, Wang, Lu, and Shen (2017) investigated how cloud-integrated platforms could facilitate seamless data-driven decision-making by enabling remote machine health monitoring and alert systems [11].

Despite such advancements, current CNC monitoring platforms often present information in formats that are dense, technical, and unintuitive for the average operator. Most systems still rely heavily on numerical telemetry displays or coded alarm messages, placing a burden on operators to interpret the data accurately and act accordingly. This complexity increases both the cognitive effort required and the potential for error, especially under high-stress or time-sensitive conditions.

To address these challenges, our assistant system focuses on selective data presentation and linguistic simplification. It delivers information about key operational parameters such as feed rate, spindle behavior, and system alarms through conversational language rather than raw metrics. The backend combines structured data querying with AI-powered response generation to ensure that feedback is contextual, easy to understand, and relevant to the operator's query. This approach emerged from direct feedback collected in our initial operator surveys, where respondents frequently expressed a desire for systems that explain machine behavior clearly and succinctly.

C. Accessibility Limitations in Conventional CNC Interfaces

Despite the technological progress in CNC control systems, accessibility remains a persistent bottleneck. Many of the standard Human-Machine Interfaces (HMIs) used today continue to be optimized for expert users, with little regard for the varying skill levels, physical contexts, and language preferences of the actual operators. The lack of user-centered design is evident in several recurring issues identified through both literature reviews and on-site operator feedback.

Traditional HMIs are often overly complex, featuring deep menu structures and jargon-laden diagnostics that require memorization or prior training. For operators who are not native English speakers, interpreting such interfaces adds an extra layer of difficulty. Additionally, because these interfaces are typically fixed to a console, they do not accommodate physical constraints such as needing to interact with the system while wearing gloves or performing hands-on machine adjustments. This rigid design can hinder efficiency, delay response to alarms, and even pose safety risks if operators are unable to access crucial information promptly.

Our solution takes a fundamentally different approach by prioritizing accessibility as a core design objective. The use of a mobile app allows operators to interact with the system from anywhere on the floor. Voice interaction and hands-free continuous listening ensure usability even during multitasking scenarios. Moreover, multilingual support offering responses in English, Hindi, and Vietnamese directly targets the language-related challenges reported in our preliminary surveys. By aligning feature development with real-world accessibility concerns voiced by operators, our system provides a more inclusive, responsive, and empowering alternative to traditional HMIs.

III. SYSTEM DESIGN AND ARCHITECTURE: ENABLING ACCESSIBILITY

The system architecture is designed to ingest, process, and deliver CNC machine insights through an accessible, conversational interface. While incorporating robust backend technologies, the design prioritizes pathways that support the key accessibility features of the mobile assistant. The overall data flow moves from machine sensors through processing layers to the user-facing application, with each stage contributing to the final accessible experience.

A. Real-Time Data Handling and Contextual Processing

CNC machines continuously generate telemetry such as spindle speed, feed rate, and alarm codes. This raw data is streamed using Apache Kafka, a high-throughput messaging system ideal for real-time communication between the machine layer and processing systems.

- ➢ Why Kafka? Its buffering capability ensures no data is lost, enabling consistent and timely delivery of telemetry even under heavy system load.

- ➢ Accessibility benefit: Timely data access ensures that when operators ask for machine status or recent errors, they get up-to-date insights critical for preventing errors and reducing frustration.

Once streamed, data is stored in a PostgreSQL database and accessed through Hasura's GraphQL API. This layer allows for selective querying of relevant data rather than retrieving entire logs or dashboards. The system filters and simplifies this information before sending it to the conversational model.

- ➢ Accessibility benefit: Reduces cognitive load by showing only necessary information rather than overwhelming the user with raw machine data.

Data is further refined using Apache Airflow, which schedules automated pipelines for cleaning, normalizing, and extracting insights from telemetry.

- ➢ Example: Rather than listing sensor values, the assistant might respond, "Spindle speed on Machine 4 has fluctuated unusually in the past hour."

This backend orchestration makes the assistant capable of transforming raw data into accessible summaries, as requested by surveyed operators who favoured "readable conclusions" over technical figures.

B. Conversational AI and Multilingual Intelligence

At the core of the system lies a Large Language Model (LLM) integrated with a Retrieval-Augmented Generation (RAG) architecture. This AI layer enables the assistant to parse user queries, identify intent, fetch appropriate telemetry, and generate simplified, contextual responses.

➢ Query flow:
- Operator enters a query (e.g., voice/text).
- Backend fetches the most relevant machine data via GraphQL.
- LLM generates a human-readable, context-aware response.

➢ Benefits for accessibility:
- Eliminates the need for learning complex command syntax
- Makes advanced telemetry readable by non-technical users
- Provides context-specific answers using real-time machine data

This system also supports multilingual responses, initially in English, Hindi, and Vietnamese. The model detects the input language and ensures the reply is returned in the same language using natural phrasing.

- ➢ Accessibility benefit: Supports global shop floors where operators are more comfortable in their native languages.

C. Mobile Interface and Multimodal Interaction

The frontend is built using Flutter, a cross-platform mobile development framework. The app is optimized for operator environments mobile, cluttered, noisy and offers voice and text interaction modes.

➢ Interface features:
- Chat-style layout for intuitive conversation
- Voice input button and visual recording indicators
- Light/dark mode toggle for visual clarity
- Clear fonts and layout responsive to screen size
- Sidebar with query history and cached responses

- ➢ Mobile advantage: Unlike fixed HMIs, operators can access machine information while moving across the floor or handling tools, enhancing flexibility and safety.

➢ The assistant supports multimodal interaction:
- Speech-to-Text (STT) via OpenAI Whisper accurately transcribes queries even in noisy environments.
- Text-to-Speech (TTS) via Azure Cognitive Services plays back natural-sounding responses in multiple languages.
- Cached audio responses for common questions provide faster feedback without roundtrip processing.

➢ Why this matters:
- Voice input allows hands-free operation during physical tasks
- Audio output ensures users can receive information without reading
- Multilingual TTS enhances comprehension for non-English speakers

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D. Accessibility-Focused Interaction Flow

The system's interaction flow was designed around real operator scenarios identified during early surveys. A typical flow using continuous conversation mode might proceed like this:

- Operator activates hands-free mode while performing a task.
- Speaks: *"Machine 2 ka current status kya hai?"*.
- Audio is transcribed using STT.
- The assistant fetches the current status (e.g., 'Idle') from the backend.
- LLM formulates a response in Hindi: *"Machine 2 abhi 'Idle' state mein hai."*
- TTS engine generates the audio, which is played back to the operator.

Survey relevance: This scenario matches real-world needs where operators requested "voice-only mode" to access system information without stopping work.

This flow exemplifies how the system reduces dependence on visual interfaces, removes language barriers, and supports operators in physically demanding tasks—key dimensions of accessibility on the shop floor.

IV. EVALUATION METHADOLOGY

To measure the effectiveness of the assistant in real-world scenarios, a comprehensive evaluation was conducted using a mix of simulated operator tasks, real CNC machine data, and survey-guided usability testing. The primary goal was to determine whether the assistant improved operator accessibility, reduced cognitive load, and increased task efficiency compared to traditional methods such as console-based HMIs or static manuals. The evaluation strategy integrated both quantitative metrics and qualitative feedback, simulating a range of user abilities and conditions to reflect the diversity of modern manufacturing workforces. By using real telemetry and field-informed query types, the study ensured a high degree of ecological validity.

A. Approach and Participant Simulation

Due to practical constraints in gaining access to a broad set of live CNC operators, the evaluation relied on carefully crafted operator personas that reflected varying levels of experience, language proficiency, and digital literacy. These personas were based on prior survey results and discussions with plant supervisors. Simulated users were asked to complete key CNC-related tasks using both traditional methods and the new assistant. Each task was selected to test a core feature of the system, particularly those related to accessibility:

- Routine Monitoring: Users asked for spindle speed, machine status, and feed rates using voice and text input.
- Troubleshooting: Given an error code or abnormal data, users queried the system for the root cause and solution.
- Multilingual Interaction: Queries were submitted in Hindi and Vietnamese to assess STT accuracy and TTS output quality.
- Hands-Free Operation: Operators used the continuous voice mode while multitasking, simulating on-floor conditions.

These scenarios were designed based on feedback from early survey responses, which emphasized the need for systems that support non-English queries, quick diagnostics, and minimal-touch interfaces.

B. Metrics and Data Collection

The assistant was evaluated across multiple dimensions relevant to operator accessibility:

➢ Task Completion Time:

- Compared how long users took to complete specific queries using traditional HMIs versus the assistant.
- Shorter times indicated more efficient interaction and reduced friction.

➢ Response Latency:

- Measured the time between query submission and system reply (text or audio).
- While not directly linked to accessibility, excessive delays can disrupt workflow and reduce trust.

➢ Information Clarity and Comprehension:

- Users rated how easy responses were to understand.
- Responses generated by the assistant were rated significantly clearer than raw telemetry displays or manual alarm tables.

➢ Hands-Free and Voice Accuracy:

- STT transcription quality was assessed for common query types in all three supported languages.
- TTS clarity and user satisfaction were measured for each language as well.

C. Baseline Comparison and Accessibility Impact

To contextualize the results, all assistant interactions were compared against standard HMI workflows, such as:

- Navigating menu structures on a console.
- Manually looking up alarms in a printed or digital reference table.
- Reading raw sensor outputs on dashboards.

In many cases, these traditional methods required significant time, interpretation, or assistance from a supervisor particularly for new or non-native operators.
Key accessibility outcomes of the assistant:

- Up to 40% reduction in task completion time, especially for diagnostics.
- Improved comprehension, especially among non-English speakers using Hindi or Vietnamese.
- Positive feedback on hands-free mode for use while engaged in physical tasks.
- Clear preference for conversational over menu-based interaction models.

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These improvements directly align with survey-reported pain points particularly with language barriers, data overload, and the physical limitations of console-only interaction.

V. RESULTS

The evaluation yielded clear indicators that the multimodal assistant significantly improved accessibility, usability, and efficiency for CNC operators. Across all simulated tasks and operator profiles, the assistant outperformed traditional interaction methods—particularly in scenarios requiring quick comprehension, multitasking, or language support.

These results are interpreted through the lens of accessibility metrics, tying user performance and experience directly to system design choices. Importantly, user feedback collected through structured post-task surveys reinforced the measurable benefits with strong qualitative validation.

A. Task Efficiency and Cognitive Load Reduction

One of the most significant outcomes was a reduction in task completion time for both monitoring and troubleshooting tasks. When using the assistant, users completed information retrieval tasks 30–40% faster on average compared to navigating console-based HMIs or consulting manuals.

Diagnostics that typically took 15–20 minutes using traditional methods (due to manual log inspection or alarm lookup) were resolved in 9–12 minutes using the assistant. Voice interaction further accelerated workflows, especially when users' hands were occupied, eliminating the need to interrupt their tasks.

This time saving also corresponded with a subjective reduction in cognitive load. Participants reported less mental strain when using the assistant, citing the conversational format and natural language replies as easier to understand than traditional HMI outputs.

B. Clarity of Information and Multilingual Effectiveness

Users consistently rated the assistant's responses as more understandable than data tables or error codes presented on console screens. Responses generated by the LLM were perceived as clear, direct, and informative—even when describing technical faults.

Operators using Hindi or Vietnamese reported higher comprehension and confidence in system use. Multilingual TTS responses were described as natural and contextually accurate, enhancing trust in the assistant.

The assistant's ability to respond in the same language as the query was identified as a critical feature for multilingual shop floors, directly promoting inclusion and reducing the risk of misinterpretation.

C. Responsiveness and System Reliability

The assistant's average response latency was measured at ~14 seconds, with variations based on query complexity and backend processing load.

Users tolerated this latency well, especially when audio cues ("Processing your request...") were provided to maintain engagement. Response consistency across similar queries remained at approximately 80%, indicating high reliability, though further improvements in intent recognition were noted as desirable.

While the system was generally responsive, users did highlight the occasional need to rephrase queries suggesting that continued refinement of natural language understanding could improve trust and usability further.

VI. DISCUSSION

The evaluation results demonstrate the significant potential of conversational, multimodal systems to reduce accessibility barriers in CNC operation. While traditional HMIs remain powerful for expert users, they often fail to accommodate the real-world challenges faced by operators with varying language skills, physical limitations, or digital literacy. The assistant we developed offers a model for how AI-powered, user-centered design can create more inclusive interfaces in smart manufacturing environments.

A. Mitigating Key Accessibility Barriers

The assistant directly tackles several long-standing operator challenges that were consistently surfaced through surveys and usability feedback:

- Cognitive Load: The conversational format eliminates the need to navigate complex menus or remember technical codes. Operators engage through natural language and receive context-rich summaries instead of raw data.
- Language Diversity: With multilingual voice and text support, the assistant allows operators to interact in their native languages boosting comprehension and comfort, particularly during training or emergency response.
- Physical and Situational Constraints: Mobile deployment, hands-free voice mode, and real-time speech synthesis enable operators to access critical information while performing manual tasks, eliminating the need to stop and operate a console.
- Data Interpretation: By transforming raw telemetry into simplified insights (e.g., "Machine 4's spindle load is increasing abnormally"), the system helps operators make informed decisions quickly, even with limited technical background.
- Digital Literacy Gaps: The chat-style interface and guided prompts reduce the need for prior system knowledge, creating a lower barrier to entry and making the system approachable for less tech-savvy users.

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B. Implications for Inclusive Manufacturing and Operator Empowerment

The assistant represents more than just a tool—it shifts how CNC operators interact with data, machines, and decision-making. By lowering interaction barriers, it expands the number of people who can meaningfully engage with smart systems, promoting broader workforce participation in Industry 4.0 initiatives.

- Empowerment: Operators are no longer passive recipients of alerts; they can independently investigate, troubleshoot, and optimize based on data they understand.
- Safety and Confidence: Reducing delays and misunderstandings in responding to machine states directly contributes to a safer working environment.
- Scalability: The assistant's modular backend and multilingual frontend make it suitable for deployment across varied plant environments without requiring custom hardware or language-specific retraining.

This approach aligns with broader goals in smart manufacturing to democratize access to digital tools and ensure that human workers remain at the center of increasingly automated workflows.

C. Limitations and Deployment Context

While results are promising, this study had some limitations:

- Simulation vs. Live Testing: Tasks were based on realistic but simulated operator profiles. Live deployment in an actual plant setting may introduce new challenges such as environmental noise, training resistance, or device availability.
- Limited Language Set: The current version supports three languages, which may not be sufficient for globally distributed operations.
- Consistency and Learning Curve: While response accuracy was high, some variation in language generation remains. Continued refinement of natural language understanding and caching of phrased responses can improve consistency and trust.

Despite these challenges, the system's architecture and early performance strongly suggest its potential for real-world success. A full pilot in a manufacturing facility would provide deeper insights into long-term usability, adoption, and impact.

D. Future Work

While the assistant demonstrates strong early performance, several areas remain open for future development:

- Real-World Pilot Testing: Deploying the system in live shop-floor environments will reveal deeper insights into long-term use, learning curves, noise resilience, and integration challenges.
- Expanded Language and Accessibility Features: Support for more languages (e.g., Tamil, Spanish) will increase inclusivity in global factories. Enhanced visual accessibility options (e.g., screen magnifiers, dyslexia-friendly fonts) can further expand user reach.
- Predictive and Proactive Intelligence: Integrating predictive analytics or early warning systems into the assistant could transform it from a reactive tool to a proactive operator advisor.
- Offline Capabilities and Edge Support: To ensure availability in network-constrained environments, local processing and offline fallback responses should be explored.
- Integration with Training Systems: Embedding the assistant into operator onboarding programs could accelerate learning and improve long-term skill development.

VII. CONCLUSION

Modern CNC environments demand precision, speed, and adaptability but the human-machine interfaces used to operate these systems have not evolved at the same pace. This research addressed that gap by designing and evaluating a multimodal, mobile-first conversational assistant aimed at making CNC operation more accessible to a diverse operator base.

Through a layered architecture combining real-time telemetry processing, AI-driven query interpretation, and multimodal mobile interaction, the system enables natural language communication with machines. Key features like multilingual voice support, contextual data simplification, and hands-free mode were not just technical additions they were direct responses to user needs, identified through targeted surveys and field analysis.

The result is a system that doesn't just *function*, but actively *supports* a wider range of operators including those with limited digital skills, non-native language fluency, or physical mobility constraints.

Evaluation results showed measurable improvements in task speed, comprehension, user confidence, and satisfaction. Operators found the assistant easier to use, faster to interact with, and more informative than traditional HMIs. These outcomes reinforce the value of inclusive, user-centered design in industrial settings especially where high-stakes decisions must be made quickly and correctly.

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