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A Digital Colleague as intuitive operator support system in a HMLV Production Environment

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Abstract

High-Mix Low-Volume (HMLV) manufacturing, driven by the demand for customized and flexible products, has increased the complexity and variability of tasks for operators. To maintain efficiency, support systems must provide operators with precise, relevant information and actions without overwhelming them. We introduce a 'Digital Colleague,' a modular and intuitive human-centric architecture designed to streamline design and production information for operators upon request. Built on large language models (LLMs), a skill-based robot framework and a hierarchical knowledge base, this research highlights the potential of AI to enhance operator support, paving the way for advancements in smart manufacturing technologies.

Keywords: HMLV, LLM, CHAKRA, AI, industry 5.0.

1. Introduction

1.1. Context and Problem Statement

In recent years, High-Mix Low-Volume (HMLV) manufacturing has emerged as a critical response to increasing demand for customized, flexible products (1). Unlike mass production environments, HMLV operations require operators to manage a wide variety of tasks, often shifting between different products and processes throughout the day. This shift in manufacturing complexity places a significant cognitive load on operators, who must constantly adapt to varying production requirements, manage diverse assembly instructions, and ensure product quality, all while maintaining efficiency (2,3).

As the manufacturing sector transitions from Industry 4.0 to Industry 5.0, the emphasis is shifting from full automation to human-centric solutions, where advanced technologies collaborate with humans to create more personalized, sustainable production environments (4–6). Traditional support systems often fall short of providing the real-time, contextualized assistance operators need to navigate the dynamic nature of HMLV tasks. These systems either overwhelm operators with too much information or lack the flexibility to adapt to constantly changing demands.

1.2. Objective and Significance

In response to these challenges, we present the 'Digital Colleague,' a modular, human-centric support system that embodies the principles of Industry 5.0 (5). Leveraging advanced AI technologies, including large language models

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(LLMs), a skill-based robotic framework and a hierarchical knowledge base, the Digital Colleague delivers task-specific guidance to operators on demand. This system aims to streamline the flow of production information, reducing cognitive load, and enhancing operator efficiency, fostering a more collaborative interaction between humans and machines in HMLV manufacturing.

This paper presents the design and technologies behind the Digital Colleague, validated through a manufacturing use case involving the assembly of light switches. A usability study, using the User Experience Questionnaire (UEQ) (7), was conducted to assess its effectiveness in supporting operators in a high-mix, low-volume environment, providing insights into AI-driven operator assistance within Industry 5.0..

2. Related work

This section reviews existing tools for operator support and recent advancements in AI and digital assistants within manufacturing. We discuss tools that assist with assembly tasks, followed by an overview of AI-driven technologies that enhance human-machine interactions in production environments.

2.1. Operator support tools

A range of tools and systems support manufacturing operators, particularly in delivering assembly instructions. Traditional methods, like face-to-face guidance or text-picture instructions on screens and paper, are widely used but limited in adaptability. Movie-based instructions enhance understanding by visually demonstrating tasks, while augmented reality (AR) enables remote, real-time assistance from experts (8,9) . Mixed reality (MR) takes this further, overlaying interactive digital instructions onto physical objects, providing immersive and adaptable task guidance (10).

Beyond instructions, human-machine interactions are increasingly integrated into manufacturing. Next to providing assembly instruction, immersive MR technologies allow operators to visualize data and access task-relevant information in real-time, enhancing their capabilities on the shop floor. Collaborative robots (cobots) work safely alongside operators, assisting with repetitive tasks and promoting human-robot collaboration. Additionally, adaptive manufacturing systems respond to human input, enabling a flexible production environment that leverages both human decision-making and machine efficiency (11) .

2.2. AI and digital assistants

Artificial Intelligence (AI), especially Machine Learning (ML), is reshaping manufacturing by optimizing processes, predicting maintenance needs, and enhancing quality control (12). AI-driven cyber-physical systems (CPS), which integrate sensors, machines, and software, enable real-time monitoring and decision-making, creating responsive, intelligent production environments (13).

Voice-enabled Assistants (VA) presents a promising technology for enhancing human-machine interaction within AI-driven CPS. However, further research is needed to fully harness VA's potential in complex manufacturing tasks (14).

3. System Architecture

The Digital Colleague system integrates Digital Work instructions (DWI), AI and robotics to assist operators in high-mix, low-volume manufacturing environments. This section outlines the architecture and core components of the system, designed to deliver real-time, task-specific guidance and improve operator efficiency and wellbeing.

3.1. Overview

The digital colleague architecture, as displayed in Figure 1, combines several key technologies to enable operator support.

The Digital Colleague architecture is designed like a human colleague, with each component fulfilling a unique role. At the core is SKIROS, a skill-based extension of the ROS framework, which serves as the nervous system. SKIROS enables interaction with both operators and physical entities (acting as limbs) via agents that possesses parametrized skills.

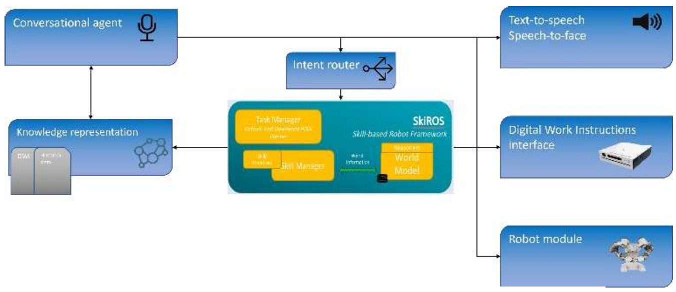

Fig. 1. Simplified architecture of the digital colleague.

Operators engage with the system through the conversational agent (the "face"), which includes Automatic Speech Recognition (ASR), a Large Language Model (LLM), speech synthesis, and facial animation synthesis. This interface allows operators to interact conversationally, creating intuitive human-machine interaction.

The knowledge base, acting as the brain, integrates diverse knowledge about the shop floor and assembly processes. This structure allows the system to provide accurate, context-specific guidance, ensuring operators have the support they need in real-time.

3.2. Key Technologies

3.2.1. SKIROS

SkiROS is an open source skill-based robot control platform built on top of ROS that provides a layered, hybrid control structure for automated task planning and reactive execution, supported by a knowledge base for reasoning about the world state and entities (15) The Digital Colleague architecture leverages two main components of SKIROS: the World Model and Skill Managers.

The World Model serves as a digital representation of the work cell, mapping the 3D locations of all relevant parts and containers in the assembly process. Each element in the world model is semantically defined in an ontology, allowing the system to reason about and interact with these components intelligently. This structured representation enables dynamic task adjustments based on real-time work cell conditions.

An Agent within SKIROS is any entity capable of interacting with and updating the world model during task execution. It achieves this through a set of parametrized primitives (low-level actions) and skills (composite actions built from primitives or other skills). Typically, an agent is associated with a physical entity, such as a robot, that can manipulate elements within the work cell. By executing these skills, agents support operators in performing assembly tasks.

3.2.2. Hierarchical Knowledge Base

The knowledge base provides federated access to a variety of workstation data sources containing information about the current assembly. The knowledge base is constructed using the CHAKRA framework. CHAKRA specifies a general-purpose knowledge model as well as a functional specification for a programming interface for that model. Using CHAKRA to construct a knowledge base from distributed heterogeneous data requires the implementation of interfaces for each of the concrete data sources and engineering the coordination of these interfaces.

In CHAKRA, knowledge is represented as a sequential, hierarchical configuration of entities called *constituents*. Constituents can be associated with intrinsic data values called attributes and extrinsic labels called *properties*. Each constituent is uniquely identifiable and is associated with a (possibly empty) sequence of other constituent identifiers, called its *particles*.

CHAKRA knowledge structures are accessed using the dedicated hierarchical query language which is defined in terms of the low-level operations of the CHAKRA interface. Crucially, the abstraction discipline used by CHAKRA allows expressions of the query language, as well as other knowledge base clients, to be defined completely independently of the underlying format and location of the concrete data.

3.2.3 Conversational Agent

The conversational agent is the primary interface through which operators interact with the Digital Colleague, enabling a hands-free, intuitive experience. It combines several key technologies: Automatic Speech Recognition (ASR), a Large Language Model (LLM), speech synthesis, and facial animation synthesis. Together, these elements create a flexible and accessible interaction point for the operator.

Automatic Speech Recognition (ASR) and speech synthesis facilitate voice-driven interactions, allowing operators to engage with the system hands-free. This functionality not only supports ease of use but also helps integrate workers who may speak different languages, as the system can provide instructions in an operator's native language.

The Large Language Model (LLM) is central to the conversational experience, supporting multiple functions:

- Natural Interaction: The LLM enables communication with the system in a conversational style, mirroring human-to-human interactions.
- Knowledge Access: Acting as an interface with the hierarchical knowledge base, the LLM allows operators to retrieve assembly-specific and shopfloor-specific information seamlessly.
- Agent Control: The LLM acts as an intermediary between operators and physical agents, such as robots, translating natural language commands into actionable skills. This allows operators to, for example, instruct robots in conversational language or request data from quality inspection cameras, with the system responding in a way that is context-aware and tailored to specific tasks.

Finally, facial animation synthesis provides a degree of embodiment for the Digital Colleague, adding a friendly, approachable visual presence. This element fosters a more engaging interaction experience, making the system feel more personable and enhancing the overall human-machine interaction.

4. Implementation and Methodology

This section outlines the specific use case deployed to evaluate the Digital Colleague architecture and the methodology used to assess its usability.

4.1. Use Case: Assembly of a Light Switch

The Digital Colleague system was deployed in an industrial setting focused on the assembly of light switches. This use case integrates two key physical agents: a collaborative robot (cobot) and a smart projector, both of which are equipped with parametrized primitives and skills, allowing operators to interact with them as needed.

The smart projector provides dynamic, on-demand presentation of digital work instructions, displaying relevant information such as pick-and-place locations, images, and instructional text directly onto the workspace. This visual support streamlines the assembly process by making instructions readily accessible and context-specific. The co-bot assists with specific assembly tasks, executing them upon request by the operator. This on-demand assistance helps reduce manual workload and enhances task efficiency.

In this setup, a specialized knowledge base was implemented to support task-specific guidance and ensure that assembly-specific details were accessible. This knowledge base used CHAKRA to integrate the digital work instructions for the light switch assembly, encoded in XML, with historical execution data capture by the Arkite system. Each data source was encapsulated with a CHAKRA interface. The historical execution knowledge was augmented with additional structure representing completed assemblies as well as subtasks. Additional knowledge was added representing the connection between historical assemblies and subtasks to steps in the digital work instructions. The resulting hierarchical knowledge base allows for reasoning about the average time required for the assembly and subtasks, as well as difficulty and user experience. For example, an operator request such as "how long does it take to complete this assembly?" corresponds with the follow CHAKRA query expression (in abstract syntax):

```
SELECT( TYPE( isExecutionOf ) &&
        LASTPART(DWI)):
    MAP( PROJ ( TYPE( Event )));
          MAP( GET( duration )); SUM );
    AVG()
```

This query can be understood as first selecting all constituents which represent assembly executions of the current digital work instruction (DWI), and then mapping over these constituents with an operations which first, projects them onto the level of events, sums the todal duration of each, and takes the average.

The CHAKRA knowledge base and query language are implemented in the Julia programming language and publically available via Jupyter notebooks (https://github.com/nick-harley/data-integration).

Figure 2 illustrates the physical setup, showing the real integration of each component within the work cell.

Fig. 2: Physical setup integrating the components.

4.2. Usability assessment

A preliminary user study was conducted to assess the usability of the Digital Colleague. In this study, 21 participants were asked to interact with the system to complete the light switch assembly task. Each session lasted approximately 5–10 minutes, with no prior instructions provided to avoid influencing the users' natural interactions with the system.

Following each session, participants completed the User Experience Questionnaire (UEQ) to evaluate their experience with the Digital Colleague. Participants were also given the opportunity to provide additional feedback regarding the system. The results from this usability assessment are presented in Section 5.

5. Results and Discussion

This section summarizes the usability results for the Digital Colleague and reflects on its alignment with Industry 5.0 principles. Section 5.1 highlights user feedback, showing both strengths and areas for improvement. Section 5.2 discusses how the system supports human-centric design, language flexibility, and adaptability. Section 5.3 outlines limitations of the study and future directions, focusing on response times, personalization, and advanced sensing for real-time quality control.

5.1. Usability Results

The UEQ results, reveal an overall positive reception for the Digital Colleague system across most dimensions. Benchmarking them against a dataset of over 21.000 products, presented in figure 3 , provides a relative assessment of the system's usability. Key findings include the following:

Attractiveness, Stimulation and Novelty scored highly, placing them somewhere in between the "Above average" and "Excellent" range. Indicating strong user engagement and overall appeal.

Perspicuity and Dependability received "Bellow Average" to "Good" ratings. Users found the system mostly intuitive and reliable. But there is definitely room for improvement.

Efficiency was the lowest-rated dimension, falling into the "Bad" and "Bellow average" range, suggesting that users felt the system could improve in supporting task performance effectively. Additional feedback revealed that this was mainly due to the system's slow response times.

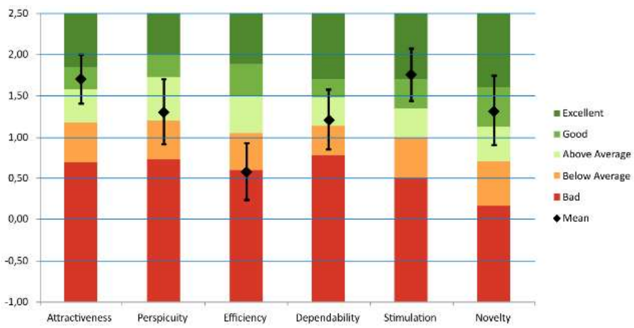

Fig. 3: Usability test results compared to benchmark

Additional user's feedback included hallucinations, i.e. the digital colleague sometimes made up fake instructions.

5.2. Reflection of the Digital Colleague as an Industry 5.0 Solution

The Digital Colleague aligns with Industry 5.0 by focusing on human-centric design, adaptability, and real-time assistance. It centers the operator, giving them control over task flow and creating a demand-driven assembly process where they guide the pace and order of operations.

A key feature is its language-agnostic capability: operators can receive instructions in their preferred language via automatic speech recognition and translation, fostering inclusivity without the need for an on-site interpreter.

The smart projector and collaborative robot provide real-time task support. The projector displays relevant work instructions on demand, while the cobot assists with specific tasks, easing the operator's workload. This setup ensures a smooth, intuitive experience, allowing operators to focus on higher-level aspects of assembly.

Built on a flexible, use case-agnostic framework, the Digital Colleague can be adapted to other assembly scenarios in high-mix, low-volume manufacturing. While this adaptability is promising, further tests are needed to determine the effort required for new applications.

In sum, the Digital Colleague showcases Industry 5.0's vision by enhancing operator autonomy, inclusivity, and responsive assistance on the shop floor.

5.3. Limitations and Future Work

5.3.1. Study Limitations

The usability study of the Digital Colleague system encountered several limitations that may have influenced the results. The short test duration of 5-10 minutes per session likely restricted participants' ability to fully engage with the system and explore its functionalities. Additionally, the study was conducted with a limited sample size of 21 participants, which may not adequately represent the diverse user base in high-mix, low-volume manufacturing environments. Furthermore, the participant pool consisted primarily of researchers and personnel from research organizations rather than actual operators, potentially skewing feedback and insights toward a more technical perspective. Lastly, the focus on a single use case —light switch assembly— limits the generalizability of findings to other manufacturing tasks.

5.3.2. Opportunities for future development

Future development of the Digital Colleague system presents several promising directions. Enhancing response times, particularly by decreasing the LLM inference time, is critical for improving user efficiency and overall satisfaction. Additionally, expanding the system's applicability to various assembly tasks will validate its versatility and effectiveness across different contexts.

Implementing personalization features could tailor interactions to individual operator preferences, thereby improving user experience. Addressing issues related to hallucinations—instances where the system generates incorrect information—is essential for ensuring dependability and trustworthiness, especially in a manufacturing related context. Exploring alternative interfaces, such as integrating augmented reality (AR) projections or mobile robotic platforms, could further enhance interaction quality.

Finally, a significant opportunity lies in incorporating advanced sensing technologies, such as cameras and human monitoring metrics. This would provide contextual awareness to the Digital Colleague, allowing it to function as an interactive quality control system that monitors operations in real-time and intervenes when necessary. Such enhancements could transform the system into an interactive support tool for experienced operators, ensuring higher quality and efficiency in high-mix, low-volume manufacturing environments.

6. Conclusion

The Digital Colleague system represents a significant advancement in human-centric support for high-mix, low-volume (HMLV) manufacturing, aligning with the principles of Industry 5.0. By leveraging advanced AI technologies, including large language models and collaborative robotics, the system provides real-time, context-specific guidance that enhances operator efficiency and reduces cognitive load.

The usability study conducted during the light switch assembly task revealed strong user engagement, particularly in dimensions such as attractiveness and novelty. However, challenges remain, particularly regarding system efficiency and response times. These insights highlight the need for further refinement to optimize user experience.

Looking ahead, opportunities for development include improving response times, expanding the system's applicability to various manufacturing tasks, and integrating advanced sensing technologies to enhance contextual awareness. By addressing these areas, the Digital Colleague can evolve into a more robust solution that not only supports operators but also fosters a collaborative and adaptive manufacturing environment.

In summary, the Digital Colleague showcases the potential of AI-assisted systems to transform HMLV manufacturing by enhancing operator autonomy and responsiveness, paving the way for a more inclusive and efficient future in smart manufacturing.

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