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NOVEL OPERATOR-CENTRIC DIGITAL TECHNOLOGIES FOR A SUSTAINABLE INDUSTRIAL WORKPLACE

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1. Introduction

Industry 4.0 technologies are revolutionising industrial workplaces by advancing system and worker health management, enhancing Human-Machine Interaction, and enabling flexible manufacturing solutions. These innovations, underpinned by digital technologies, have their roots in predictive maintenance, reconfigurable and collaborative robotic systems, and AI-driven Human-Machine Interfaces, which are key enablers in creating sustainable, efficient, and adaptable production environments.

Predictive maintenance empowers production systems to become self-aware, self-predictive, self-configuring, and self-maintaining (Zonta et al., 2020). By equipping machinery with sensors that continuously monitor their condition, it is possible to detect early signs of faults, identify the specific type of fault, and predict the Remaining Useful Life (RUL) of equipment (Jardine, Lin & Banjevic, 2006). This proactive approach minimises downtime, optimises machinery longevity, and enhances overall efficiency. The collection of data from reconfigurable manipulation systems is crucial in this context, as it allows for the training, validation, and testing of data-driven approaches for diagnostics and prognostics in highly dynamic environments.

Integrating robotic manipulators with automatic production lines is crucial for achieving this flexibility, and deployability and reconfigurability are key enabling factors. Cable-driven Parallel Robots (CDPRs) offer a promising solution for reconfigurable and they have been proposed for various applications, including assisted or automated assembly (Pott, Meyer & Verl, 2010), high-rack warehouse storage and retrieval (Bruckmann et al., 2012), and palletising tasks (Marchesini, 2023). Optimising the performance of CDPRs involves selecting the appropriate

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sensors for calibration, estimation, or control, as small sensor errors can be amplified by the robot's transmission chain and control algorithms, leading to performance issues (Idà, Merlet & Carricato, 2019), (Gabaldo, Idà & Carricato, 2023). Digital prototyping tools dedicated to optimising the robot's mechatronic architecture—its geometry, inertia components, sensors, overall size, and installed power—are essential for enhancing the industrial involvement of CDPRs. These tools contribute to improved sustainability in reconfigurable automation, achieving levels of efficiency not possible with current solutions.

As automation becomes more prevalent, Human-Machine Interaction (HMI) become of interest, as understanding the factors that influence collaborative task quality and operator well-being is essential (Ayaz et al., 2012; Krugh & Mears, 2018). Automation changes human roles in complex ways, requiring a deeper understanding of human behaviour and environmental factors. Mental Workload (MWL), defined as the mental effort required to perform tasks, has been identified as a critical factor affecting productivity and task performance (Pacaux-Lemoine et al., 2022). The research underscores the importance of designing intelligent manufacturing systems that not only support human operators but also effectively manage MWL, thereby optimising working conditions. Addressing issues such as automation complacency and Out-Of-The-Loop (OOTL) performance is essential for improving working conditions through AI-enhanced human-machine collaboration.

Particularly, when dealing with collaborative robots, techniques such as kinesthetic teaching, where a human guides the robot to perform tasks, have been effective in addressing kinematic discrepancies (Billard et al., 2008). However, there is a growing need for more advanced human-robot interfaces that enable bidirectional information exchange during manual guidance. Technologies like motion capture systems, which track human kinematics, and haptic devices, which measure grip strength, are essential for enhancing this interaction (Häring, Bee & André, 2012; Walker, Zink & Mutschler, 2010). Additionally, surface electromyography (sEMG) has emerged as a valuable tool, providing real-time data that, when combined with machine learning and probabilistic modelling, enhances programming by demonstration for collaborative robots (Meattini et al., 2018). The integration of these technologies facilitates more intuitive and effective human-robot collaboration, ultimately boosting productivity and work performance.

The paper describes some aspects of novel digital technologies developed in one of the PNRR PE 11 *Made in Italy Circolare e Sostenibile* (MICS) projects, to be integrated for the development of self-sustaining production systems, enhancing human-machine collaboration, and enabling the deployment of flexible, reconfigurable robotic solutions. These advancements are crucial for meeting the evolving demands of modern manufacturing, ensuring sustainability, and optimising overall system efficiency and performance. Section 1 deals with the Predictive maintenance aspect of the project, while Section 2 with reconfigurable robotic systems. Section 3 introduces the studied HMI Technologies, and Section 4 focuses on collaborative robots programming. In the end, the project's expected outcomes are highlighted.

2. Predictive maintenance

Predictive maintenance, as the most advanced strategy, utilises sensor-collected data to predict the future health behaviour of these systems. It involves early fault detection and the prediction of Remaining Useful Life (RUL), which denotes the time until failure (Jardine, Lin & Banjevic, 2006). These practices are crucial in the industrial field, aligning with economic and sustainability goals by preventing incorrect working conditions and unexpected breakdowns. They also enhance safety for operators, optimise component lifespan, and reduce scrap.

The Prognostics and Health Management approach to predictive maintenance includes collecting weak and noisy operational signals, extracting health-related information (feature extraction), and employing advanced Machine and Deep Learning models. These models establish connections between input parameters, health stages (fault detection and diagnostics), and RUL prediction (Lei et al., 2018).

Digitalisation and ICT technologies play a pivotal role in data collection, model development, and inference. Edge computing, for instance, enables early fault detection and quick restoration of nominal functions by operators. It facilitates rapid extraction of pertinent information from raw signals, circumventing the time-consuming process of data transmission (Xu et al., 2021).

This approach empowers operators by providing real-time insights into equipment conditions, enabling prompt corrective actions and minimising downtime. Simultaneously, it reduces scrap rates, maintains productivity, and enhances spare parts management through improved forecasting of RUL (Zhuang et al., 2023).

Despite the promise of data-driven methods, practical implementation remains nascent due to challenges such as data availability and quality. While ideal conditions involve simulated and labelled data for all possible scenarios, complex systems present obstacles in fault simulation due to economic and safety concerns. Variations in working conditions further impact predictive accuracy, especially in reconfigurable systems designed for diverse tasks and environments (Calabrese et al., 2022).

Human-machine collaboration emerges as crucial in overcoming these challenges. It enables automated labelling of datasets using sequence classification and regression methods, while unsupervised deep learning models uncover novel behaviours and fault conditions. Operators contribute by defining these novel behaviours, ensuring their incorporation into diagnostic and prognostic model training.

In conclusion, while data-driven approaches hold immense potential, addressing practical challenges requires advancements in data acquisition, labelling techniques, and adaptive modelling.

3. Reconfigurable robotic systems

Cable-driven Parallel Robots (CDPRs) are a noteworthy highly-reconfigurable solution for large-scale operations. They are parallel-architecture robots characterised by many servo-actuated cables attached to a working platform in a parallel fashion and whose spooling on servo-winches displaces the platform in space. The workspace they can achieve is practically limited only by the amount of cable that can be spooled by winches, and by just re-arranging how cables are connected to a shared End-Effector (EE), or a supporting frame, their properties may be conveniently changed. In addition, cables are optimally loaded structural components, thus able to withstand severe loads with negligible weights. Unlike existing market solutions, this project is developing a reconfigurable robot with flexibility, deployability, and adaptability in mind.

The project addresses several key challenges. The first challenge is achieving flexibility through deployability, enabling the robot to adapt to various tasks and conditions autonomously. Unlike traditional CDPRs with fixed frames, the proposed design aims to make the robot self-contained within the EE, with all winches and cable-guiding elements integrated into the moving part. This makes the EE bulkier but also easier to transport, operate, and store, which is essential for freeing up factory floor space. The second challenge is the automatic determination of the optimal robot installation for a given task, critical for tasks like painting flat surfaces of varying sizes and conducting inspections. This challenge involves two major problems: defining a set of tasks that the machine can interpret and developing a workspace computation algorithm to optimise the robot's structure based on performance. The third challenge focuses on automatic calibration to maintain high accuracy despite frequent robot assembly and disassembly. This involves developing a calibration procedure that operates without human intervention, using conventional sensors integrated for both control and calibration. The project will explore advanced sensor fusion techniques and nonlinear least square approaches to solve this problem, with the performance of automatic calibration compared to traditional, operator-assisted methods.

To address these challenges, the project will design and manufacture a demonstrator of the reconfigurable robotic system, focusing on its basic control functionalities. The methodology includes the integration of internal sensors for autonomous calibration, the development of a task interpretation system, and the creation of a control-aware workspace computation tool. The robot's performance will be tested computationally and experimentally, with tasks such as painting and inspection used to demonstrate the system's effectiveness.

4. HMI technologies

This research explores the complex relationship between Mental Workload (MWL) caused by automation and its effects on worker performance and well-being. By reviewing 426 papers published between 2003 and 2023, three key research areas emerged in the field of human-machine interfaces and MWL.

First, the assessment of MWL has evolved from traditional methods, such as the NASA Task Load Index, to more advanced approaches. Non-invasive electroencephalography (EEG) now stands out for measuring cerebral responses in the prefrontal cortex during tasks, providing a deeper understanding of MWL (Jin et al., 2022). This shift to sophisticated techniques reflects a broader trend in understanding the cognitive processes behind MWL.

Second, the research emphasises optimising task allocation between human operators and collaborative robots (cobots) to enhance productivity and worker well-being. Balancing workload is crucial to prevent cognitive overload and improve overall productivity while safeguarding worker health (Calzavara et al., 2023). Cobots play a critical role in this balance by taking over repetitive or physically demanding tasks, allowing human operators to focus on more complex, cognitively engaging activities.

Third, the focus shifts to real-time measurement and optimisation of workload capacity. Real-time physiological sensing technologies, integrated with Artificial Intelligence (AI), enable continuous monitoring of MWL. AI is particularly significant as it allows a shift from reactive to predictive MWL management, improving task quality and operator well-being (Thorpe, Nesbitt & Eidels, 2020). AI's real-time analysis and prediction of MWL open new possibilities for dynamic task allocation and personalised intervention strategies.

This research aims to contribute by advocating a proactive approach to managing MWL, highlighting the benefits of AI in MWL management, and advancing efforts to manage MWL effectively. A Proof-of-Concept (PoC) is being developed to demonstrate these ideas in practice. The PoC addresses specific user needs, such as robots creating optimal working conditions and understanding operators' abilities to complete tasks effectively. The PoC will showcase an AI-based tool operating in three stages: real-time MWL assessment, MWL prediction, and tailored countermeasures with feedback.

Developing this PoC presents several challenges, particularly in measuring MWL accurately. A multi-faceted approach is proposed, combining physiological metrics like EEG and heart rate with subjective assessments such as the NASA Task Load Index. Data collection involves a two-stage experimental procedure—Calibration and Data Collection—to gather subjective, objective, and scenario data. This dataset will train AI tools, accounting for individual variations in MWL responses.

Data processing steps include preprocessing to correct artefacts, feature extraction using signal processing techniques, and MWL prediction through statistical and machine learning methods. Adaptation and feedback mechanisms will optimise MWL, with continuous recording and analysis of intervention effectiveness.

5. Collaborative robots programming

Collaborative robots are becoming essential across various sectors, demonstrating precise behaviours through kinesthetic teaching. Traditional methods struggle to adapt to modern robotic functionalities, prompting the development of augmented kinesthetic teaching to enhance bidirectional communication during manual guidance. The integration of wearable devices shows promise in real-time detection of human motor intentions, aiming for effective and intuitive robot programming. Advanced techniques, including machine learning, are targeted to align teaching approaches with operators' implicit knowledge, enhancing human-robot collaboration.

The AI-Based Collaborative Robots PoC focus on improving teaching methodologies, exploiting the integration of wearable and/or grounded devices, which shows promise in real-time detection of human motor intentions, aiming for effective and intuitive robot programming. Advanced techniques, including machine learning, are targeted to align teaching approaches with operators' implicit knowledge, enhancing human-robot collaboration. Initially, the primary objective is to investigate and outline a framework for intuitive trajectory programming to assist operators in target activities. The framework comprises a robot manipulator capable of learning trajectories through manual guidance. Advanced interfaces measuring additional user inputs are connected to the system, and machine learning algorithms are employed to extract information from these interfaces. This enables the improvement of trajectory features through intention detection which is not possible with manual guidance alone.

This PoC aims to bridge the gap between traditional kinesthetic teaching and modern collaborative robotics needs. By integrating machine learning and possibly physiological signals for enhanced teaching, the platform empowers operators with intuitive interfaces. The goal is to develop a dynamic teaching approach that improves efficiency and effectiveness in industrial robotisation endeavours. Understanding user requirements is fundamental to advancing human-robot interaction with intuitive programming solutions for collaborative robots. Insights into workflows and tasks where improved human-robot interaction can be effective are considered, with validation conducted in agreement with user experience and selected workflows. Evaluating the framework involves metrics such as usability tests, questionnaires measuring the perceived intuitiveness of programming solutions, and collaborative robotic task success rates. These metrics will be collected through specific tests related to user responses in using the prototype collaborative system.

6. Expected results

The research focuses on integrating advanced digital technologies to enhance industrial systems, improve human-machine collaboration, and optimise overall efficiency. A critical component of this research is the application of predictive maintenance to extend the Remaining Useful Life (RUL) of equipment. By collecting sensor data from reconfigurable Cable-Driven Parallel Robots (CDPRs), the project will train and validate models to predict RUL and detect faults. This proactive approach will minimise downtime, enhance machinery longevity, and optimise overall efficiency. The reconfigurable CDPR system itself will be designed to autonomously adapt to various tasks, including painting and quality control. The integration of advanced sensors and AI will facilitate automatic calibration and performance optimisation, allowing the robot to maintain high performance with minimal human intervention. A pivotal outcome is the development of a sophisticated AI-based tool for real-time Mental Workload (MWL) management. This tool will utilise real-time physiological sensing and advanced machine learning to proactively monitor and optimise MWL, fostering a human-centric approach that improves task performance and worker well-being. Additionally, the research will develop an intuitive teaching interface for collaborative robots, incorporating advanced user input and intention detection technologies. This interface will enhance trajectory programming and human-robot interaction, improving the efficiency and effectiveness of robotic operations.

Overall, the integration of AI, predictive maintenance, reconfigurable robotics, and advanced human-machine interfaces aims to create a comprehensive digital solution that manages MWL, predicts RUL, and advances human-robot collaboration. This holistic approach will demonstrate how these technological advancements collectively enhance productivity, optimise equipment lifespan, and support innovation in sustainable and adaptable production environments that strongly focus on workers' needs and well-being.

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