Current state of research and contributions regarding the design and implementation of a robotic manufacturing cell

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Abstract. The paper presents a comprehensive analysis of the current state of the art in the design, optimisation and control of robotic manufacturing cells, with a focus on modern trends in industrial automation and discrete event system modelling. The study integrates significant contributions from international literature, covering topics such as automatic model and PLC code generation for collision avoidance, jam-free control using Petri nets, energy and time optimisation of robotic layouts, modular and reconfigurable architectures for flexible cells, Digital Factory technologies, and the design of human-robot collaborative systems. Advanced approaches based on 3D simulation, hybrid models, optimisation heuristics, distributed control systems and RSHPN metamodeling that reduce complexity and design time are highlighted. Practical applications are also analysed, including robotic cells for machining, assembly, handling, transport and process automation in various industries, from automotive and CNC machining to food and construction. The paper highlights the crucial role of Petri nets in modelling, optimising, diagnosing and avoiding bottlenecks in complex robotic systems. The conclusions highlight the need for integrated design, simulation and control methods capable of managing resource dynamics, uncertainty and flexibility requirements specific to modern production, providing a solid theoretical basis for the development of the future robotic cell proposed in the doctoral research.

1. Introduction

Modern industry is undergoing an accelerated process of transformation, driven by ever-increasing demands for flexibility, productivity and quality in manufacturing processes. The concept of Industry 4.0 has generated significant changes in the architecture of production systems, promoting the intelligent integration of equipment, the digitisation of technological flows and the use of advanced

simulation models to optimise the operation of industrial assemblies [1]. In this context, robotic manufacturing cells have become central elements of modern systems due to their ability to perform complex operations with high precision, repeatability and adaptability. The design of an efficient robotic cell is a multidisciplinary process involving mechanics, electronics, advanced control, software engineering and optimisation methodologies [2], [3].
The emergence of 3D simulation tools and virtual testing environments has significantly reduced the risks associated with physical configuration, allowing for the prior evaluation of kinematic behaviour, possible collisions, manipulation strategies, and operational parameters. However, the increasing complexity of robotic systems, especially when integrated into flexible lines or distributed industrial networks, requires the use of rigorous formal models to represent and analyse the discrete behaviour of the system [4].
In this regard, Petri nets have established themselves as an essential theoretical tool in modelling discrete event systems, providing a robust mathematical framework for describing competition, synchronisation and conflicts in industrial processes [5], [6]. These models allow not only the representation of the operational structure of a robotic cell, but also the verification of functional properties, such as the absence of deadlocks, liveness, boundedness or the security of work sequences. Extended methods, such as hierarchical, timed or hybrid Petri nets, facilitate the analysis of complex scenarios involving both discrete behaviours and continuous or timed phenomena. The integration of simulation techniques with formal models based on Petri nets contributes to the development of a coherent methodology for the design and validation of robotic manufacturing cells [6]. This approach allows, on the one hand, the optimisation of processes by reducing cycle times, increasing availability and minimising the risks of collision or blockage, and on the other hand, facilitates the implementation of distributed and adaptive control strategies, in accordance with the requirements of smart manufacturing [7] .
This paper aims to systematically investigate the current state of technologies dedicated to the design and implementation of robotic cells, emphasising the role of discrete event models in their analysis and optimisation. By examining recent contributions in the literature, it highlights the major directions of development, emerging software tools and methodological trends relevant to the evolution of modern manufacturing systems. This analysis provides a solid basis for formulating an integrated conceptual framework to support the design, implementation and validation of the robotic cell proposed in the context of doctoral research.

2. Formal models and simulation of robotic cells

2.1. Formal models used in the design of robotic cells (Petri nets)

The paper "[8] " presents a hybrid method for analysing a robotic processing cell by combining Petri nets with fault trees, resulting in the Lambda Petri Net (λPN) model shown in Fig. 1. This approach, implemented in LabView, allows the detection and evaluation of faults by graphically representing the relationships between conditions and events, being validated by mathematical properties and simulations performed both in normal and fault modes.

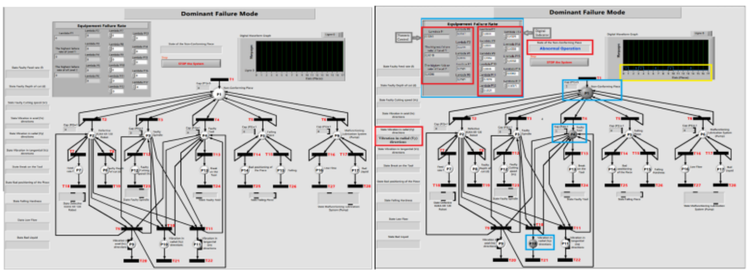

Fig. 1. LabView front panel of the λPN system - a) Error-free modelling b) Model with errors [8]

According to the approach presented in [9], the analysis of robotic systems can be streamlined by transferring the properties of the RSHPN meta-model to the developed models, thereby limiting the state-space explosion.

The method allows only task-dependent components to be analysed, eliminating the need for complete reanalysis and significantly shortening design time. The results presented in Fig. 2 confirm the value of Petri nets as a robust formal tool for verifying the properties of robotic systems.

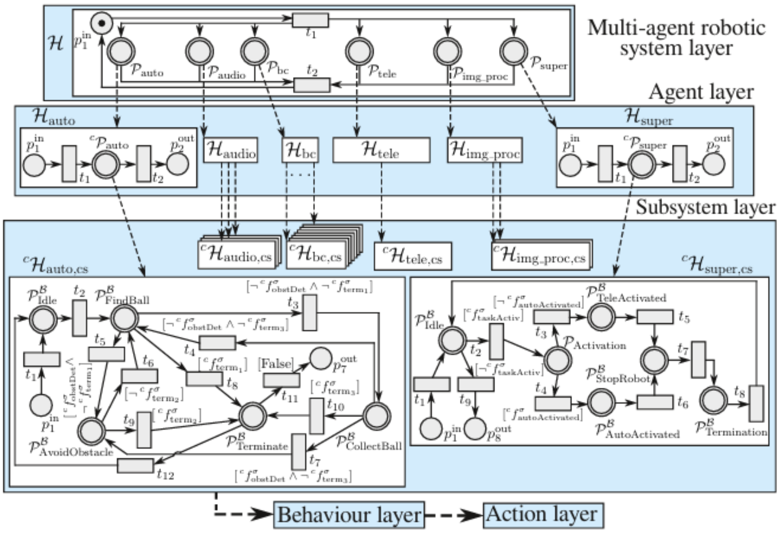

Fig. 2. System activity modelling [9]

In the study presented in [10], a robotic manufacturing system is examined using coloured Petri nets to assess various configurations of a three-machine flow and multiple part types illustrated in Fig. 3. The simulations highlight possible bottlenecks as well as differences in efficiency between scenarios with individual robots, a portal robot or two-machine processing. The results demonstrate the usefulness of coloured Petri nets in evaluating the performance and behaviour of robotic systems.

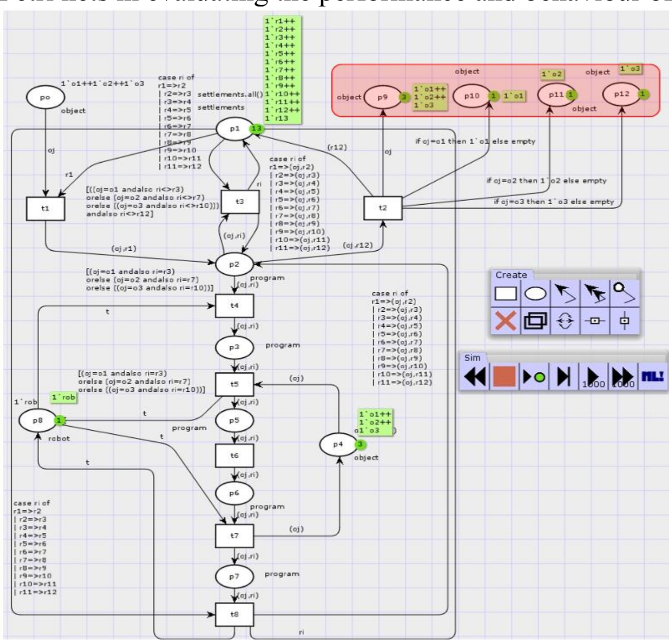

Fig. 3. Coloured Petri net model [10]

The study presented in [11] investigates a High-Level Robot Team Petri Net (HLrtPN) model for planning the movements of a heterogeneous robot team, incorporating mission specifications and individual behaviors within the Nets-within-Nets framework.

Through a global synchronisation function, the solution ensures compliance with the constraints imposed by regions of interest, being validated by simulations based on linear temporal logic. The results presented in Fig. 4 demonstrate the feasibility and flexibility of the model in coordinating multi-robot movements.

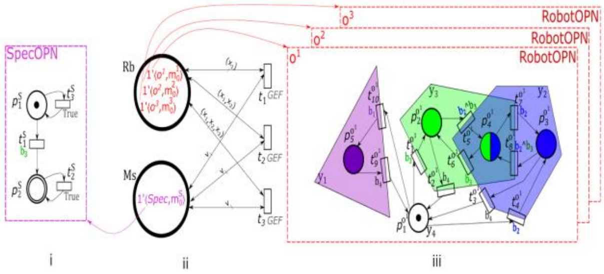

Fig. 4. Illustrative example supporting the intuitive explanation of the Nets-within-Nets formalism [11]

2.2. *Digital technologies for cell (Digital Twin)*

The work presented in [12] examines the issue of diminished reliability in robotic cells and proposes an optimisation strategy grounded in Digital Twin technology alongside predictive maintenance. The digital twin model allows the simulation of cell behaviour and the identification of critical components, on which advanced analysis is applied. The study shows that integrating Digital Twin with data-based analysis increases the reliability and availability of robotic cells, aligning with Industry 4.0 requirements. Fig. 5 shows the Digital Twin architecture.

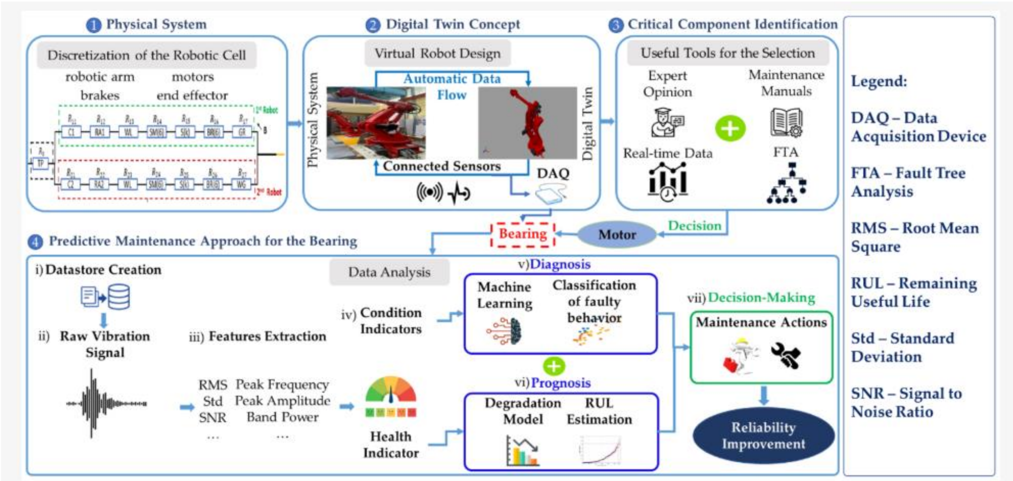

Fig. 5. General architecture of the Digital Twin system [12]

The study presented in [13] investigates the role of digital twins in human-robot collaboration (HRC) within the context of Industry 4.0, where IoT and cyber-physical systems facilitate the creation of virtual replicas synchronized with physical systems. The study presents the main approaches used for DT development in HRC, highlighting in particular the Layer-Based Approach, structured into the physical layer, the virtual layer and the connectivity layer. This architecture allows the mapping of data from sensors and their real-time transmission to the virtual model, ensuring the monitoring and optimisation of the behaviour of collaborative robots. The paper also discusses major challenges, such as the complexity of modelling and the need for high accuracy between the real system and the digital model. Scenarios are also analysed in which manufacturers can offer cloud-based DTs, facilitating the monitoring, diagnosis and parameterisation of the real robot. Fig. 6 presents the conceptual SBA and LBA for the Digital Twin.

The study in [14] proposes a Digital Twin framework tailored to Industry 5.0 requirements, integrating advanced deep learning techniques to enhance the safety and reliability of human-robot collaboration, as illustrated in Fig. 7.

Digital twins are used to generate synthetic data and monitor operators and robots in real time, enabling their detection and classification of actions through algorithms such as Faster R-CNN. To reduce the differences between the digital and real environments, a semi-supervised detector is introduced, which improves performance compared to fully supervised models.

Evaluations on real scenarios with collaborative robots, such as UR10, demonstrate high accuracy in detecting and interpreting actions. The paper makes available to the community both the collected data and a semi-automatic annotation tool generated within Digital Twin.

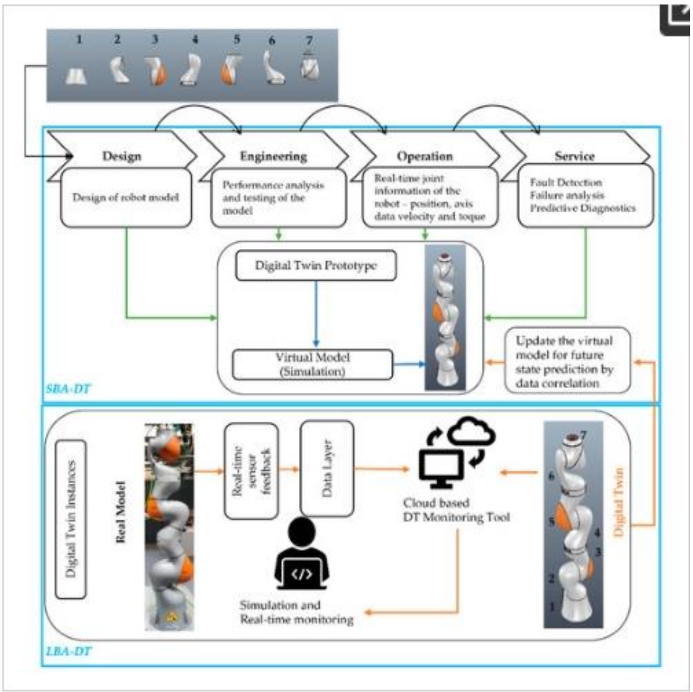

Fig. 6. Conceptual SBA and LBA for the Digital Twin (DT) of the collaborative robotic arm [13]

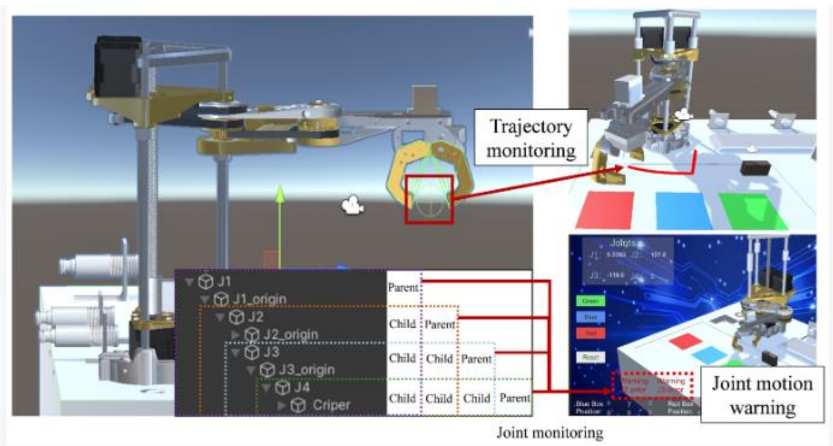

Fig. 7. Setting the relationships between the joints of the virtual robot and data monitoring [14]

3. Software and collaborative robotics

3.1. Software platforms used in the design of robotic cells (Tecnomatix).

The study presented in [15] emphasizes the necessity of employing advanced simulation tools, such as Tecnomatix, in the context of accelerated product life cycle reduction and heightened demands on production lines.

Offline robot programming reduces the risk of errors in the programming stage and minimises line downtime. The study confirms that the use of Tecnomatix leads to faster design processes, fewer errors and increased reliability of robotic cells. Fig. 8 shows a robotic welding cell modelled in Tecnomatix.

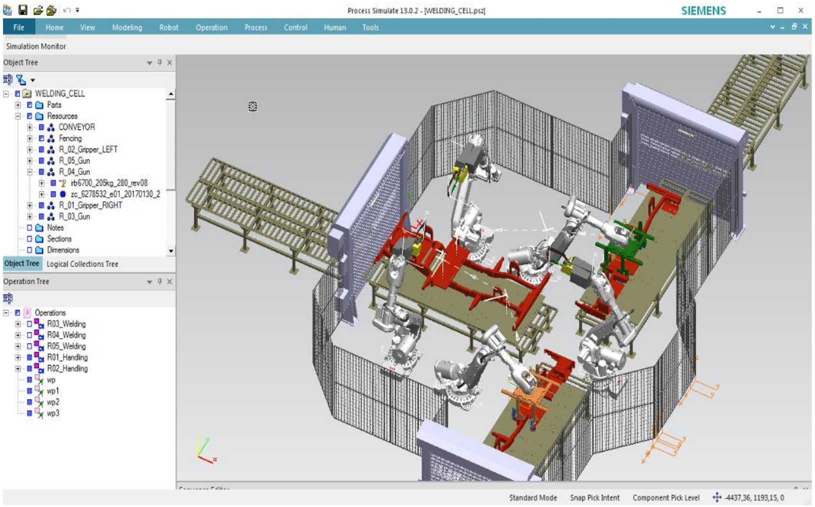

Fig. 8. Robotic welding cell in Tecnomatix [15]

The paper [16] analyses the use of the **Process Designer** module in Tecnomatix, highlighted in Fig. 9, for the design and evaluation of a workstation in an assembly line. The software allows for a detailed static layout of the workplace and the creation of a simulation of manufacturing activities, through which process deficiencies can be identified in advance. The simulation highlights potential bottlenecks, ergonomic issues or operational overloads, thus enabling designers to optimise the flow before physical implementation. The results generated by Process Designer include recommendations for eliminating these deficiencies, contributing to increased efficiency and reliability of the assembly line. Thus, the study confirms the usefulness of Tecnomatix in the early design and validation of industrial systems.

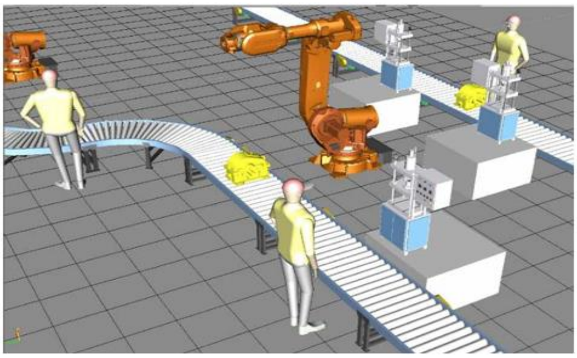

Fig. 9. Optimised workstations OP540 and OP610 in the Process Designer module [16]

The study presented in [17] underscores the effectiveness of utilizing the Tecnomatix Plant Simulation module, illustrated in Fig. 10, for modelling and optimising production processes.

Starting from an initial model of a packaging assembly line, the software is used to evaluate the performance of each machine and workstation and to identify areas that cause delays or bottlenecks. The study shows that adjusting equipment parameters in the virtual environment has a major impact on line behaviour, allowing the most efficient adjustment options to be selected. Through successive iterations, the factory model was optimised, bottlenecks were eliminated, and the workflow was balanced. The end result is an impressive **230%** increase in line efficiency compared to the initial configuration. This work confirms the value of Tecnomatix Plant Simulation as a tool to support managerial decisions on industrial process improvement.

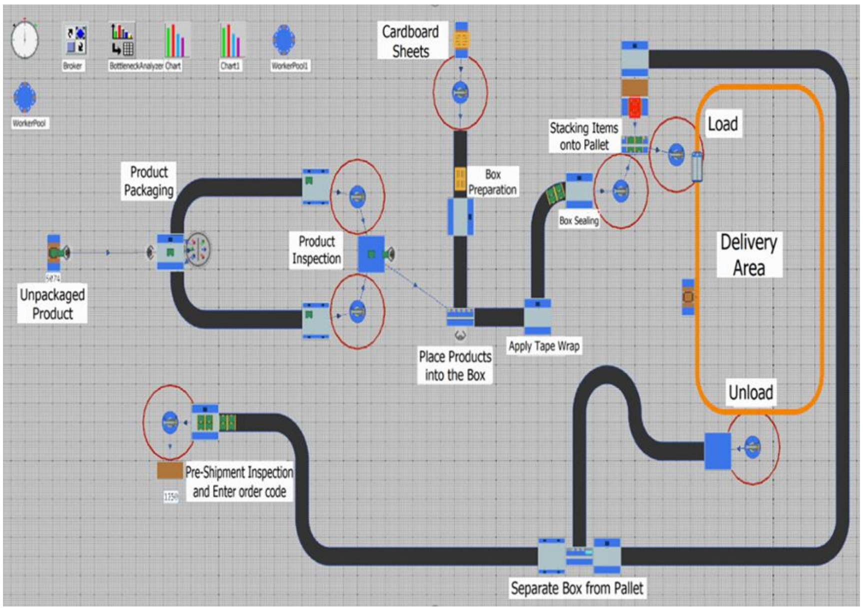

Fig. 10. Model of the packaging and shipping line after improvements were implemented [17]

3.2. Collaborative robotic cells (Cobots)

Paper [18] presents the design of an automated collaborative cell for industrial production, based on the Omron TM5-900 cobot shown in Fig. 11. The system automates processes such as screwing, adhesive application and component assembly, and was developed in collaboration with the Finnish company Cariitti Oy.

The cell integrates advanced equipment — OnRobot end effectors, a Techcon pneumatic dispenser and a task selection interface — all coordinated through the TMflow platform. The cobot performs different processes depending on manual selection, offering high flexibility and reducing human involvement in repetitive operations. Evaluations show significant performance gains, including an 85% reduction in processing time for spot manufacturing and superior accuracy compared to manual processing.

From an economic point of view, the solution achieves a return on investment of approximately 1.4 years, demonstrating the feasibility of adopting cobots in SMEs. The paper thus highlights the practical benefits of collaborative automation in terms of productivity, consistency and quality.

The paper [19] provides a comprehensive analysis of collaborative robot programming for industrial tasks, emphasising that the main challenge lies in combining an intuitive element — necessary for operators to easily configure tasks — with a 'human-aware' element that allows the cobot to adapt to human behaviour.

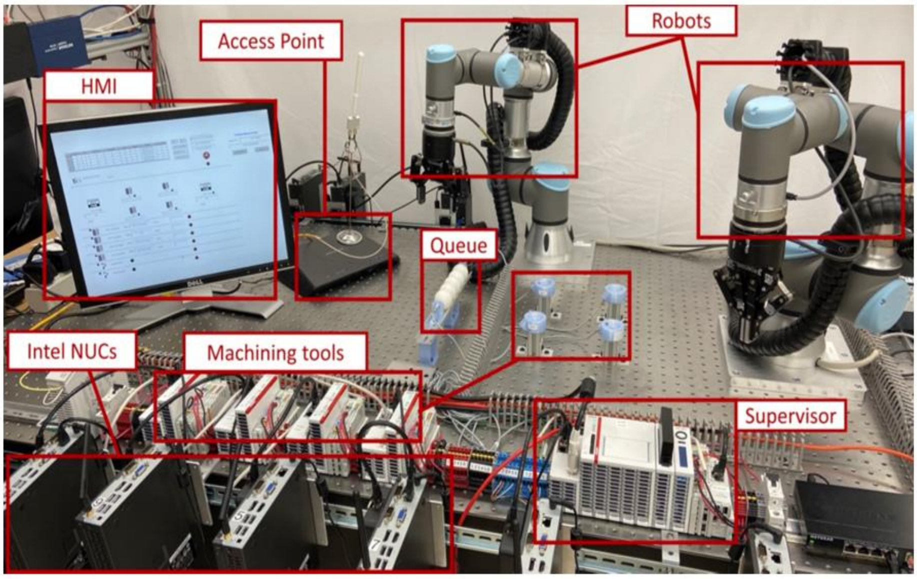

Fig. 11. Essential elements of a cobot work cell [18]

The authors present an overview of the main collaborative industrial scenarios and identify the essential programming requirements for effective human-robot collaboration. The study classifies current programming methods into three major directions: communication, optimisation and learning, highlighting the advantages and limitations of each. Fig. 12 shows the force modelling used for torque calculation. The paper concludes by highlighting future development directions, emphasising the need to create programming systems that are more intuitive, adaptive, and better integrated. Such systems should be capable of supporting human–robot collaboration in a safe and efficient manner, even in complex industrial scenarios characterised by high variability in processes, dynamic workflows, and multiple interactions between different types of equipment and operators. The authors stress that progress in this area will be essential for increasing productivity, reducing errors, and ensuring greater flexibility in the smart factories of the future.

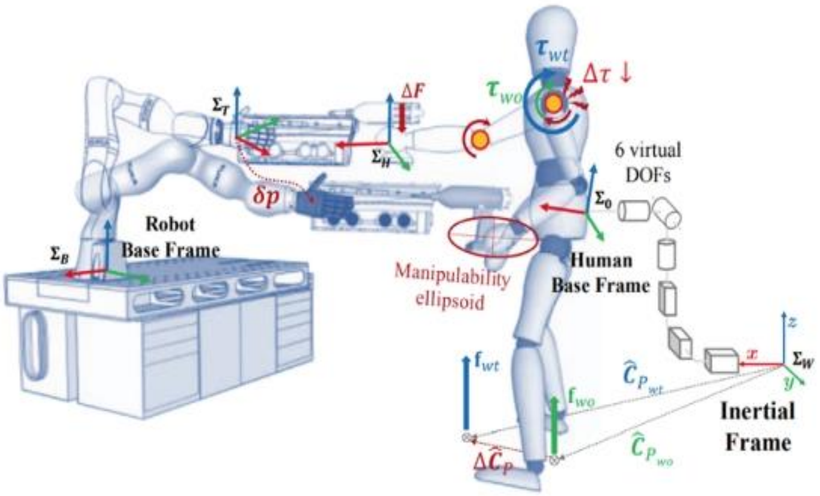

Fig. 12. Force modelling used for calculating human joint torques [19]

The study presented in [20] explores the use of a commercial collision avoidance platform, based on Dynamic Road-map algorithms, to perform unorganised tasks within a cell integrating industrial robots, cobots, human operators, and obstacles, as depicted in Fig. 13.

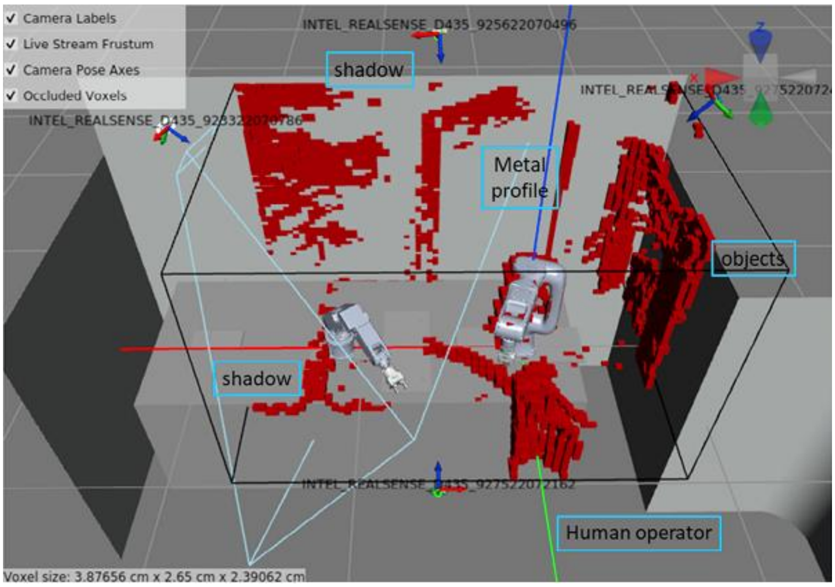

Fig. 13. Map with obstacles in the working area [20]

The platform allows real-time trajectory planning, ensuring the safe and simultaneous operation of all agents in the cell. The solution reduces costs, increases accuracy and allows the robot to be temporarily stopped when the operator enters the work area, thus contributing to increased productivity and flexibility of the robotic cell.

4. Artificial intelligence in robotic manufacturing cells

The paper [21] highlights the use of AI for the safe navigation of mobile robots, the adjustment of exoskeleton support according to the task, and the guidance of human-robot collaboration through intelligent AR systems.

The virtual shopfloor, updated in real time, allows for adaptive route planning and collision prevention, as shown in Fig. 14. Overall, AI coordinates the mixed human-robot flow, optimises ergonomics, and increases the precision of operations in the assembly cell.

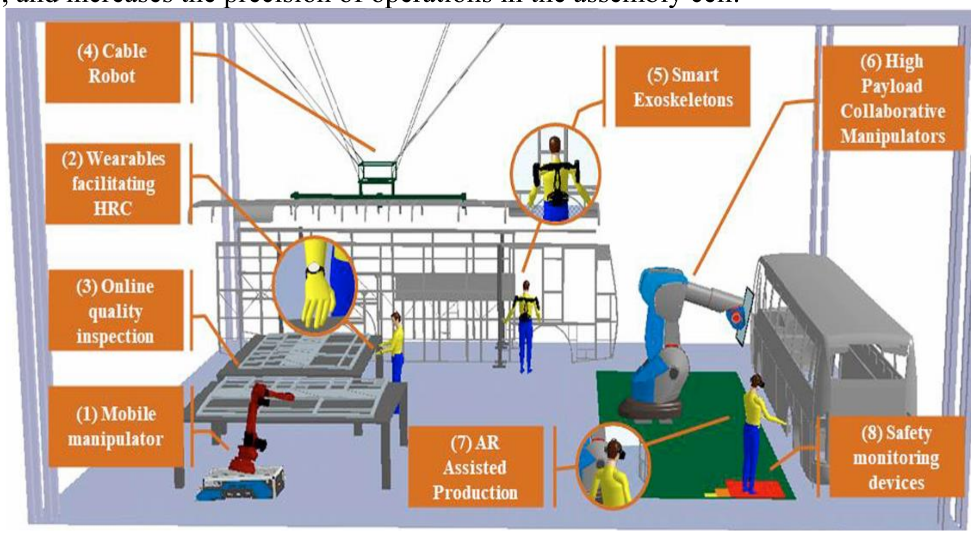

Fig. 14. Case study layout [21]

The study presented in [22] emphasizes the critical role of artificial intelligence in the adaptive manufacturing of modular satellites in orbit, where processes demand high precision and rapid response. AI enables automatic planning, defect detection, and anomaly identification in real time, optimising the bimanual robotic manipulation shown in Fig. 15. The learned models autonomously adjust the robot's tests and movements. In case of automation failure, AI algorithms assist teleoperation through adaptive haptic fixtures, ensuring safe and reliable assembly.

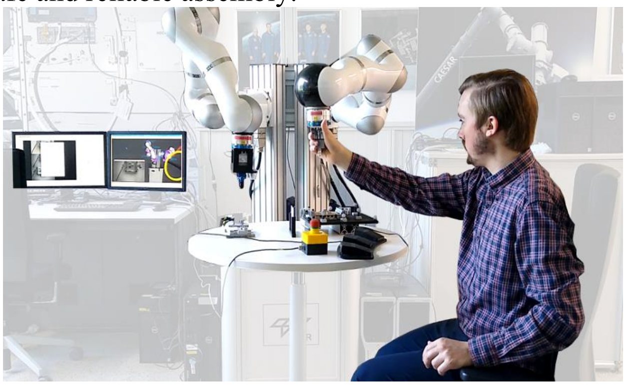

Fig. 15. HUG bimanual robotic system in teleoperation mode [22]

5. Conclusions

The literature review demonstrates that the evolution of robotic cells is profoundly influenced by the integration of artificial intelligence, cobots, and Industry 5.0 principles. AI is becoming the key element that transforms robots from rigid executors into adaptive partners, capable of detecting defects, avoiding collisions, understanding operators' actions and optimising processes in real time. Cobots facilitate safe human-robot collaboration, and combining them with Digital Twin and advanced simulations enables rapid design, virtual validation, and intelligent operation of cells.

Industry 5.0 emphasises customisation, ergonomics and human-centricity, and AI provides the necessary support for task adjustment, effort sharing and autonomous decision-making. Overall, the synergy between AI, cobots and Digital Twin supports the transition to flexible, safe and deeply collaborative manufacturing systems, with defining the next generation of intelligent robotic cells.

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