Robotical Automation in CNC Machine Tools: A Review

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DOI 10.2478/ama-2024-0048

ROBOTICAL AUTOMATION IN CNC MACHINE TOOLS: A REVIEW

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received 22 August 2023, revised 14 December 2023, accepted 15 December 2023

Abstract: Robotics and automation have significantly transformed Computer Numerical Control (CNC) machining operations, enhancing productivity, precision, and efficiency. Robots are employed to load and unload raw materials, workpieces, and finished parts onto CNC machines. They can efficiently handle heavy and bulky components, reducing the demand of manual labour and minimizing the risk of injuries. Robots can also be used in CNC machine tools to perform tasks such as automatic tool changing system, part inspection, and workpiece positioning. Automation technologies, including in-line inspection systems and Non-Destructive Testing (NDT) methods, can be integrated into CNC machining cells to enhance accuracy and reduce scrap and rework in machining operations. These systems collect real-time data on process parameters and machine tool performance to predict maintenance, optimize machining parameters, and improve overall efficiency. In the current study, applications of robotics and automation in the modification of CNC machine tools are reviewed and discussed. Different applications of robotics and automation in CNC machine tools, such as automated material handling, automatic tool changing, robotic work cells, adaptive machining, machine tending, quality inspection, data monitoring and analysis, and production line integration, are discussed. Thus, by analysing recent achievements in published papers, new ideas and concepts of future research works are suggested. As a result, accuracy as well as productivity in the process of part production can be enhanced by applying robotics and automation in CNC machining operations.

Keywords: robotics, automation, CNC machine tools, automated material handling, automatic tool changin

1. INTRODUCTION

Robotics and automation play a crucial role in computer numerical control (CNC) machining operations, offering numerous advantages in terms of efficiency, precision, and productivity. Robotics and automation have revolutionized CNC machining operations and automated material handling, providing numerous benefits in terms of productivity, efficiency, and cost-effectiveness. Robots are integrated into CNC machining operations to perform various tasks such as part loading and unloading, tool changing, and even complex machining operations [1]. Industrial robots can be programmed to execute precise movements and repetitive tasks with high accuracy and speed, reducing the need for manual labour and improving overall productivity. They can work around the clock without fatigue, ensuring continuous and efficient operation [2]. This aspect enables manufacturers to produce complex components at a faster rate and with higher quality, contributing to the advancement of modern manufacturing industries [3, 4]. Advanced robotic systems equipped with sensors and artificial intelligence capabilities can perform adaptive machining [5]. These systems can monitor and adjust machining parameters in real time based on feedback from sensors, ensuring optimal performance, improved accuracy, and reduced scrap rates [6]. Adaptive machining enables efficient machining of complex parts and the ability to respond to variations in material properties. Automated material-handling systems are employed to streamline the movement of raw materials, workpieces, and finished parts within the CNC machining facility [7]. These systems utilise conveyors, gantries, robotic arms, and other automated mechanisms to transport materials between different workstations, CNC machines, and storage areas [8]. By eliminating manual handling, automated material-handling systems reduce the risk of errors, damage, and injuries, while also increasing throughput and minimizing production delays [9, 10]. Automation in CNC machining operations often involves the use of advanced sensors and identification systems. For example, barcodes, radio-frequency identification (RFID) tags, or QR codes can be attached to workpieces and materials to enable automated tracking throughout the manufacturing process [11]. This facilitates seamless integration with CNC machines and ensures accurate identification and routing of materials, reducing the chances of errors and mix-ups [12]. Here are some of the key advantages of incorporating robotics and automation in CNC machining operations:

- Increased productivity: Automation enables continuous operation of CNC machines, reducing downtime and maximising productivity. Robots can work tirelessly without breaks or fatigue, leading to higher output and increased efficiency [13].
- Enhanced precision and accuracy: Robots are highly precise and repeatable, ensuring consistent and accurate machining operations. They can achieve tight tolerances and eliminate human errors, resulting in improved part quality and reduced scrap or rework [14].
- Improved safety: Automation removes the need for manual intervention in hazardous or physically demanding tasks. This reduces the risk of accidents, injuries, and exposure to harmful environments, making the workplace safer for operators [6].

DOI 10.2478/ama-2024-0048 acta mechanica et automatica, vol.18 no.3 (2024)

- Higher production speeds: Robots can perform CNC machining operations at significantly faster speeds compared to human operators. They can execute complex movements and tool changes quickly, resulting in reduced cycle times and increased production rates [15].
- Flexibility and adaptability: Robotic systems can be programmed to perform a wide range of tasks, allowing for greater flexibility in CNC machining operations. They can easily switch between different machining operations or workpieces, enabling efficient batch production or rapid product changeovers.
- 24/7 operation: Automated systems can run continuously, including outside regular working hours, without the need for human supervision. This maximizes machine utilisation and can lead to round-the-clock production, improving overall production capacity [16].

Also, disadvantages of using robotics in CNC machine tools can be presented as:

- High initial investment: Implementing robotics and automation in CNC machining operations requires a significant upfront investment. Costs include the purchase of robotic systems, integration with existing CNC machines, programming, and training. This may be a barrier for smaller businesses with limited budgets [14].
- Complex setup and programming: Setting up and programming robotic systems for CNC machining can be complex and time-consuming. Skilled personnel or specialized expertise may be required to program the robots accurately and optimize their performance. This can increase implementation costs and project timelines [17].
- Integration and programming: To implement robotics and automation in CNC machining operations, the integration of different systems is crucial. This includes programming the robotic systems, developing software interfaces for seamless communication between machines, and integrating control systems for coordinated operations. Additionally, specialised software tools enable offline programming and simulation, reducing downtime and optimizing the production process [18].
- Limited adaptability to small batch sizes or customisation: While automation excels in high-volume production, it may be less suitable for small batch sizes or highly customized products. Adapting automation systems to frequent product changes or small production runs can be challenging and may result in reduced efficiency [19].
- Potential for job displacement: Automation can lead to a reduction in manual labour requirements. As robots replace some human operators in CNC machining operations, there is a potential for job displacement or reduced employment opportunities for certain roles. However, automation can also create new job roles that focus on robot programming, maintenance, and system supervision [20, 21].
- Dependency on power supply and maintenance: Robotic systems require a stable power supply and regular maintenance to operate optimally. Power outages or equipment breakdown can disrupt production and lead to downtime. Maintaining robotic systems also requires skilled technicians and spare parts, which can add to operational costs [22].

Soori et al. [23] suggested virtual machining techniques to evaluate and enhance CNC machining in virtual environments [23-26]. To investigate and enhance performance in the component-production process employing welding procedures, Soori et al. [27] suggested an overview of current developments in friction-stir welding techniques. Soori and Asamel [28]s examined the implementation of virtual machining technology to minimise residual stress and displacement error throughout turbine blade five-axis milling procedures. Soori and Asmael [29] explored applications of virtualized machining techniques to assess and reduce the cutting temperature throughout milling operations of difficult-to-cut objects. Soori et al. [30] indicated an advanced virtual machining approach to improve surface characteristics throughout five-axis milling procedures for turbine blades. Soori and Asmael [31] created virtual milling processes to reduce the displacement error throughout five-axis milling operations of impeller blades. In order to analyse and develop the process of part production in virtual environments, virtual product development is presented by Soori [32]. Soori and Asmael [33] proposed an overview of current advancements from published research to review and enhance the parameter technique for machining-process optimisation. To improve the efficiency of energy consumption, the quality and availability of data across the supply chain, and the accuracy and dependability of component manufacture, Dastres et al. [34] proposed a review of the RFID-based wireless manufacturing systems. Soori et al. [35] explored machine learning and artificial intelligence in CNC machine tools to boost productivity and improve profitability in production processes of components, employing CNC machining operations. To improve the performance of machined components, Soori and Arezoo [36] reviewed the topic of measuring and reducing residual stress in machining operations. To improve surface integrity and decrease residual stress during Inconel 718 grinding operations, Soori and Arezoo [37] proposed the optimum machining parameters employing the Taguchi optimisation method. To increase the life of cutting tools during machining operations, Soori and Arezoo [38] examined different methods of tool wear-prediction algorithms. Soori and Asmael [39] investigated computer-assisted process planning to boost productivity in the part-manufacturing procedure. Dastres and Soori [40] addressed improvements in web-based decision-support systems to provide solutions for data warehouse management using decision-making assistance. Dastres and Soori [41] reviewed applications of artificial neural networks in different sections, such as analysis systems of risk, drone navigation, evaluation of welding, and evaluation of computer simulation quality, to explore the execution of artificial neural networks for improving the effectiveness of products. Dastres and Soori [42] proposed employing communication systems for environmental concerns to minimise the negative effects of technological advancement on natural catastrophes. To enhance network and data online security, Dastres and Soori [43] suggested the secure socket layer. Dastres and Soori [44] studied the developments in web-based decision-support systems for developing the methodology of decision-support systems by evaluating and suggesting the gaps between proposed approaches. To strengthen network-security measures, Dastres and Soori [45] discussed an analysis of recent advancements in network threats. To increase the potential of image-processing systems in several applications, Dastres and Soori [46] evaluated image processing and analysis systems. Dimensional, geometrical, tool deflection, and thermal defects have been modified by Soori and Arezoo [47] to improve the accuracy in five-axis CNC milling processes. Recent developments given in published articles are examined by Soori et al. [48] to assess and improve the impacts of artificial intelligence, machine learning, and deep learning in advanced robotics. Soori and Arezoo [49] developed a virtual machining system application to examine whether cutting parameters affect tool life and cutting

DOI 10.2478/ama-2024-0048

temperature during milling operations. Soori and Arezoo [50] studied the impact of coolants on the cutting temperature, roughness of the surface, and tool wear during turning operations with Ti6Al4V alloy. Recent developments from published papers are reviewed by Soori [51] to examine and alter composite materials and structures. Soori et al. [52] examined the Internet of Things (IoT) application for smart factories in Industry 4.0 to increase quality control and optimise part-manufacturing processes. To minimise cutting tool wear during drilling operations, Soori and Arezoo [53] designed a virtual machining system. Soori and Arezoo [54] decreased residual stress and surface roughness to improve the quality of items produced utilising abrasive water jet machining. To enhance accuracy in turbine blade five-axis milling operations, deformation errors are calculated and compensated by Soori [55]. To analyse and enhance accuracy in CNC machining operations and structures, applications of the finite element method in CNC machine tool modification are reviewed by Soori and Arezoo [56]. In order to analyse and optimise energy consumption in industrial robots, different methods of energy usage optimisation are reviewed by Soori et al. [57]. To analyse and modify the application of virtual manufacturing in productivity enhancement of part production, advanced virtual manufacturing systems are reviewed by Soori et al. [58]. Meta-heuristic algorithms for assessing the collapse risk of steel moment frame mid-rise buildings are presented by Karimi Ghaleh Jough and Şensoy [59] to provide a better risk-management strategy for steel moment frames. The steel moment-resisting frame dependability via interval analysis using the FCM-PSO method is studied by Karimi Ghaleh Jough and Şensoy [60] to enhance accuracy and decrease execution time in the calculation of siesmic fragility curves. Assessment of out-of-plane behaviour of non-structural masonry walls using FE simulations is presented by Karimi Ghaleh Jough and Golhashem [61] to reduce the self-weight axial compression of the walls with modern lightweight masonry units.

The paper reviews and discusses the application of robotics and automation in the modification of CNC machine tools. Robotics and automation are used in CNC machine tools for a variety of purposes, including integrated production lines, automated material handling, automatic tool changing, robotic work cells, adaptive machining, machine tending, and quality inspection. Thus, fresh thoughts and suggestions for the subsequent research tasks are proposed by examining previous successes in published articles. As a consequence, by implementing robots and automation in CNC machining processes, accuracy as well as productivity in the process of component manufacturing may be improved.

2. AUTOMATED MATERIAL HANDLING

The Robotics and automation play a crucial role in CNC machining operations and automated material handling. Robots can be employed to load and unload raw materials and finished parts onto CNC machines. They can pick up raw materials from a storage area, place them in the CNC machine for machining, and then transfer the finished parts for subsequent operations or storage [62]. This automation significantly reduces cycle times and enables lights-out machining, where operations continue without human intervention [63]. This eliminates the need for manual labour, reduces setup time, and ensures consistent and accurate placement of materials [64]. The integration of robotics and automation in CNC machining operations and automated material handling brings numerous benefits, including increased productivity, improved precision, reduced labour costs, enhanced safety, and better utilisation of resources [65]. It allows manufacturers to streamline their operations, optimise production flow, and respond quickly to changing demands in a competitive manufacturing environment [66]. How these technologies are used in these areas is explored below:

1. CNC machining operations:
   - Robotic arms: Industrial robots equipped with articulated arms can perform various tasks in CNC machining operations. Robots can be programmed to handle different types of materials and workpieces, adapting to various machining requirements. They can handle the loading and unloading of workpieces into the CNC machines, change cutting tools, and perform quality inspections [67].
   - Automated tool changing: CNC machines can be equipped with automatic tool changers (ATCs) that are controlled by computer programs. This enables the machine to switch between different cutting tools without manual intervention, reducing downtime and increasing efficiency [68].
   - Continuous operation: Automated material-handling systems ensure a constant supply of raw materials and removal of finished products, minimising downtime [69].
   - Optimised workflow: Robots can perform repetitive tasks with high precision and speed, allowing for a streamlined production process.
   - Reduced errors: Automation minimises the chances of human errors, resulting in more precise machining and fewer defects [70].
   - Energy efficiency: Optimised processes and reduced idle time in material handling contribute to energy savings, making the manufacturing process more cost-effective.
   - Vision systems: Automated vision systems can be integrated with CNC machines to perform tasks such as part inspection, alignment, and measurement. These systems use cameras and image-processing algorithms to ensure accuracy and quality control [71].
   - In-process monitoring: Sensors and probes can be incorporated into CNC machines to monitor the cutting process in real time. This allows for adaptive control, where the machine automatically adjusts parameters like cutting speed, feed rate, and tool path to optimise performance and prevent errors [72].
2. Automated material handling:
   - Conveyor systems: Automated conveyor systems are commonly used in CNC machining operations for material handling. They transport workpieces, raw materials, and finished parts between different stages of the manufacturing process, reducing manual handling and improving efficiency [73].
   - Automated guided vehicles (AGVs): AGVs are autonomous vehicles that can navigate within a manufacturing facility without human intervention. They can transport materials, such as raw stock and finished parts, between CNC machines, storage areas, and inspection stations [74].
   - Palletising systems: Automated palletising systems are used to stack and organise workpieces or finished parts on pallets. These systems can handle heavy loads and precisely position the parts for efficient transportation and storage. This facilitates continuous machining by enabling the preparation of the next workpiece while the machine is still in operation [75].
   - Robotic material handling: Industrial robots equipped with specialised end-effectors can handle materials, such as loading and unloading workpieces onto CNC machines, palletising

finished parts, or sorting and organising materials in a warehouse or storage area [76].
- Material tracking and management software: These systems can provide insights into production efficiency, predict maintenance needs, and optimise overall manufacturing processes.

Cloud robotics for material handling in cognitive industrial Internet of things is shown in Fig. 1 [77].

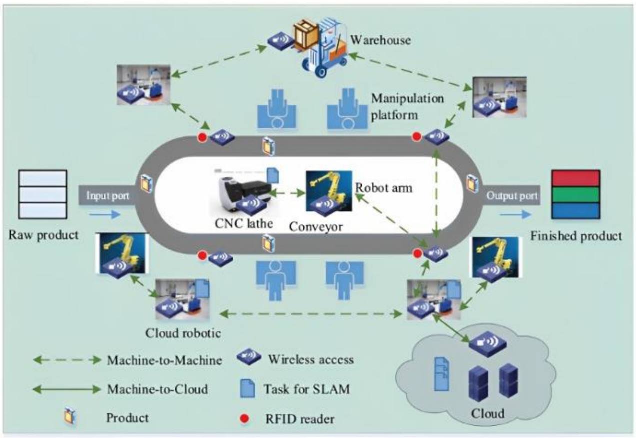

Fig. 1. Cloud robotics for material handling in cognitive industrial Internet of things [77]

Overall, robotics and automation have transformed CNC machining operations and have automated material handling, enhancing productivity, quality, and efficiency. These technologies continue to evolve, with advancements in artificial intelligence, machine learning, and collaborative robotics opening up new possibilities for the future of CNC machining [78]. The specific choice of automated material-handling solutions will depend on the type of CNC machine, the nature of the materials being processed, and the desired production goals. In the next section, the applications and benefits of automatic tool-changing systems in CNC machining operations will be discussed. The integration of robotic arms in tool changing not only streamlines the process but also extends the capabilities of CNC machines, offering dynamic adaptability and minimising human intervention.

3. AUTOMATIC TOOL CHANGING FROM CLASSICAL CHANGER TO ROBOTICAL CHANGER

CNC machines often require different tools for different operations. Robots are employed to handle tooling tasks in CNC machining centres. Automation in CNC machine tools, particularly in the context of tool changing, involves the use of various technologies and systems to streamline the process of switching tools during machining operations. They can automatically load and unload cutting tools, reducing manual intervention and minimising machine downtime [79]. This results in increased productivity and improved machine utilisation. Robots can be employed to handle tooling tasks in CNC machining centres to enhance accuracy and productivity in machining operations [17, 80]. They can automatically load and unload cutting tools, reducing manual intervention and minimising machine downtime [81]. Some CNC machines are equipped with in-machine probing systems that can measure and verify tool dimensions without the need for manual intervention. Using such systems results in increased productivity and improved machine utilisation [82]. It allows for increased productivity, reduced downtime, and the ability to perform complex machining tasks without human intervention [83]. An overview of how automated tool changing works in CNC machining is given below:
- Tool magazine: The CNC machine is equipped with a tool magazine, which is essentially a storage unit for holding various cutting tools. The tool magazine can be located on the machine itself or as a separate unit adjacent to the machine [84].
- Tool identification: Each cutting tool is uniquely identified using a barcode, RFID, or some other form of identification system. This identification helps the machine recognise and select the appropriate tool for a specific machining operation [85].
- Tool selection: When a particular machining operation requires a tool change, the CNC machine's control system sends a command to the tool-changer mechanism to retrieve the required tool from the magazine. The command is usually based on the program being executed and the specific tool needed at that stage [86].
- Tool-changing mechanism: The CNC machine is equipped with a tool-changing mechanism, often referred to as an ATC. The ATC consists of a gripper or a robotic arm that can grasp and manipulate the cutting tools [80]. Linear tool changers are systems where the tools are arranged in a linear fashion, and a mechanism moves along the line to select and change tools. Rotary tool changers are mounted on a rotary carousel, and the carousel rotates to bring the desired tool into position [87].
- Tool retrieval and replacement: The tool-changer mechanism moves to the designated position in the tool magazine and retrieves the required tool. It then moves to the spindle area where the previous tool is stored [88].
- Tool exchange: The ATC releases the current tool and grasps the new tool using its gripper or robotic arm. The tool-exchange process is usually automated and performed with precision to ensure proper alignment and secure attachment of the new tool [89].
- Tool calibration and verification: After the tool exchange, the CNC machine may perform calibration and verification processes to ensure the new tool is properly aligned and ready for use. This can include checking the tool length, diameter, and other parameters to ensure accurate machining [82].
- Resuming machining: Once the tool change is completed and verified, the CNC machine resumes the machining operation using the new tool. This process can be repeated multiple times during a machining operation, depending on the complexity and requirements of the workpiece [90].

Structure of an ATC of CNC machine tools is shown in Fig. 2 [91].

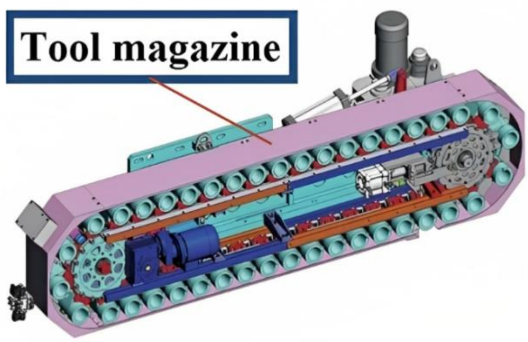

Fig. 2. Structure of an automatic tool changer of computer numerical control machine tools [91]

DOI 10.2478/ama-2024-0048

Application of robots in the vertical machining centre tool changer is shown in Fig. 3 [92].

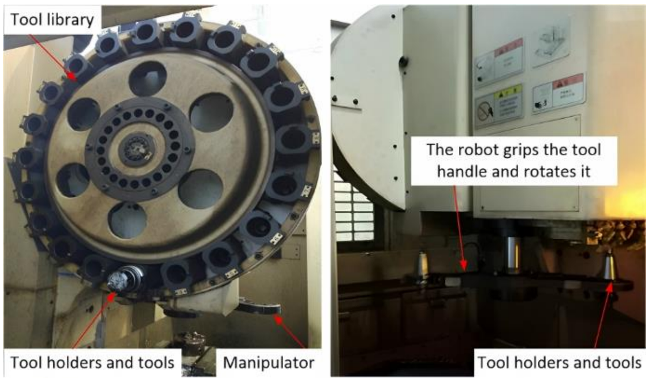

Fig. 3. Application of robots in the vertical machining centre tool changer [92]

The ATC significantly reduces manual intervention and minimises downtime associated with manual tool changes. It enables CNC machines to perform complex machining tasks with multiple tools seamlessly increasing productivity and efficiency in manufacturing processes [93]. Robotic work cells can efficiently manage tool changes by coordinating with the automatic tool-changing systems, ensuring a smooth transition between machining operations. In the next section, applications of robotic work cells in the automation of CNC machine tools are discussed.

4. ROBOTIC WORK CELLS

Robotics and automation play a significant role in CNC machining operations, particularly in the form of robotic work cells. These advanced systems combine CNC machines with industrial robots to enhance the productivity, efficiency, and flexibility in manufacturing processes [94, 95]. Robotic work cells in the context of CNC machine tools refer to integrated systems where robots are deployed to perform various tasks alongside or in collaboration with CNC machines. Robotic work cells combine multiple machines, such as CNC machines, measuring systems, and assembly stations, with robotic arms [96]. These cells enable seamless integration and coordination between different processes, optimising production flow and minimising cycle times [97]. Here are some key aspects and benefits of robotic work cells in CNC machining:

- Increased productivity: Robotic work cells can operate continuously without breaks, leading to increased productivity and reduced cycle times. Robots can perform repetitive tasks with high accuracy and speed, minimising human errors and maximising output [98].
- Flexibility and adaptability: Robots are programmable and can be easily reprogrammed or reconfigured to handle different machining tasks or part variations. This flexibility enables manufacturers to efficiently switch between different product lines or adapt to changing production requirements [99].
- Enhanced precision and consistency: CNC machines provide precise control over machining operations, and when combined with robots, they ensure consistent and repeatable results. This level of accuracy is crucial for industries like aerospace and automotive, where tight tolerances are required [100].
- Improved safety: Robots can handle hazardous or physically demanding tasks, reducing the risk of injuries to human workers. They can operate in enclosed work cells or behind safety barriers, safeguarding operators from potential accidents associated with machining processes [101].
- Offline programming and simulation: Robots and CNC machines can be programmed offline using simulation software [102]. This allows for the optimisation of robotic movements and CNC machining processes without interrupting actual production [103].
- Reduced labour costs: Robotic work cells can replace manual labour for routine machining operations, leading to cost savings in terms of labour expenses. While human operators are still needed for tasks like programming and supervision, the overall labour requirement can be significantly reduced [104].
- Lights-out manufacturing: With robotic work cells, it is possible to achieve lights-out manufacturing, where production can continue unattended even during non-working hours. This can optimise machine utilisation and increase overall production capacity [105].
- Integration with other automation technologies: Robotic work cells can be integrated with other automation technologies, such as conveyor systems, part feeders, vision systems, and quality control devices. This integration streamlines the production process, improves material flow, and enhances overall system efficiency. Moreover, it can facilitate real-time monitoring, scheduling, and optimisation [106].
- Predictive maintenance: Robotics and CNC systems can be equipped with sensors for predictive maintenance. This helps in identifying potential issues before they lead to downtime, reducing unplanned interruptions in production [16, 107].
- Data collection and analysis: Robotics and automation systems in CNC machining often come with advanced data-collection capabilities. By collecting real-time data on machine performance, tool wear, and part quality, manufacturers can analyse and optimise their processes for improved efficiency and predictive maintenance [108].

KUKA milling robot is shown in Fig. 4 [109].

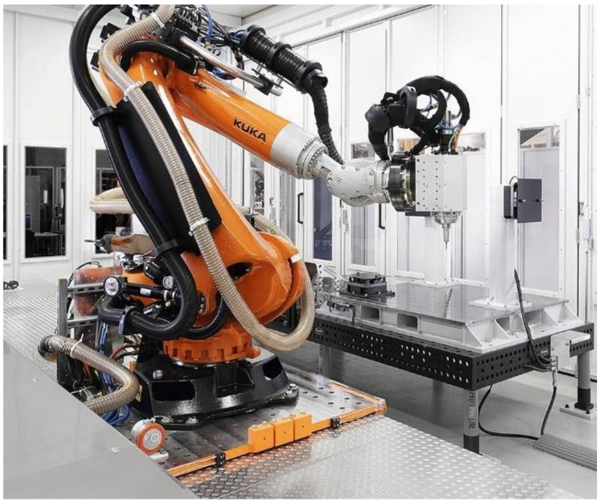

Fig. 4. KUKA milling robot [109]

The implementation of robotic work cells in CNC machine tools is a key component of Industry 4.0, where smart manufacturing technologies converge to create more agile and responsive production systems [110, 111]. Robotic work cells can be part of flexible manufacturing systems where CNC machines and robots work together to handle a variety of tasks. Also, robots can be employed to load raw materials onto CNC machines and unload finished products, streamlining the material-handling process [112]. While the benefits of robotic work cells in CNC machining operations are substantial, their implementation requires careful planning, programming, and maintenance. It is essential to consider factors like workspace layout, robot programming, safety measures, and proper training for operators to ensure successful integration and operation of robotic work cells [113]. Adaptive machining using robots and automation introduces a dynamic approach to manufacturing, allowing for real-time adjustments in machining processes based on changing conditions, which is discussed in the next section.

5. ADAPTIVE MACHINING USING ROBOTS AND AUTOMATION

Adaptive machining in CNC machining operations refers to the application of robotics and automation to dynamically adjust the machining process based on real-time feedback and data. It involves the integration of sensors, control systems, and intelligent algorithms to optimise machining operations for improved efficiency, accuracy, and productivity [114]. Advanced robotic systems are equipped with sensors and vision systems that enable them to adapt to variations in workpiece dimensions or alignment [115]. Sensor data can be used to adapt machining strategies dynamically, compensating for variations in workpiece geometry, material properties, and tool wear. This capability allows for real-time adjustments in machining parameters, ensuring precise and accurate results, even with slight variations in the workpiece [16]. Some key aspects of adaptive machining in CNC operations are given below:

- Real-time sensing: Adaptive machining relies on sensors such as force sensors, acoustic emission sensors, temperature sensors, and vision systems to collect data during the machining process. These sensors provide feedback on factors like cutting forces, tool wear, workpiece condition, and dimensional accuracy [116].
- Data analysis and interpretation: The collected sensor data is analysed using advanced algorithms and machine learning techniques to extract valuable insights. This analysis helps in identifying patterns, anomalies, and deviations from the desired machining parameters [117].
- Decision-making and control: Based on the data analysis, adaptive machining algorithms make real-time decisions to optimise the machining process. These decisions can include adjusting feed rates, changing tool paths, modifying cutting parameters, or replacing worn-out tools [118].
- Dynamic adjustments: Adaptive machining systems use robotics and automation to implement the necessary adjustments identified through the data analysis. This can involve automatically repositioning the workpiece, changing cutting tools, adjusting spindle speeds, or modifying tool paths to ensure optimal machining conditions [119].
- Optimisation objectives: Adaptive machining aims to achieve various optimisation objectives, including reducing cycle times, improving surface finish quality, minimising tool wear, maximising tool life, maintaining dimensional accuracy, and reducing energy consumption [120].

Benefits of adaptive machining in CNC operations:

- Improved efficiency: By dynamically adjusting machining parameters, adaptive machining optimises the process to reduce cycle times, minimise material waste, and increase productivity [121].
- Enhanced accuracy and quality: Real-time adjustments based on sensor feedback help maintain dimensional accuracy, improve surface finish quality, and reduce errors in CNC machining operations [122].
- Extended tool life: Adaptive machining systems detect tool wear in real time and make necessary adjustments, leading to longer tool life and reduced tooling costs. Also, adaptive machining systems can continuously monitor and adjust cutting parameters based on real-time data, optimising tool paths for improved accuracy and cutting tool life during machining operations.
- Reduced downtime: By monitoring the machining process continuously, adaptive machining systems can detect anomalies and potential issues, allowing for proactive maintenance and reducing unplanned downtime [123].
- Reduced scrap and rework: Adaptive systems can adapt cutting speeds, feeds, and other parameters to optimise machining and minimise scrap [124].
- Flexibility and adaptability: Adaptive machining enables CNC machines to handle variations in workpiece material properties, tool wear, and other factors, making the process more adaptable to changing production requirements [125].

Block diagram of robotic belt grinding trajectory planning steps is shown in the Fig. 5 [126].

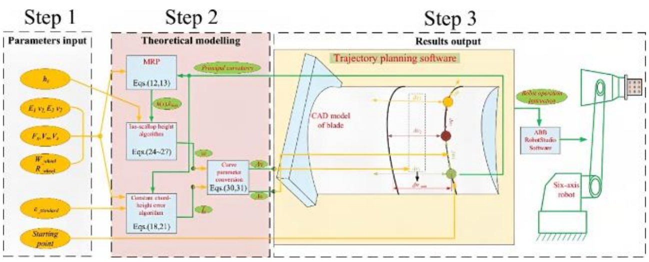

Fig. 5. Block diagram of robotic belt grinding trajectory planning steps [126]

Overall, adaptive machining utilising robotics and automation plays a crucial role in optimising CNC machining operations and improving efficiency, accuracy, and productivity, while reducing costs and downtime [127]. By integrating robots and automation into CNC machine tools, manufacturers can achieve a more adaptive and responsive manufacturing environment, leading to improved overall efficiency, product quality, and competitiveness in the market.

6. MACHINE TENDING

Machine tending refers to the process of loading and unloading workpieces to and from CNC machines. Robotics and automation have revolutionised CNC machining operations, particularly in the area of machine tending. Robots can be used to tend multiple CNC machines simultaneously, optimising production throughput [128]. They can load and unload workpieces, initiate machining processes, and perform inspections or measurements. Automation in machine tending aims to replace or assist human operators

DOI 10.2478/ama-2024-0048

in these repetitive and often labour-intensive tasks. This process is critical for maximising the efficiency of CNC machining operations and reducing manual labour [129]. An overview of a machine-tending system is shown in Fig. 6 [130].

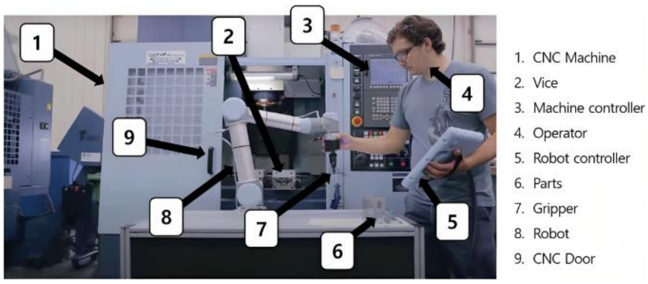

Fig. 6. Overview of a machine-tending system [130]

By integrating robotics and automation into machine-tending tasks, several advantages can be achieved:
- Increased productivity: Automation eliminates the need for human operators to manually load and unload workpieces, allowing the CNC machines to operate continuously without interruptions. This leads to higher productivity and reduced cycle times [131].
- Enhanced safety: CNC machines can be hazardous to operate, especially during the loading and unloading of heavy workpieces. By employing robots, human operators can be kept at a safe distance from the machine, minimising the risk of accidents and injuries [132].
- Improved accuracy and consistency: Robots are capable of precise movements and can consistently position workpieces with high accuracy. This ensures consistent and repeatable machining results, reducing errors and scrap rates.
- Flexibility and adaptability: Robots can be programmed to handle various types of workpieces and can quickly switch between different tasks. This enables manufacturers to respond to changing production needs, such as varying product designs or batch sizes, without significant retooling or reprogramming [133].
- Extended machine uptime: Automated machine tending allows CNC machines to operate continuously, even outside regular working hours. This maximises machine uptime and overall production capacity, leading to increased efficiency and reduced idle time.
- Reduction in labour costs: By automating machine-tending tasks, manufacturers can reduce their dependency on manual labour, resulting in cost savings associated with labour wages, training, and employee benefits [134].
- Integration with other processes: Robotic machine tending can be seamlessly integrated with other automation processes, such as material handling, quality inspection, and post-processing. This holistic automation approach further optimises the entire production workflow [135].

To enhance the efficiency of the machine-tending system in advanced CNC machining operations, the application of the digital twin is studied. The flowchart of a developed machine-tending system using the digital twin system is shown in Fig. 7 [130].

To implement robotics and automation in machine tending, various technologies are employed, including industrial robots, vision systems, sensors, and advanced programming techniques. Additionally, collaborative robots (cobots) are gaining popularity, as they can work safely alongside human operators, further increasing the flexibility and versatility of machine-tending operations [136]. Overall, machine tending by automation in CNC machine tools plays a crucial role in enhancing the efficiency, safety, and precision in manufacturing processes. Robotics and automation have significantly transformed CNC machining operations, making them more efficient, safe, and adaptable to evolving manufacturing demands [137]. In smart CNC machining operations, robotics, artificial intelligence, and machine learning are applied to enhance the capabilities of automated machine-tending systems.

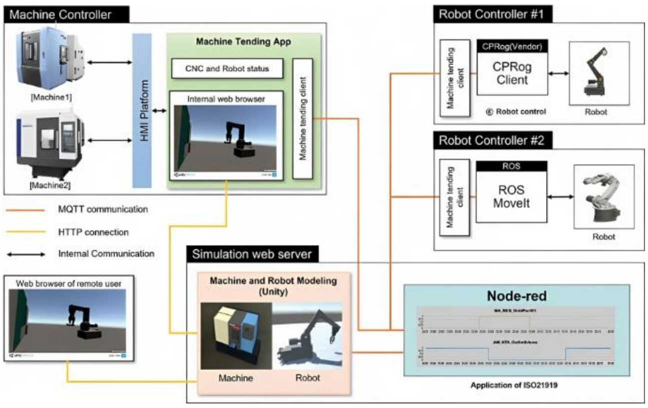

Fig. 7. The flowchart of a developed machine-tending system using the digital twin system [130]

7. QUALITY INSPECTION

Robotics and automation have significantly impacted CNC machining operations, particularly in the area of quality inspection. Automated systems can be integrated with CNC machines to inspect and measure machined parts using sensors, vision systems, or coordinate measuring machines (CMMs). This ensures that parts meet specified tolerances, reduces human error, and improves overall quality control [138]. Implementing automation in CNC machine tools for quality inspection not only improves the efficiency and accuracy of the inspection process but also contributes to reducing the likelihood of defects and increases overall productivity [139]. Some ways in which robotics and automation are used in CNC machining quality inspection are given below:
- Automated measurement systems: Robots are often integrated with automated measurement systems to perform precise and accurate measurements of machined parts. These systems use advanced sensors, such as laser scanners or CMMs, to capture dimensional data. The robots can move the sensors along programmed paths to inspect critical features of the machined parts [140].
- Vision systems: Vision systems, including cameras and image-processing algorithms, are commonly employed in CNC machining quality inspection. Robots equipped with vision systems can capture images of machined parts and analyse them to detect defects, surface-finish irregularities, or dimensional deviations. They can compare the captured images with reference models to ensure that the parts meet the required specifications [141].
- Automated sorting and packaging: Once parts are inspected and meet the quality criteria, automated systems can be employed for sorting and packaging, reducing the risk of human error and ensuring consistency [142].

- In-process monitoring: Robotics and automation enable real-time monitoring of CNC machining operations. Sensors and probes can be integrated into the machining process to collect data on parameters like tool wear, cutting forces, temperature, and vibration. These data are then analysed by automated systems to detect anomalies and ensure that the machining process is within the desired parameters, ultimately enhancing the quality of the machined parts [143].
- Non-destructive testing (NDT): Robotic systems can be used to perform NDT on machined parts. For example, automated ultrasonic or eddy current testing systems can be employed to inspect the integrity of critical components. The robots can position the testing equipment precisely and perform scans according to pre-defined paths, allowing for efficient and reliable quality inspections [144].
- Defect identification and sorting: Robots equipped with machine vision and robotic arms can identify defective parts and sort them accordingly. Once defects are detected during the quality-inspection process, the robots can remove or separate the faulty parts from the production line, ensuring that only high-quality components are delivered [145].
- Data analysis and feedback loop: Automation systems can collect and analyse vast amounts of data generated during CNC machining operations. By using machine-learning algorithms, patterns and trends can be identified, enabling predictive maintenance, process optimisation, and continuous improvement in quality inspection [146].
- Statistical process control: Automation can be applied to implement statistical process-control methods, monitoring key process parameters and ensuring that the machining process operates within specified tolerances.

Probing tool of robotic arms for the quality control is shown in Fig. 8 [147].

Overall, the integration of robotics and automation in CNC machining quality inspection brings several benefits, including increased accuracy, efficiency, and reliability. These technologies allow for faster inspections, reduced human error, and enhanced process control, ultimately leading to improved product quality and higher customer satisfaction. It is important to carefully design and integrate these automation solutions based on the specific requirements of the CNC machining operations and the desired quality standards.

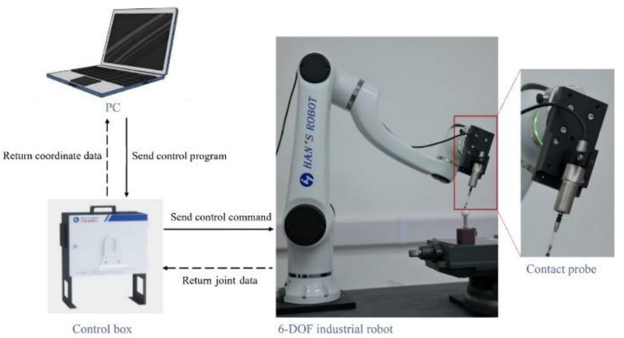

Fig. 8. Probing tool of robotic arms for quality control [147]

8. DATA MONITORING AND ANALYSIS

Robotics and automation have significantly transformed the CNC machining industry by enabling enhanced data monitoring and analysis capabilities. These advancements have resulted in improved productivity, accuracy, and efficiency in machining operations [148]. Automation systems can collect real-time data from CNC machines, such as cutting parameters, machine performance, and tool wear. These data can be analysed to optimise processes, predict maintenance requirements, and improve overall efficiency [149]. Continuous improvement based on data-driven insights is key to achieving higher levels of efficiency and productivity. How robotics and automation have impacted data monitoring and analysis in CNC machining is given below:

- Real-time data collection: Automated systems integrated with CNC machines can collect real-time data during machining operations. These data include information such as cutting speeds, tool wear, temperatures, vibrations, and other relevant parameters. Robots and sensors can be used to capture these data accurately and consistently [150].
- Data integration and connectivity: Automation allows for seamless integration and connectivity between CNC machines and data-monitoring systems. The collected data can be transmitted to centralised databases or cloud platforms for storage and analysis. This connectivity enables real-time monitoring, remote access, and analysis of machining data from anywhere, facilitating timely decision-making [16].
- Condition monitoring and predictive maintenance: By analysing the collected data, advanced algorithms and machine-learning techniques can identify patterns and anomalies related to the machine condition. This enables predictive maintenance, where potential issues can be detected early and maintenance actions can be scheduled proactively. Also, remote monitoring and control of CNC machines can be implemented using data monitoring and analysis. Machine-learning algorithms can be used to predict tool wear, optimise cutting parameters, and improve overall machining efficiency. This approach minimises unplanned downtime and optimises machine availability [148].
- Performance optimisation: Data monitoring and analysis can help identify inefficiencies in machining processes. By examining the collected data, manufacturers can analyse factors such as tool paths, cutting parameters, and material characteristics to optimise machining performance. This leads to improved cycle times, reduced scrap rates, and enhanced overall productivity [151].
- Quality control and process improvement: Data analysis enables manufacturers to monitor and control product quality in real time. By comparing machining data with pre-defined quality parameters, any deviations or defects can be quickly identified, allowing for immediate corrective actions. Continuous data analysis also provides insights for process improvement, enabling manufacturers to refine their machining strategies and achieve higher quality standards [152].
- Data-driven decision-making: The availability of accurate and timely data empowers manufacturers to make informed decisions. Through data analysis, manufacturers can identify bottlenecks, optimise workflows, allocate resources effectively, and identify opportunities for cost reduction and process optimisation. This data-driven decision-making approach enhances overall operational efficiency [153].
- Traceability and compliance: Automated data monitoring and analysis provide a comprehensive record of machining operations, including the parameters used, measurements taken, and quality checks performed. This traceability is valuable for regulatory compliance, quality audits, and product validation [154].

DOI 10.2478/ama-2024-0048

Applications of digital twin and big data analysis in cloud-based manufacturing systems are shown in Fig. 9 [155].

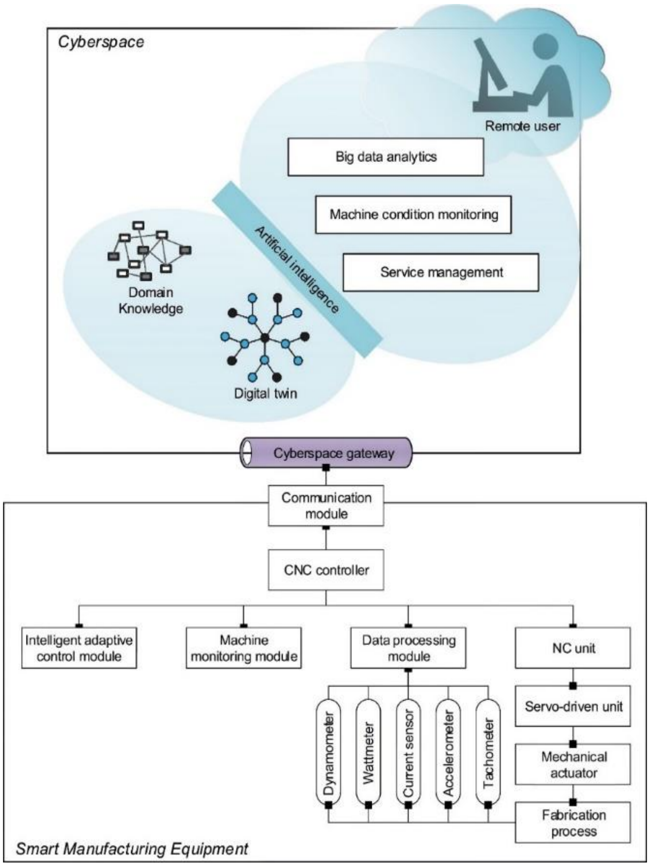

Fig. 9. Applications of digital twin and big data analysis in cloud-based manufacturing systems [155]

In summary, robotics and automation have revolutionised data monitoring and analysis in CNC machining operations [156]. Real-time data collection, connectivity, predictive maintenance, performance optimisation, quality control, data-driven decision-making, and traceability are some of the significant benefits offered by these advancements. The obtained data from CNC machines can be integrated with manufacturing execution systems to provide a comprehensive view of the entire manufacturing process. As a result, these capabilities lead to improved productivity, enhanced quality, and increased efficiency in CNC machining processes [14]. However, implementing a comprehensive data monitoring and analysis system for automation in CNC machine tools requires a multi-disciplinary approach involving technology integration, data science, and a thorough understanding of the machining process.

9. COLLABORATIVE ROBOTICS

Robotics and automation have revolutionized CNC machining operations, making them more efficient, precise, and safe. Collaborative robotics, specifically, has played a significant role in enhancing the capabilities of CNC machines and improving human–robot interactions [157]. Collaborative robots, or cobots, can work alongside human operators in CNC machining operations. These robots are designed to be safe to work with and can assist in tasks such as part handling, deburring, or cleaning, thereby enhancing productivity and relieving workers from repetitive or hazardous tasks [158]. They are equipped with sensors and advanced control systems that allow them to detect and respond to the presence of humans, ensuring a safe working environment. This collaboration enables a more flexible and adaptive manufacturing process where humans and robots can work together on different tasks, with the robot handling repetitive or strenuous tasks, while humans focus on more complex and cognitive aspects [159]. This integration leads to improved efficiency, reduced costs, and a safer and more collaborative working environment [160]. Some key aspects of robotics and automation in CNC machining operations, with a focus on collaborative robotics, are given below:

- Automated material handling: Collaborative robots (cobots) are used to automate material-handling tasks in CNC machining operations. They can pick up raw materials, place them in the machine, and remove finished parts. Cobots are equipped with sensors and vision systems that allow them to detect and grasp objects safely, enabling efficient material handling without the need for physical barriers or safety cages [160].
- Machine tending: Cobots are commonly employed for machine-tending tasks in CNC machining. They can load and unload workpieces, set up the machine, and initiate the machining process. Cobots work alongside human operators, taking over repetitive and physically demanding tasks, while humans focus on more complex operations, such as programming and quality control [161].
- Safety features: Traditional industrial robots are often separated from human workers by physical barriers for safety reasons. Collaborative robots are designed with safety features that enable safe interaction with human workers. They are equipped with force-sensing technologies that allow them to detect human presence and apply force accordingly [162]. This ensures that if a human comes into contact with the robot, it will stop or slow down to prevent injuries. Additionally, cobots have rounded edges and lightweight construction to minimise the risk of harm during accidental collisions [163].
- Programming and flexibility: Collaborative robots in CNC machining operations are programmed using intuitive interfaces. This simplifies the programming process, making it accessible to non-experts. Operators can teach cobots tasks by physically guiding their movements or by using graphical programming interfaces. This flexibility allows quick reprogramming and reconfiguration of the robot for different tasks, making them highly adaptable to changing production requirements [164].
- Enhanced precision and quality: Robotics and automation improve the precision and quality of CNC machining operations. Collaborative robots can perform tasks with high repeatability, ensuring consistent results. They can execute complex movements and follow precise paths, resulting in improved machining accuracy and reduced errors. Additionally, cobots can integrate with measurement systems to perform in-process inspections, enhancing quality control throughout the machining process [165].
- Easy integration: Cobots are designed to be easily integrated into existing workflows and systems. They can be programmed to work in tandem with CNC machine tools, handling tasks such as material loading and unloading, tool changes, and part inspection.

- Increased productivity: By automating repetitive and time-consuming tasks, collaborative robots increase productivity in CNC machining operations. Cobots can work around the clock, reducing machine idle time and maximising production efficiency. They can perform tasks with high speed and accuracy, resulting in shorter cycle times and increased output [166].
- Human–machine collaboration: Cobots allow for a closer collaboration between human workers and machines. While the cobot takes care of routine and physically demanding tasks, human workers can focus on more complex activities that require decision-making, problem-solving, and creativity.
- Maintenance and diagnostics: Collaborative robots can be programmed to perform routine maintenance tasks on CNC machines, such as cleaning, lubricating, or even diagnosing simple issues. This proactive maintenance approach helps prevent unplanned downtime and ensures the longevity of CNC machine tools [167].
- Adaptive machining: Cobots can be integrated into the CNC machining processes to adapt to changes in the production environment. They can dynamically adjust their movements and tasks based on real-time feedback, improving overall system flexibility [168].
- Workforce augmentation: Collaborative robotics in CNC machining operations do not replace human workers but rather augment their capabilities. By taking over mundane and physically demanding tasks, cobots free up human operators to focus on higher-level activities that require creativity, problem-solving, and decision-making. This leads to a more skilled and engaged workforce [169].

Conceptual design of a collaborative robot for drilling modelled after human operation is shown in Fig. 10 [170].

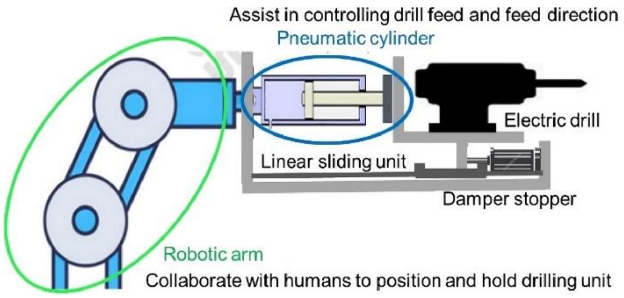

Fig. 10. Conceptual design of collaborative robot for drilling modelled after human operation [170]

In summary, collaborative robotics has transformed CNC machining operations by automating material handling, machine tending, and other tasks. Collaborative robotics enhances automation in CNC machine tools by combining the precision of CNC machining with the flexibility and adaptability of robots. This integration leads to improved efficiency, reduced costs, and a safer and more collaborative working environment [171].

10. PRODUCTION LINE INTEGRATION USING ROBOTICS AND AUTOMATION

Robotics and automation play a crucial role in CNC machining operations and production line integration. They offer numerous benefits such as increased productivity, improved precision, enhanced safety, and reduced labour costs [172]. Automation systems enable the integration of multiple CNC machines into a cohesive production line [173]. Robots can transport workpieces between different machining stations, optimising the workflow and minimising idle time [174, 175]. Automated systems can also communicate with other manufacturing systems, such as enterprise resource planning (ERP) software, for seamless production management. Some key aspects of robotics and automation in CNC machining are given below:

- Robotic material handling: Robots can be employed for the automated loading and unloading of raw materials and finished parts in CNC machines. They can handle heavy loads, operate in a precise and repeatable manner, and eliminate the need for manual intervention [176].
- Machine tending: Robots can be utilised for the continuous operation and supervision of CNC machines. They can perform tasks like tool changes, part measurement, and coolant application. This minimises downtime and maximises machine utilisation [177].
- Palletized automation: Palletized automation systems involve the use of robots to move workpieces between different CNC machines, inspection stations, and other manufacturing processes. This allows for seamless integration and optimisation of the entire production line [178].
- Vision systems: Vision-guided robotics enable robots to locate workpieces, align them accurately, and perform tasks with high precision. They use cameras and advanced algorithms to analyse the environment, ensuring precise positioning and improved quality control [179].
- In-process inspection: Automated inspection systems can be integrated into CNC machining operations, allowing robots to measure dimensions, check tolerances, and detect defects in real time. This reduces the need for manual inspection and improves quality control [180].
- Collaborative robots (cobots): Cobots are designed to work alongside human operators, enhancing productivity and safety in CNC machining operations. They can assist with tasks such as part loading, deburring, and quality inspection, while ensuring human–robot collaboration [181].
- Data analytics and integration: Robotics and automation systems generate vast amounts of data that can be leveraged for process optimisation. By integrating CNC machines and automation systems with data analytics tools, manufacturers can gain insights into machine performance, predictive maintenance, and production efficiency [180].
- Programming and simulation: Offline programming tools can be used to simulate and optimise the robot's movements before actual implementation. This can involve using a common programming language or developing a communication interface between the robot controller and the CNC machine [182].
- Flexibility and scalability: Robotic systems offer the advantage of flexibility and scalability. They can be easily reprogrammed to adapt to different parts, product variations, and production volumes. This allows manufacturers to respond quickly to changing market demands [183].

The structure of a modern smart manufacturing factory using robotics and automation is shown in Fig. 11 [180].

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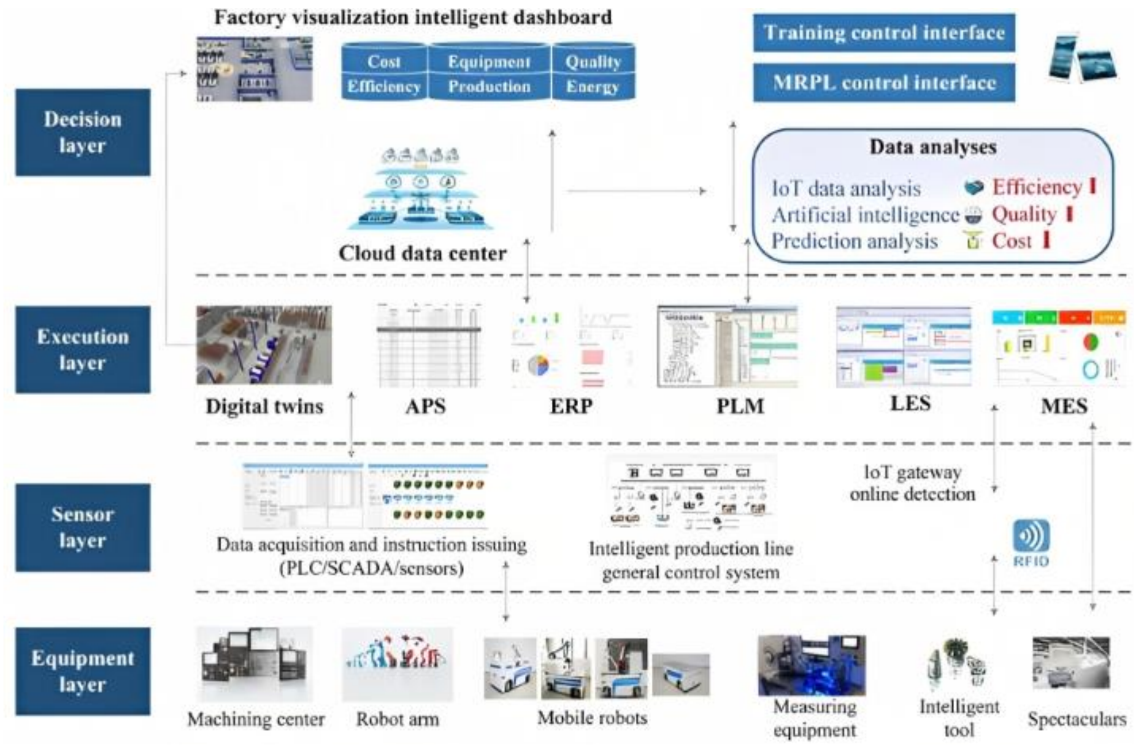

Fig. 11. Structure of a modern smart manufacturing factory using robotics and automation [180]

Overall, the integration of robotics and automation in CNC machining operations and production lines leads to increased efficiency, improved quality, reduced cycle times, and enhanced competitiveness in the manufacturing industry [184]. However, it is crucial to carefully plan and integrate these systems to ensure a smooth and efficient operation in terms of productivity enhancement of CNC machining operations.

11. CONCLUSION

Robotics and automation play a significant role in CNC machining operations, revolutionising the manufacturing industry. The use of robotics and automation in CNC machining operations brings greater efficiency, accuracy, and productivity while reducing costs, human error, and downtime. It enables manufacturers to meet increasing demands, improve quality control, and stay competitive in the industry. Robots are used to load and unload workpieces from CNC machines. They can handle heavy and bulky materials with precision, reducing the need for manual labour and increasing efficiency. Robotic machine tending allows for continuous operation, as robots can work 24/7 without fatigue. CNC machines often require different tools for various machining operations. Automation systems, such as tool changers, enable the machine to automatically switch between tools based on the programmed instructions. This eliminates the need for manual tool changes, saving time and reducing human error. Robots equipped with sensors and vision systems can perform accurate measurements and inspections of machined parts. They can compare the dimensions of the workpiece against the CAD model or predefined specifications, ensuring the quality and consistency of the output. Robots can be programmed to automatically change tools based on the machining requirements. This eliminates the need for manual intervention and reduces downtime during tool changes.

Automation systems integrated with CNC machines can adapt the machining process in real time based on feedback from sensors and monitoring systems. This allows for adjustments to compensate for tool wear, material variations, or environmental factors, resulting in improved precision and reduced scrap. Cobots are designed to work alongside human operators in CNC machining operations. They can assist in tasks such as part loading, deburring, or finishing, enhancing productivity and safety. Cobots have built-in safety features, such as force sensing and collision detection, allowing them to operate in close proximity to humans. Automation in CNC machining operations enables the collection of vast amounts of data, including process parameters, tool wear, and machine performance. These data can be analysed using advanced analytics techniques to identify trends, optimise processes, and predict maintenance requirements, leading to improved efficiency and reduced downtime.

The integration of several CNC machines into an integrated production line is made possible by automation systems. By moving objects between several machining stations, robots may streamline the operation and save downtime. Additionally, automated systems can interface with other manufacturing systems, such as ERP software, to provide smooth production management. Automation in CNC machining allows for the collection of vast amounts of data related to machining parameters, tool performance, and production metrics. These data can be analysed using artificial intelligence and machine-learning algorithms to identify patterns, optimise processes, and improve overall efficiency.

Future research in robotics and automation in CNC machining operations is likely to focus on several key areas. Here are some potential avenues of investigation:

– Advanced machine learning and AI algorithms: Researchers can explore the application of advanced machine learning and artificial intelligence algorithms to improve CNC machining operations. This includes developing algorithms for predictive maintenance, tool wear prediction, optimising machining parameters, and adaptive control systems.

- Collaborative robotics (cobots): Cobots are designed to work alongside human operators, enhancing their capabilities and improving safety. Future research can investigate the development of more sophisticated cobots that can perform intricate tasks in CNC machining operations while maintaining safe and efficient collaboration with human workers.
- Intelligent process monitoring and control: Research can focus on developing intelligent monitoring and control systems that can analyse real-time data from CNC machines, sensors, and other sources to make informed decisions. This can involve the integration of machine-learning algorithms to detect anomalies, optimise cutting parameters, and ensure consistent product quality.
- Multi-axis machining and complex geometry: As the demand for intricate and complex parts increases, future research can explore advancements in multi-axis machining. This includes developing algorithms and strategies for efficient machining of complex geometries, such as freeform surfaces and non-uniform rational basis splines (NURBS).
- Automated tool path planning: Optimising tool paths is crucial for efficient machining. Future research can focus on automated tool path planning algorithms that minimise cycle time, reduce tool wear, and optimise chip evacuation. This may involve considering factors like material properties, machine dynamics, and geometric constraints.
- Human–machine interfaces (HMIs): User interfaces play a critical role in CNC machining operations. Future research can investigate intuitive and user-friendly HMIs that enable operators to interact with machines more effectively. This includes exploring the use of augmented reality (AR) and virtual reality (VR) technologies to enhance training, programming, and monitoring processes.
- Integration of IoT and Industry 4.0 technologies: The integration of the IoT and Industry 4.0 technologies can enable real-time data collection, analysis, and remote monitoring of CNC machines. Future research can focus on developing scalable and secure architectures to enable seamless connectivity and data exchange between machines, sensors, and other systems.
- Sustainability and energy efficiency: As sustainability becomes increasingly important, future research can explore ways to make CNC machining operations more environmentally friendly. This includes investigating energy-efficient machining strategies, optimising material usage, and minimising waste generation through advanced process monitoring and control.
- Energy efficiency and sustainability: With growing concerns about energy consumption and environmental impact, future research can focus on developing energy-efficient machining strategies and optimising the use of resources in CNC operations. This can involve investigating novel machining techniques, tool materials, or cooling strategies to minimise energy consumption and reduce waste.
- Cybersecurity and safety: As CNC machines become more connected and integrated into manufacturing networks, ensuring cybersecurity and safety becomes crucial. Future research can concentrate on developing robust cybersecurity measures to protect CNC machines from potential threats and implementing safety protocols to prevent accidents or unauthorised access.
- Machine learning for defect detection: Applying machine-learning techniques to detect defects or anomalies in machined parts can help improve quality control. Future research can focus on developing algorithms that can automatically analyse sensor data, such as vibration, temperature, or acoustic signals, to detect and classify defects in real time.
- Adaptive control systems: Research can be directed towards the development of adaptive control systems that can dynamically adjust machining parameters based on real-time feedback. These systems can optimise cutting parameters, tool wear compensation, and feed-rate control, leading to improved machining accuracy and reduced production time.
- Sensor integration and data analytics: Exploring advanced sensing technologies and integrating them into CNC machining processes can provide valuable data for optimisation. Future research can investigate the integration of various sensors, such as force/torque sensors, vision systems, and 3D scanners, and utilise data analytics techniques to extract valuable insights for process improvement.
- Intelligent process planning: Research can be conducted to develop intelligent algorithms that can optimise the process-planning phase in CNC machining. These algorithms can consider various factors such as tool selection, toolpath optimisation, and fixture design, aiming to improve the efficiency, accuracy, and cost-effectiveness.
- HMIs: Enhancing the interaction between humans and CNC machines can lead to improved productivity and ease of use. Future research can explore the development of intuitive user interfaces, AR or VR systems, and haptic feedback to facilitate efficient programming, monitoring, and control of CNC machines.

These research areas have the potential to drive significant advancements in robotics and automation in CNC machining operations, improving productivity, flexibility, and overall manufacturing efficiency.

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