Concept of the reconfigurable CNC machine with distributed control

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Abstract. The emergence of Industry 4.0 has changed manufacturing by integrating advanced digital technologies, enabling extensive real-time interconnection between information technologies (IT) and operational technologies (OT) within Industrial Control Systems (ICS). This ubiquitous information exchange enables manufacturing systems to operate flexibly and respond quickly to changing market demands and a growing diversity of products. The reconfiguration of manufacturing systems, both physical and functional, is driven by the Industrial Internet of Things (IIoT), which leverages Cyber-Physical Systems (CPS) as its core enabling technology. This transition initiates a shift from centralized control systems, where a single central unit manages all control tasks, to a distributed control system architecture. Within a distributed control system, the main control task is achieved through the intensive cooperation of smart devices, such as sensors and actuators, equipped with computation and communication modules. In this work, we present a concept of a Computerized Numerical Control (CNC) system with distributed control, based on the cooperation of Low-Level Controllers (LLC), which execute local tasks while receiving primary control commands from a High-Level Controller (HLC). The proposed approach considers both functional and physical properties to ensure system reconfigurability and scalability.

Keywords: Industry 4.0, Cyber-Physical Systems, Industrial Internet of Things, Computerized Numerical Control, Motion Control.

1 Introduction

The advent of Industry 4.0 has transformed manufacturing through introducing advanced digital technologies and enabling effective integration of information technologies (IT) with operational technologies (OT) in Industrial Control Systems (ICS) [1]. OT traditionally comprised hardware and software dedicated to the control of shop floor operations, but these systems were often isolated and not part of a broader networked infrastructure. With the IT and OT convergence, OT components can interact efficiently with each other, as well as with centralized servers via an IT network, enabling efficient information exchange [2]. This integration introduces a widespread connection between system elements and new levels of automation, empowering manufacturing systems to adapt quickly to dynamic market demands and increasing product diversity. The Industrial Internet of Things (IIoT) based on Cyber-Physical Systems (CPS) enhances the interconnected framework by enabling the efficient reconfiguration of manufacturing systems, both functional and physical [3, 4].

The deployment of CPS based technologies and the use of smart devices (i.e. sensors and actuators) play a crucial role in enabling real-time information exchange, which is critical for the functional reconfiguration of manufacturing systems. CPS provide an integrated framework that enables manufacturing processes to be easily tailored to operational changes or production demands [5].

The physical reconfiguration also highlights the crucial role of CPS. In particular, physical reconfiguration requires modular equipment that can be efficiently integrated at both the mechanical and control subsystem levels [6]. Systems designed with CPS principles specifically meet these requirements, as each mechanical module (linear axis, pneumatic cylinder, etc.) is equipped with a dedicated local controller (LC) [7]. This integration transforms mechanical components into smart devices, with embedded computational and communication capabilities.

1.1 Centralized and distributed CNC architectures

This study focuses on Computerized Numerical Control (CNC) systems as the core of advanced manufacturing technology. CNC systems have traditionally relied on a centralized control architecture, with the Numerical Control (NC) controller serving as the main control unit. In a centralized control architecture, the high-level controller (HLC) is responsible for all primary control functions, including trajectory planning, interpolation, and error compensation. This monolithic design simplifies initial implementation but faces significant limitations as manufacturing demands rise. In particular, it can lead to bottlenecks in computation, especially as the number of axes or complexity of tasks increases. Reconfiguration, in this case, can be time-consuming and labor-intensive, requiring extensive rewiring and adjustments of low-level control parameters. Furthermore, any failure in the HLC can result in a complete system shutdown, which emphasizes the vulnerability of such designs [8].

On the other hand, distributed control architecture introduces a modular structure, where a part of the control task is allocated to the low-level controllers (LLC) responsible for the control of individual axes. HLC retains responsibility for high-level planning and coordination, whereas each LLC manages real-time tasks for its assigned axis, such as position and velocity control. LLCs communicate with the HLC and other modules over standardized comunication protocols, providing the framework necessary for the efficient integration of additional axes or subsystems. This modularity makes distributed systems inherently scalable and reconfigurable, which are important characteristics for advanced manufacturing applications that require high flexibility and the ability to adapt quickly to changing demands. The distribution of tasks between LLCs and HLC not only mitigates the computational burden on the HLC but also enhances system resilience by localizing potential failures [8].

1.2 State of the art of the distributed CNC architectures

The control of CNC systems, particularly motion control as a key element, has attracted significant research attention. The open CNC architecture presented in [9] consists of four control programs executed on different processing units, with interpolation, online axis coordination, feedrate control, and acceleration/deceleration (Acc/Dec) control performed before the LLC. A coordination strategy and decentralized control structure for distributed interpolation using autonomous agents are developed in [10], where each agent controls a linear axis and communicates via discrete data packets to ensure synchronized multi-axis movement. In the open architecture controller proposed in [11], the host PC is responsible for NC code interpretation, validation, and interpolation tasks, whereas decentralized microcontroller-based client nodes are used for position control and sensor monitoring. An architecture for embedded CNC systems is presented in [12], utilizing the PLCopen standard and Cloud Computing technology to enhance system performance. This approach aims to improve real-time motion control, extend system functions, and overcomes the incompatibility between intelligence requirements and limited hardware resources.

These studies employ an architecture in which task distribution is limited to position control at the LLC, whereas other motion control tasks are centrally executed on an HLC. Therefore, that way of distribution hinders system compatibility due to the significant user effort needed for reconfiguration.

In this paper, we present the concept of a CNC system with distributed control, taking into account its physical and functional reconfigurability. In the context of functional reconfigurability, we analyze two architectures based on whether Acc/Dec control performs before or after interpolation. In addition, we summarize different points of motion control task distribution from the perspectives of communication bandwidth and real-time requirements. In terms of physical reconfigurability, three different 3D configurations are analyzed.

The remainder of the paper is structured as follows. Section 2 focuses on functional reconfiguration, particularly on the distribution of motion control tasks. Physical reconfiguration with examples of 3D machine configurations is shown in Section 3. Finally, conclusions and future work guidelines are provided in Section 4.

2 Functional reconfiguration: Distribution of the motion control tasks

Control systems in machines designed for executing complex, programmable trajectories, such as industrial robots and machine tools, rely on motion control as a key element. A typical CNC machine control unit comprises the Human-Machine Interface (HMI), the Programmable Logic Controller (PLC), and the Numerical Control Kernel

(NCK) [13]. The HMI serves various purposes, including part program input, program transfer from other ICS elements like the Manufacturing Execution System (MES), program simulation, machine supervision during automatic operation, and manual machine control. The PLC handles machine functions that are not related to its trajectory, such as spindle activation, coolant control, tools magazine control, detection of errors, and alarm activation. The NCK, as the most important element, represents the core of the control unit responsible for machine motion control.

To enable machine reconfigurability, it is crucial to integrate modularity in the control software and hardware to correspond with the modularity already present in the mechanical subsystem. In machines with motion control, this can be realized through the introduction of (Fig. 1):

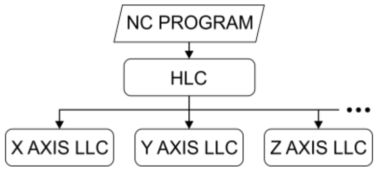

Fig. 1. Distribution of motion control tasks

- High-level Controller responsible for HMI and certain PLC and NCK functions, and
- Low-level controllers, dedicated to single axes, responsible for the control of specific NCK functions and PLC tasks (such as limit switches).

The structure of the NCK determines how its functions are distributed to HLC and LLC. In particular, the introduction of acceleration/deceleration into trajectory segments defines two main types of NCK (Fig. 2) [13]:

i. Acc/Dec Control After Interpolation (ADCAI),
ii. Acc/Dec Control Before Interpolation (ADCBI).

ADCAI based NCK is organized into a series of software modules. The process starts with the interpreter module, which parses the part program and converts it into an internal format suitable for further processing. This step includes the calculation of trajectory segments (start/end points, radius, arc centers, etc.) considering local coordinate systems and workpiece, tool compensation, and other part program elements [13]. Once interpreted, the data are transferred to the rough interpolator, which calculates the incremental reference positions for each axis. These positions ensure the axes move synchronously and achieve the commanded machine trajectory. After the rough interpolation stage, the data is processed by the Acc/Dec module, which regulates the motion of each axis separately, providing a gradual velocity transition through profiles such as trapezoidal or S-curve. The subsequent module performs fine interpolation to align the sampling interval of the rough interpolator with the higher rate sampling interval of the position control loop. The resulting incremental reference positions are passed to the position controller for execution.

On the other hand, in ADCBI, the order of operations differs, with Acc/Dec control applied to the full trajectory segment prior to rough interpolation, in contrast to

ADCAI, where it is applied separately to each axis segment. In addition, a look-ahead module is placed before the Acc/Dec control to mitigate potential slowdowns between subsequent sections. By inspecting the interpreted command several segments ahead, this module calculates suitable speeds at the segment start and end points, depending on their length, to ensure the commanded feedrate is maintained. The fine interpolator and position controller are applied after the rough interpolator.

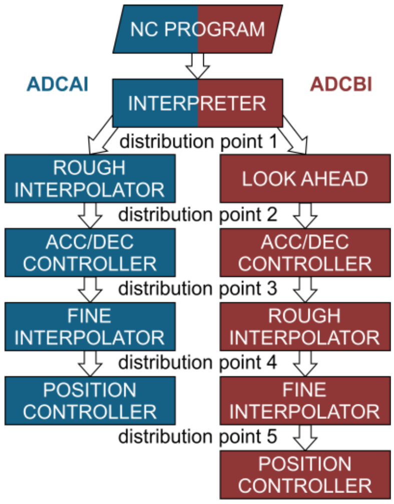

Fig. 2. The architecture of NCK and possible distribution points: ADCAI and ADCBI

Regardless of the position of the Acc/Dec control, the NCK maintains a modular structure. The modules up to the rough interpolator carry out functions related to the whole machine, whereas the subsequent modules perform assigned functions on each axis individually. This structure shows that the optimal points for distributing control tasks between the HLC and LLC are located among the subsequent software modules (Fig. 2).

A comprehensive analysis of communication bandwidth and real-time requirements identified distribution point 2 for ADCAI and distribution point 4 for ADCBI as most suitable (Fig. 2) [14]. Positioned right after the rough interpolator, these points define the shift from control tasks related to the entire machine to those dedicated to individual axes. Therefore, the data corresponding to incremental positions for each interpolation period are communicated between modules at these points.

In conventional setups, NCK modules, including the position controller, were integrated within one control unit that transfers data to servo drivers for velocity control. Current servo drivers are capable of closing the position loop as well. As a result, NCK transitions from a centralized to a distributed architecture with distribution points 4 (for ADCAI) and 5 (for ADCBI) [15]. Therefore, in the industrial sector, networked motion control systems are increasingly being implemented. These systems consist of: motion controller, servo drivers, Real-time Ethernet (RTE), and I/O modules [16].

3 Physical reconfiguration

To achieve the required reconfigurability, it is crucial for hardware design to align with the adaptive nature of software, ensuring their mutual compatibility and optimal functionality. This means the physical design should effectively adapt to configuration changes to meet the dynamic features of the functional design. The reconfigurability of both components enables the system to achieve higher modularity and scalability levels, making it better suited for complex and dynamic environments. During the design phase of a CNC machine, various 3D configurations can be explored to develop a system that is both versatile and precisely tailored to the required machining tasks. This approach improves the flexibility of the CNC machine while optimizing its performance to meet the demands of complex and dynamic manufacturing processes.

3.1 Mechanical configuration

We considered three distinct configurations (Fig. 3), highlighting their characteristics, advantages, and limitations. This analysis provides a framework for understanding their applicability in diverse machining environments and supports the decision-making process for machine design.

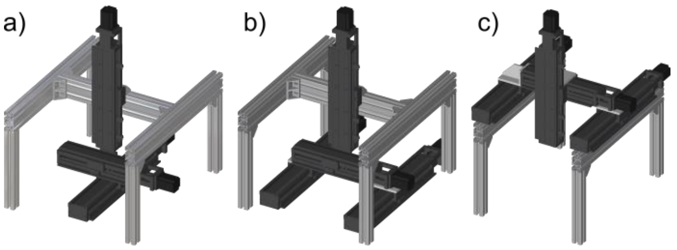

Fig. 3. Considered 3D configurations: a) cantilever beam; b) simply-supported beam; c) gantry style.

The cantilever beam configuration (Fig. 3a) is characterized by the Y axis being fixed at one end, leaving the other end free to move. This design offers a significant advantage in terms of workspace accessibility, as the absence of obstructions on one side allows for easy handling of workpieces and provides an open environment for manual adjustments or inspections. It is particularly effective for tasks that do not require high structural rigidity, making it suitable for lightweight applications.

The simply-supported beam configuration (Fig. 3b) features the Y axis supported at both ends, creating a more balanced and stable system than the cantilever design. In this setup, the Y axis is supported by two parallel X axes mounted on either side of the base frame, improving load distribution.

The gantry-style configuration (Fig. 3c) characterizes the most robust design, with the Z axis carrier supported on both sides to maximize stability. It is suitable for applications involving heavier loads or requiring greater forces, as its symmetrical structure reduces vibrations. However, despite similar weight to the simply-supported beam configuration, its design introduces greater complexity, leading to higher material and manufacturing costs. In addition, this configuration requires more installation space, which may limit its feasibility in compact setups.

In the proposed machine concept, the cantilever beam configuration is chosen for its ability to operate with only three axes, unlike the other two designs that require four axis elements. This configuration not only optimizes the hardware structure but also reduces material and manufacturing costs, contributing to a more cost-effective solution without compromising the system's performance. Regardless of the chosen configuration, the machine can be quickly reconfigured with minimal or no changes to the hardware components. This capability ensures a high level of flexibility, enabling the system to adapt effectively to varying operational requirements or changes in machining tasks without compromising efficiency or performance.

3.2 Control configuration

Further development of this research implies the implementation of the proposed concepts and the creation of a CNC system. Some of the most important system components are listed below. The machine design includes HIWIN KK86 axes (pitch of the leadscrew is 10 mm) driven by NEMA 23 stepper motors and stepper motor drivers. The motor step size is 1.8º, whereas the motor drive has microstepping capabilities ranging from 1 (full step) to 128. The control loop is closed using a high-resolution, magnetically coded BALLUFF BML-S1F1 encoder with a 1 μm resolution. In accordance with the encoder resolution, 10 microsteps will be used on the motor drive, resulting in an axes Basic Length Unit (BLU) of 5 μm.

The HLC is built on the Jetson Xavier NX embedded platform, running a Linux-based environment. It is powered by a 6-core NVIDIA Carmel ARM 64-bit CPU and a 384-core NVIDIA Volta GPU, offering high-performance processing. On the other hand, LLCs are based on low-cost NXP FRDM-K64F microcontrollers with an Arm Cortex-M4F core. The platforms chosen for the HLC and LLC have the computational capabilities to perform all tasks effectively, regardless of the NCK architecture and distribution point (Fig. 2). Communication between the HLC and LLCs is carried out via the IEEE 802.3 Ethernet protocol.

4 Conclusion

In this work, we explored the design of a flexible CNC system, considering both its physical and functional reconfigurability. The study addressed two key NCK architectures, based on the position of Acc/Dec control, whether it is carried out before (ADCBI) or after (ADCAI) interpolation. Furthermore, different NCK distribution points were examined in terms of communication bandwidth and real-time requirements. From a physical reconfigurability perspective, three distinct 3D configurations were considered, and their advantages and limitations were analyzed.

Future research will focus on developing a distributed CNC system using low-cost microcontrollers, designed to meet the criteria of physical and functional reconfigurability. We will evaluate the performance of our system in terms of positioning accuracy and compare it to systems with a centralized architecture.

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References

1. Kagermann, H., Wahlster, W., Helbig, J.: Recommendations for implementing the strategic initiative INDUSTRIE 4.0. Acatech, Berlin (2013).
2. Pivoto, D.G., De Almeida, L.F., da Rosa Righi, R., Rodrigues, J.J., Lugli, A.B., Alberti, A.M.: Cyber-physical systems architectures for industrial internet of things applications in Industry 4.0: A literature review. Journal of manufacturing systems, 58, 176-192 (2021).
3. Koren, Y., Gu, X., Guo, W.: Reconfigurable manufacturing systems: Principles, design, and future trends. Frontiers of Mechanical Engineering, 13, 121–136 (2018).
4. Monostori, L., Kádár, B., Bauernhansl, T., Kondoh, S., Kumara, S., Reinhart, G., Sauer, O., Schuh, G., Sihn, W., Ueda, K.: Cyber-physical systems in manufacturing. Cirp Annals, 65(2), 621-641 (2016).
5. Dafflon, B., Moalla, N., Ouzrout, Y.: The challenges, approaches, and used techniques of CPS for manufacturing in Industry 4.0: a literature review. The International Journal of Advanced Manufacturing Technology, 113, 2395-2412 (2021).
6. Napoleone, A., Negri, E., Macchi, M., Pozzetti, A.: How the technologies underlying cyber-physical systems support the reconfigurability capability in manufacturing: a literature review. International Journal of Production Research, 61(9), 3122-3144 (2023).
7. Lesi, V., Jakovljevic, Z., Pajic, M.: Towards plug-n-play numerical control for reconfigurable manufacturing systems. In IEEE 21st International Conference on Emerging Technologies and Factory Automation (ETFA), pp. 1-8. IEEE, Berlin, Germany (2016).
8. Morgan, J., Halton, M., Qiao, Y., Breslin, J.G.: Industry 4.0 smart reconfigurable manufacturing machines. Journal of Manufacturing Systems, 59, 481-506 (2021).
9. Correa, J.E., Toombs, N., Ferreira, P.M.: A modular-architecture controller for CNC systems based on open-source electronics. J. Manuf. Syst., 44, 317-323 (2017).
10. Dripke, C., Schoebel, D., Verl, A.: Distributed Interpolation: Synchronization of motion-controlled axes with coordination vector and decentralized segment controllers. In 16th Int. Workshop Adv. Motion Control (AMC), pp. 141-146. IEEE, Kristiansand, Norway (2020).
11. Amra, A.Q., Padayachee, J., Bright, G.: An open architecture control system for reconfigurable numerically controlled machinery. Mach. Vis. Mechatron. Pract., 309-322 (2015).
12. Wang, H., Tang, X., Song, B., Wang, X.: A novel architecture of the embedded computer numerical control system based on PLCopen standard. Proc. Inst. Mech. Eng., Part B: Journal of Engineering Manufacture, 228(4), 595-605 (2014).
13. Suh, S.H., Kang, S.K., Chung, D.H., Stroud, I.: Theory and design of CNC systems. Springer Science & Business Media, Berlin/Heidelberg, Germany (2008).
14. Lesi, V., Jakovljevic, Z., Pajic, M.: Iot-enabled motion control: Architectural design challenges and solutions. IEEE Trans. on Industrial Informatics, 19(3), 2284-2294 (2023).
15. Erwinski, K., Paprocki, M., Grzesiak, L.M., Karwowski, K., Wawrzak, A.: Application of ethernet powerlink for communication in a linux rtai open cnc system. IEEE Transactions on Industrial Electronics, 60(2), 628-636 (2013).
16. Zhou, N., Li, D.: Cyber–physical codesign of field-level reconfigurations in networked motion controllers. IEEE/ASME Transactions on Mechatronics, 26(4), 2092-2103 (2021).