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ORIGINAL PAPER

Development of new integrated CNC system for ISO 6983 data interface model

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Abstract
CNC (Computer Numeric Control) has long been used in manufacturing. Hardware and software integration is part of the CNC system. Various integrations have been developed to address issues such as vendor dependency, affordability, adaptability, and sustainability. The Open Architecture Control (OAC) technology-based system was a big hit among them. This research created a new integrated CNC system based on OAC, virtual component, and microcontroller technologies. Machine motion control, simulator, monitoring, remote access, and report generation are all included in the system. It can work with a variety of firmware and is suitable for milling machines, 3D printers, and three-axis laser cutting. The system has been put to the test and has proven to be reliable. The paper's content discusses the system's development, working principle, experimental study, and future directions.

Keywords Open CNC · ISO 6983 · G code · Virtual component technology

1 Introduction

The word CNC refers to a computer-assisted control system. In the 1970s, the first Computer Numeric Control (CNC) machine was created, with computers replacing the previous Numeric Control (NC) systems (electronic hardware and punch cards). During the 1970s and 1980s, the need for a Flexible Manufacturing System (FMS) arose due to the enormous diversity of parts manufactured [1]. CNC machines play a crucial role in achieving a flexible environment for manufacturing systems. The FMS also spark the era of Computer-Aided Design (CAD) and Computer-Aided Manufacturing (CAM) integrated systems. The goal of an integrated CAD/CAM system was to close the gap between design and production. CAD/CAM produces an NC file based on a specialized language that converts task information from a drawing to a computer-controlled machine unit. Automatically Programmed Tool (APT) was the name given to that particular language at first. International Standard Organisation (ISO) later recognized APT as an international standard ISO 6983, technically known as RS-274D and popularly known as G M codes, in 1982. In GM code programming, the operator tells the computerized machine unit "how to make". The "how to make" defines the instructions of where, how and what path to move [2].

In order to meet client requirements, today's industries have a variety of CNC machines with various controllers and capabilities. However, commercial CNC systems have a closed structure that makes them unsuitable for modern manufacturing environments due to poor compatibility, complex internal structure, difficulty in upgrading, limited software and hardware concerns, vendor dependency, high upgrade, maintenance, and production costs [3,4]. The "open way" approach was developed to meet consumer demands for high speed, flexibility, adaptability, openness, and precision to address these challenges [5]. The term "open method" refers to a system's independence from the manufacturer's

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Table 1 Summary of Integrated OAC technology based systems

Developer	CNC	Platform
[8], 2003	Linux RT based dual PC machine motion control system for two axis	PLC and C
[4], 2006	Windows based dual PC three axis machine motion control system	PLC
[9], 2007	Windows based OMAC CNC system for three axis milling machine	PLC and C++
[10], 2007	DSP and FPGA based modified commercial controller for three axis control	CNC Software with Bresenham algorithm for Simulation
[11], 2008	OMAC and SERCANS based controller for five axis control	PLC
[12,13], 2009	OMAC and SERCANS based controller for five axis control with force monitoring	SERCANS and C++
[14], 2009	PC based machine motion control system for three axis	Visual Studio and C++
[7], 2009	Dual PC based machine motion control system for three axis with PCI8174, Ethernet, DSP and ASIC	C++ and MatLAB
[15], 2009	Linux RT based Mechatrolink II with modified commercial controller for four axis control	RT Linux with CNC Software
[16], 2010	Modified commercial controller with DRC, MPU, SIM, FPGA machine motion control system for two axis control	Petri net, GTK++ and C++
[17], 2010	µC/OS-II based modified TDNCM4 with ARM for three axis control	TDNCM40A
[18], 2010	Modified controller with DSP and FPGA for two axis control	CNC Software with Bresenham algorithm for Simulation
[5], 2012	PC based GT400SV for three axis motion control	C and PLC
[19], 2012	Linux based Red Hat Kinux system	C and MatLAB
[20], 2013	PC and Arduino Leaf Mapple based two axis motion control system	QT Framework HMI and CCC
[21], 2014	PC based RTX machine motion control for three axis	C
[22], 2014	PC and Arduino ATMEGA328 based three axis motion control system	UGS
[23], 2016	PC and Arduino ATMEGA328 based motion control system for three axis	Arduino IDE
[24], 2019	PC and Arduino based motion control system for three axis	UGS and Eagle CAD
[25], 2019	PC and Arduino based motion control system for three axis	Arduino IDE, CAMotics and GCTRL
[26], 2020	PC and Arduino ATMEGA328 based motion control system for three axis	UGS

specifications, allowing the end-user to purchase hardware and software from a variety of vendors and assemble them as needed [6]. Overall, Open Architecture Control (OAC) technology aims to create a neutral vendor control system interface and give specifications for interoperability, interaction, portability, and scalability [7]. Interoperability is the ability to use the same component to work with multiple systems. Interaction ensures that standard data semantics are communicated. Portability allows application software to be easily moved from one environment to another. Scalability specification describes the incremental and destructive capacities of a system in response to client needs [4]. There have been various CNC systems developed based on OAC technology; some are addressed in Table 1.

These developments utilized various software and hardware platforms to perform specific CNC operations. However, microcontrollers-based CNC systems are popular because of their low development cost and free JAVA-based operating software like UGS. This study has developed a new microcontroller-based CNC system with virtual component technology-based operating software. The novelty of this approach is the integration of microcontroller technologies with open architecture control and virtual component technology, which aims to enhance the openness and affordability of the CNC system. The system development will be discussed in the rest of the paper, along with a validation study.

2 System development

The system development has been carried out in two stages: software development and hardware configuration. The overall design of the system is shown in Fig. 1.

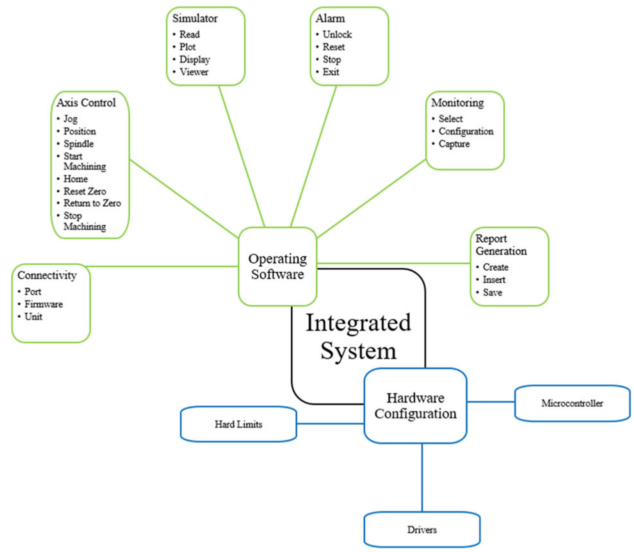

Fig. 1 System design

2.1 Software configuration

The software consists of many sub-components that include connectivity, axis control, simulator, alarm, monitoring, and report generation. Virtual component technology is used to create the overall software.

2.1.1 Connectivity

The connectivity component is in charge of establishing a USB connection between the computer and the microcontroller. This component can communicate with a variety of firmware, including grbl, mach 3, and marlin, among others. It consists of port, firmware, and unit modules, allowing users to select a connected USB port, microcontroller firmware, and working units.

2.1.2 Axis control

Jog, position, spindle, start machining, home, reset zero, return to zero, and stop machining modules make up the axis control component. The jog module is in charge of manually controlling the machine axis motors with a set of federate and step size. The machine is moved to specific coordinates by the position module. The spindle module is used to manually control the spindle of the machine. The complete G code part programmes are capable of being executed by the start machining module. The machine is moved to the home position by the home module. The reset zero module sets the machine's zero position, while the return to zero module restores the machine's zero position. The stop machining module is in charge of terminating the currently running G code part programme and returning the device to idle.

2.1.3 Simulator

Before real machining, the simulator component graphically verifies the G code part programme. It consists of four modules: read, plot, display, and viewer. The read module is in charge of reading the entire content of the input file and parsing the data for graphical simulation in the plot module. Zoom, capture, crop, draw, and other functions are available in the viewer modules.

2.1.4 Alarm

The alarm component is in charge of locking and unlocking the system in the event of an accident or an error. It contains the modules for unlocking, resetting, stopping, and exiting. The unlock and reset modules are in charge of unlocking the

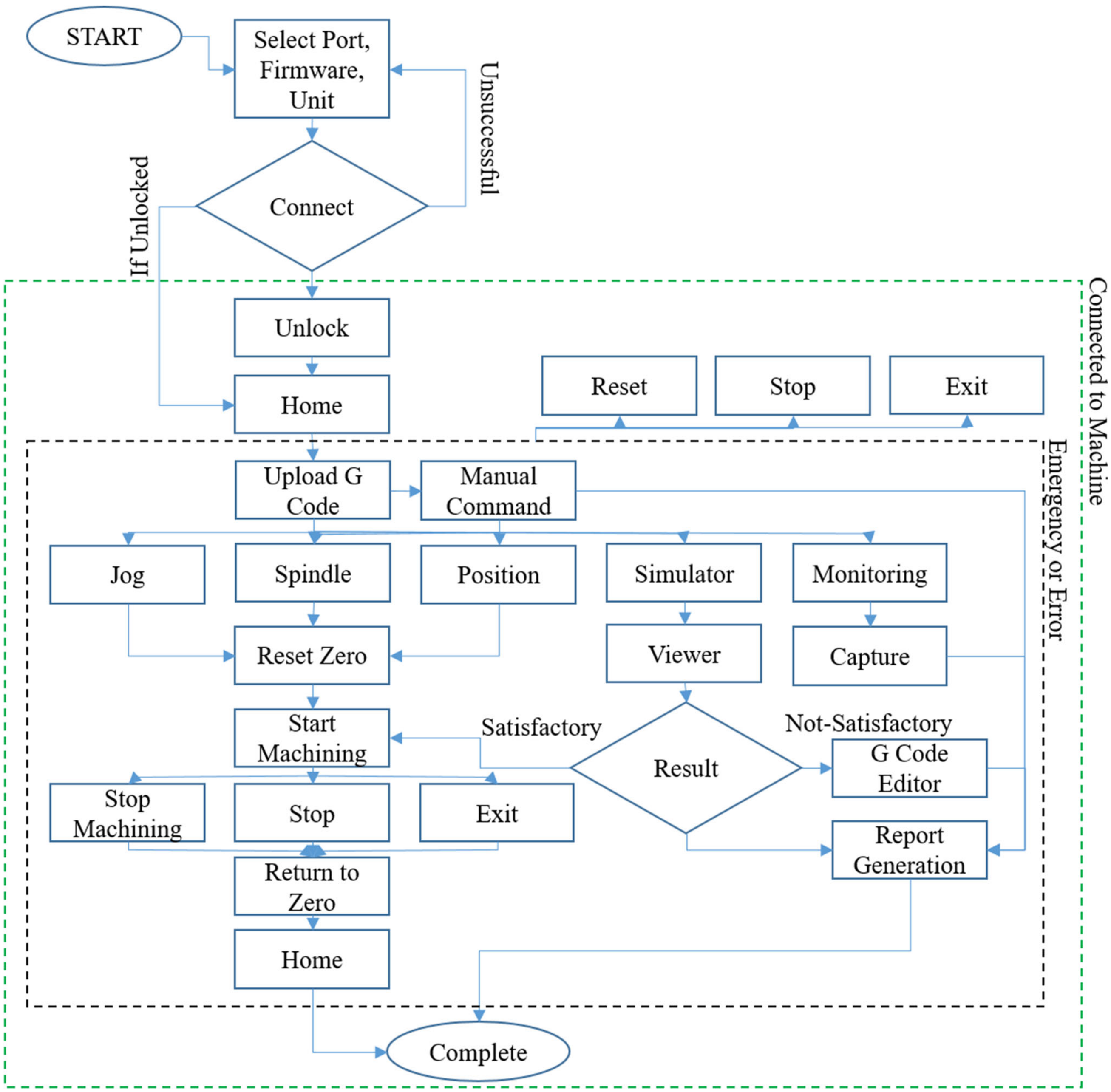

Fig. 2 System working mechanism

system in the event of a hard limit being exceeded, as well as any other mishaps or errors. Stop and exit modules, on the other hand, are used in the system for emergencies.

2.1.5 Monitoring

The monitoring component is in charge of showing live video of machining operations. It is divided into three modules: select, configuration, and capture. The select module looks for camera devices that have been installed in the system. Configuration options for camera resolution, colour settings, zooming, and drawing markings in live video are provided by the configuration module. The capture module connects the camera to the software and captures live video and images.

2.1.6 Report

The system's final module is the report generation component. This module's goal is to automatically generate and save a report of completed machining operations in the system memory. The CNC generates a soft document report with this module, reducing the use of paper and incorporat-

Fig. 3 Operating system GUI

ing a brief look at green manufacturing into the system. The module is made up of three parts: create, insert, and save. The create module is in charge of creating a blank Microsoft (MS) Word document. The data must be inserted into the generated MS Word file by the insert module. The save module is in charge of saving the generated file to the system memory in.docx and.pdf formats.

2.1.7 Operating algorithm

The software's working mechanism is depicted in Fig. 2. The connectivity component is used to establish a connection with the machine. When the connection is established, the machine hardware is unlocked and moved to the home position. It also enables the alarm component's reset, stop, and exit modules at the same time. The file upload and manual command modules were also turned on, allowing the commands to be sent to the machine controller. The jog, spindle, and position modules can now manually control the machine motion. These modules assist in moving the machine to the zero position, which is defined by the system's reset zero module. Along with them, the simulator and monitoring components are beginning to offer 3D simulation and real-time process monitoring. The 3D simulation aids in the verification of the input part programme prior to machining. The G code editor module can directly modify the part programme in the event of an error. The start machining module executes the input part programme after all of the settings and simulations have been completed successfully. Furthermore, the

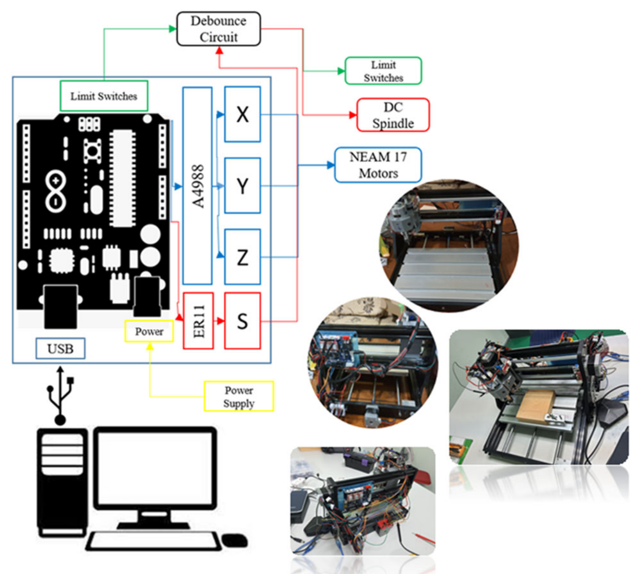

Fig. 4 Hardware configuration

machining process can be monitored from afar. The system will be controlled by reset, stop, and exit modules in the event of an error or emergency during part programme execution. The machine will be returned to its zero and home positions after the part programme is completed, completing the cycle.

2.1.8 Graphical user interface

The operating system's graphical user interface (GUI) is divided into two tabs: main and simulator, as shown in Fig. 3. The upload file, G code display and editor, manual command control, and command indicator are all located on the left side of the main tab. On the right side, you'll find the live monitoring, unlock, reset, stop, exit, start machining, stop machining, home position, reset zero, return to zero, and preview file control buttons. Connectivity, jog, position, and spindle control buttons are all located in the centre.

The upload file control button is used to upload the G code file into the system. The uploaded file is displayed as a table and can be edited for any changes before or during machining. The manual command button allows you to access the microcontroller's settings and run G code commands manually. The connect to machine button establishes a link between the machine and the operating software, as well as indicating whether the machine is connected or disconnected. The X+, X-,Y+,Y-,Z+,Z-, go to XY position, go to Z position, spindle dial, ON, and OFF buttons move the machine axis and spindle manually to the desired positions. The unlock and reset control buttons are used to soft reset the system after it has experienced an error or an alarm. The stop and exit control buttons, on the other hand, are used to disengage the system in an emergency. The live video, as well as zoom, capture, draw, and other options, are displayed in the square box. The machine status is indicated by the led above the live monitoring display, which includes idle, run, lock, and hard limit alarm. The G code part programme may be executed or aborted by using the start machining and stop G code control buttons. The reset zero control returns the machine to its original zero point. Returning to zero always resets the machine to its initial state. The home control button, on the other hand, will return the device to its original position. The graphical simulation platform will be used to simulate the input part programme when the preview file control button is pressed. Play, pause, step, rewind, forward, zoom, 360-degree view, stop, and g code editor are all included in the simulation platform.

2.2 Hardware configuration

A three-axis milling machine, NEMA 17 stepper motor, A4988 stepper motor driver, ER11 DC spindle motor and driver, microcontroller board, mechanical limit switches, USB cable, personal computer, and power supply are among the components of the prototype. The microcontroller is powered by a 2436V DC external power supply and is connected to the PC via a USB cable. The A4988 stepper motor drivers connect the three NEMA 17 stepper motors to the microcontroller pins. A microcontroller and debounce circuit are also connected to the ER11 DC spindle and six mechanical

Table 2 Openness evaluation criteria

Criteria	Support	Description
I/O interoperability	Most of the commercial I/O standards are supportable	Verified with the utilization of sensors and cameras
HMI customization	HMI can be customized with any standard programming language	Justified with virtual component technology-based GUI development
ISO programming standard	IEC-61131 (PLC) and RS-274 (CNC) standards	Verified with the case study components based on RS 274 CNC standard
Third-party integration	All commercial OS are supportable	Justified with the utilization of Windows-based applications and standard programming languages
Algorithm	Fully programmable with any standard programming language	Proofed with the development of a new operating algorithm
PC/PLC based control	Conventional PC with the third party control board, I/O and commercial OS is supportable	Justifed with the utilization of PC, micro-controllers, sensors, cameras, and operating software

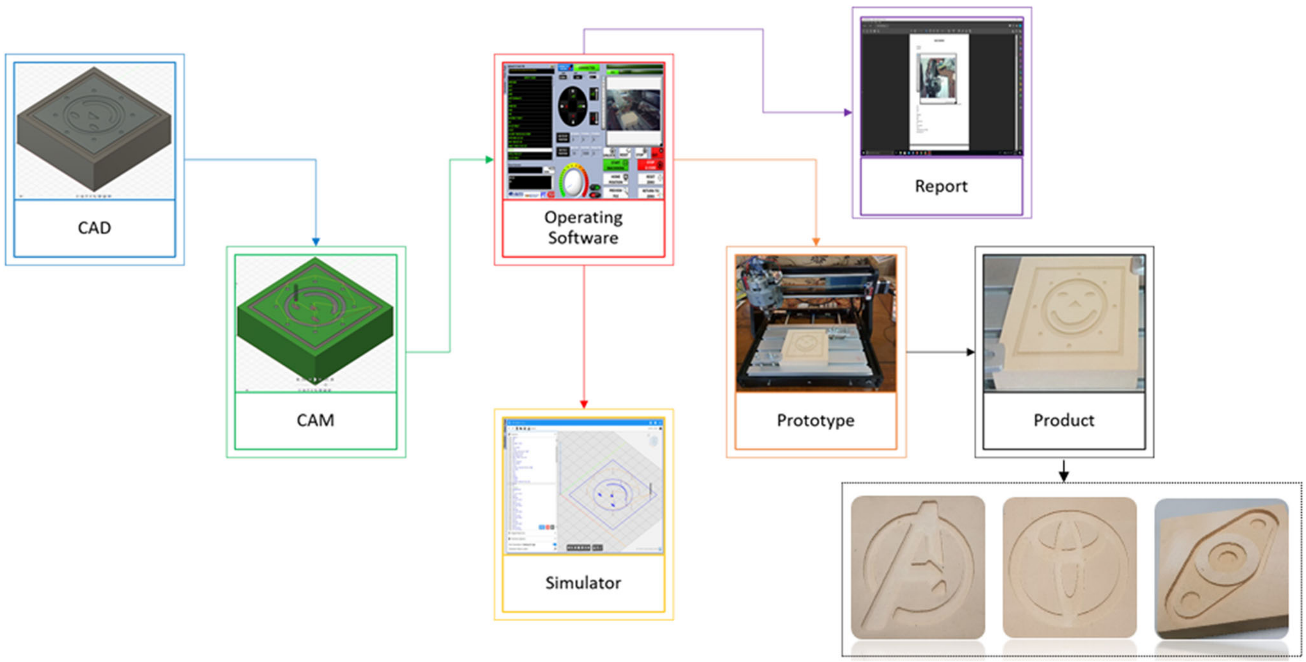

Fig. 5 Experimental Setup

limit switches, resulting in a clean output. Figure 4 shows a schematic diagram of the hardware configuration.

3 Validation study

The system has been validated based on the Open Architecture Control evaluation criteria mentioned in Table 2, verified through case studies. One of the case studies is presented in this section. The AutoDesk Fusion 360 was used to perform this study's CAD/CAM functions. The 3D part design is done in the design environment, whereas, RS-274 part program is generated in AutoDesk Fusion 360's manufacturing environment. To reduce machining time, the generated part programme was run through the [27] system. The generated part programme has been loaded into the operating software, which has been graphically verified with the help of a simulator. The machine zero position has been set up once the simulation results are satisfactory. The input part programme was then executed and monitored. During the RS-274 execution on the machine control unit, the criteria mentioned in Table 2 were observed. I/O interoperability and HMI has been observed by communication among the developed virtual component based systems, personal computer-based motion control system, and sensing hardware. The ISO standard (RS-274) execution and algorithm design were verified during the real machining execution. The successfully manufactured products shown in Fig. 5 proofs the seamless execution of ISO standards and algorithm within the system. The third-party integration has been verified with the report generation system, which communicates with MS Office and PDF software platforms. This system has generated the report in .doc and .pdf formats after the input code execution have been completed. The overall experimental setup depicted in Fig. 5 shows the complete execution process from design to manufacturing. The operating software, prototype, and report are the stages where the OAC criteria of the system were tested. The manufactured product precision and the communication among the entire hardware and software system are excellent.

4 Conclusion

CNC machines are critical components of manufacturing and are widely used in both large and small businesses. The CNC system must be open, adaptable, affordable, and long-lasting as technology advances. Openness and affordability have been addressed by open architecture control technology. There have been various PC and PLC-based CNC developments; PLC-based is more favorable for real-time response, whereas PC-based are not perfectly real-time but are affordable. Many PC-based controllers, known as open architecture controllers, only enable OS software technologies to be integrated into their control system. In such a scenario, the openness of systems is only an OS based, not the implementation of the OAC's concepts. Apart from that, many developers do not follow the standards of OAC, and cause interoperability problems. The industry hopes to get lower pricing, a better control system, and plug-and-play capabilities from the OAC technologies because the main issue in the sector is the lack of universal standards and the diversity of plant equipment. This makes PC-based solutions more popular, which can be easly to upgrade, customize, maintain, adapt, and affordable. Various systems have been developed on that; some of them are mentioned in the paper's content (Table 1). The majority of the systems were initially built by modifying commercial controllers; later, microcontrollers were used. Similarly, various platforms were used in the development of operating software. However, virtual component technology has not been fully utilized. As a result, this study developed a new integrated system based on OAC, micro-controllers and virtual component technology. The system can be used for milling, 3D printing, and laser cutting and work with various firmware. It supports most of the OAC evaluation criteria and acts as a universal system that can work with various hardware and software configurations. It's highly customizable, and it serves as a platform for integrating different features into the CNC system. The paper explains the system hardware and software development, working mechanism, and validation. The adoption of PC based OAC system and virtual component technology satisfactory matched the OAC criteria of Table 2. It is also a low-cost system with high flexibility and customization abilities. However, the system needs more improvements in real-time response to match the PLC-based systems. Also, it needs to be well addressed in the cyber security field, as it is online and open in nature. In the future the system will be expanded to improve interoperability, reliability, performance accuracy, cyber security, more axis control, various types of additive and subtractive machines control, cloud-based control, integration with [28–30] and a STEP-NC data interface model, more ISO standards integration, and other things.

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