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DEVELOPMENT OF A UNIVERSAL DESKTOP CNC MACHINE FOR HIGH-PRECISION WOOD PROCESSING: DESIGN, ELECTRONICS, SOFTWARE

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Abstract. *The field of computer numerical control (CNC) machine tools is developing rapidly, and their application has grown significantly in recent years. This article presents the design, development, and experimental testing of an inexpensive CNC milling machine developed by the author for decorative woodworking, functional prototyping, and demonstration production. Unlike common desktop hobby CNC machines, the proposed system is designed as a full-fledged industrial portal for continuous commercial operation using a rigid aluminum structure, industrial guides and ball screws, autonomous RichAuto control architecture, and advanced electromagnetic interference protection strategies.*

The machine has a rigid aluminum portal-type frame with a 48" × 48" working area, 10" Z-axis travel, and a 2.2 kW water-cooled spindle. Linear motion is implemented on HGR20 profiled guides, driven by stepper motors via ball screws. Motion control is performed by an autonomous RichAuto industrial controller operating in G-code execution mode from a USB drive. The electrical system is based on a 48-volt architecture of GloDray stepper drivers and includes an integrated emergency stop circuit and means of reducing electrical interference.

Experimental testing was carried out in real production conditions during the processing of wood and plastics with continuous cycles of up to 2.5 hours. The system demonstrated stable operation, vibration resistance, and reliable dimensional repeatability. The total cost of building the machine is about $7,000, which is significantly lower than the $10,000–18,000 range for commercial CNC systems with a comparable working area. The results confirm that industrial reliability and machining quality can be achieved within the framework of an affordable CNC architecture suitable for small-scale production, training laboratories, mobile workshops, and public demonstration production.

Keywords: *CNC, milling machine, woodworking, design, microcontroller, RichAuto industrial controller, ball screw, HGR20.*

Introduction

As is well known, the global economy is currently undergoing the fourth industrial revolution, known as Industry 4.0. The main means of improving economic efficiency at this stage are:

1) an innovative approach to production development (constant updating of production facilities and methods, acceleration of the pace of this updating, resulting in a reduction in the volume of homogeneous products while increasing quality requirements, and the predominance of serial production);

2) striving for comprehensive automation of production and other areas of life

based on intelligent technologies (the use of artificial intelligence in decision-making in management systems, expanding the use of flexible automated production processes, etc.).

These conditions and trends in the development of the modern economy have made numerically controlled (NC) equipment quite in demand. Numerical control (NC) systems have become one of the most important tools for ensuring high-precision, repeatable, and programmable material processing in a wide range of industries. The development and improvement of CNC woodworking machines is currently the main direction of development of operational control systems. The main feature of CNC machines is that the movement of the tool relative to the workpiece being processed is pre-programmed and recorded in numerical form, which ensures both extreme repeatability of the result and very high production flexibility [1-3].

The widespread use of CNC machines was hampered by their high cost. However, with the advent of affordable microprocessor technology and high-quality free CNC control software, they have become much more accessible, meaning that such machines are increasingly found not only in large industrial enterprises, but also in small businesses and even sometimes used by private consumers. Despite technological progress, the high capital cost of industrial CNC milling machines remains a significant limitation. Machines capable of providing sufficient rigidity, accuracy, and long-term reliability are usually inaccessible to small entrepreneurs, independent engineers, mobile workshops, and educational institutions. In contrast, inexpensive desktop CNC machines often suffer from insufficient structural rigidity, vibration instability, susceptibility to electromagnetic interference, and limited machining capabilities.

This requires solving two critical problems: flexible CNC machines and product data exchange. Until recently, there has been little research in this area; however, with the creation of the STEP-NC CNC data model, research efforts to solve the above problems have intensified [4-5]. This article presents the development of a full-size CNC milling machine designed by the author, with a 48″ × 48″ working area and a 10-inch Z-axis, specifically designed to bridge the gap between industrial-grade performance and affordable manufacturing for small businesses. The machine was completely designed, assembled, electrically protected, calibrated, and tested by the author in real production conditions.

Design Objectives and Engineering Requirements

The CNC system described in this paper was developed as a real production machine, not as an experimental or hobby prototype. The main engineering goal was to create a universal CNC milling machine capable of continuous commercial operation while maintaining minimal production and operating costs.

Software, G-code control, and system calibration. The CNC milling machine operates by autonomously executing G-code loaded via a USB flash drive. Toolpaths are generated using ArtCAM and VCarve CAM platforms.

The mechanical part of the machine is designed as a rigid aluminum portal with a large working area of 48″ × 48″ and a Z-axis travel of 10″. The design is optimized for:

- milling decorative panels;
- 3D reliefs;
- small-batch prototyping of wood and plastic products.

CAD software (Creo Parametric / equivalent) was used for communication and design development, which allowed us to:

- simulate all components,
- analyze the layout,
- prepare drawings for the manufacture of brackets, supports, and transition elements.

Most of the structural elements (brackets, supports, engine mounting plates) are made of 6061 aluminum alloy, which provides an acceptable balance between weight, rigidity, and manufacturability.

Research Results

In today's world of continuous scientific and technological progress, there is a constant increase in the demands on the quality of machines and the efficiency of their production. This requires the improvement of means of production, including CNC machines. The modernization of CNC machines is aimed at developing the technical characteristics of these machines that give them the above-mentioned advantages over other types of machines. Here are some examples of technical solutions that improve the basic operational properties of CNC machines. Here are some examples of technical solutions that improve the basic operational properties of CNC machines.

Tool paths for the machine are generated in the *ArtCAM* and *VCarve* CAM systems, which are widely used for:

- artistic woodworking;
- 2D/2.5D contour processing;
- 3D reliefs.

The main stages of preparing control programs:

- Creation of a 2D/3D model of the product in CAD/CAM.
- Selection of the type of machining strategy (rough/finish milling, engraving, etc.).
- Selection of tools (cutters, diameter, angle, radius, etc.) and cutting modes (rotation frequency, feed, depth per pass).
- Post-processing for RichAuto format (ISO-compatible G-code).
- Transfer of G-code to the controller via USB.

Mechanical Architecture of the Author's CNC System

The mechanical architecture of the developed CNC milling machine was designed to ensure high rigidity, dimensional stability, and vibration resistance under continuous commercial operation. The machine is based on a gantry configuration with a large 48″ × 48″ working area and 10-inch Z-axis travel, optimized for woodworking, decorative panel processing, and mechanical prototyping.

CAD software (Creo Parametric) was used to create and visualize all aspects of the proposed design for communication and documentation of ideas. The final design of the machine included four main components (CAD visualization shown in Figure 1): a) base, b) frame, c) bridge, and d) carriage. The base is located flat on the table and contains a ball screw and linear guides for movement along the Y-axis. The frame is attached to the base and contains a flat surface for parts that will be printed or attached to the workpiece.

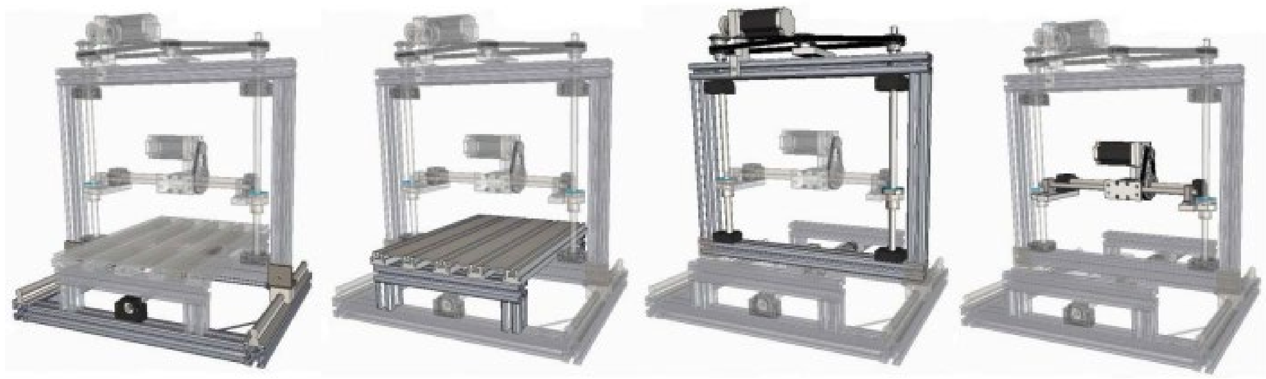

Figure 1 - CAD visualization of four main components: a) base, b) frame, c) bridge, and d) carriage

Source: [6]

Electrical System and Control Architecture

The electrical system of the developed CNC milling machine was designed for stable, interference-free, and industrial-grade operation under conditions of continuous production load. The bridge is attached to the Y-axis ball screw and moves along the linear rail of the base. It consists of two ball screws for movement along the Z-axis, which lift the ball screw and the X-axis linear rail up and down. At the top of the bridge, the Z-axis motor is positioned perpendicular to the ball screw, so a pair of bevel gears is used to transfer motion from the motor to the screw. A pair of pulleys and a belt connect the two Z-axis ball screws, synchronizing them with each other and maintaining the levelness of the X-axis.

The carriage is a unit that moves along the X-axis and holds the tool for the desired process. While the ball screw on the X-axis is fixed, the ball nut can rotate, creating linear motion. Thus, the carriage motor moves along with the entire assembly. This is achieved by a special bracket that not only holds the motor in place but also contains the bearing in which the ball nut rotates. The motor and ball nut are connected by a belt and pulley system that is attached to the ball nut by a bushing. The interchangeable tool system uses a matching hole pattern for both the spindle and the extruder head brackets, each of which can be secured with a single set of bolts.

After the design was completed, the aluminum extrusions were cut on a band saw. Two one-inch diameter holes had to be cut in the middle of one piece of aluminum extrusion using a drilling machine in order to insert the coupling through the holes. Four frame supports were cut and milled to provide a flat surface for the workpiece. A total of fifteen brackets had to be made for the machine (Fig. 2). These brackets were used to mount the stepper motors, connect the various axes of the machine, connect the motor couplings to the ball screws, and to ensure tool interchangeability. The brackets were made of 6061 aluminum alloy, which is the same type of aluminum as the frame, ensuring the strength and lightness of the machine. All these parts were manufactured in a student mechanical workshop using a manual milling machine and a manual lathe.

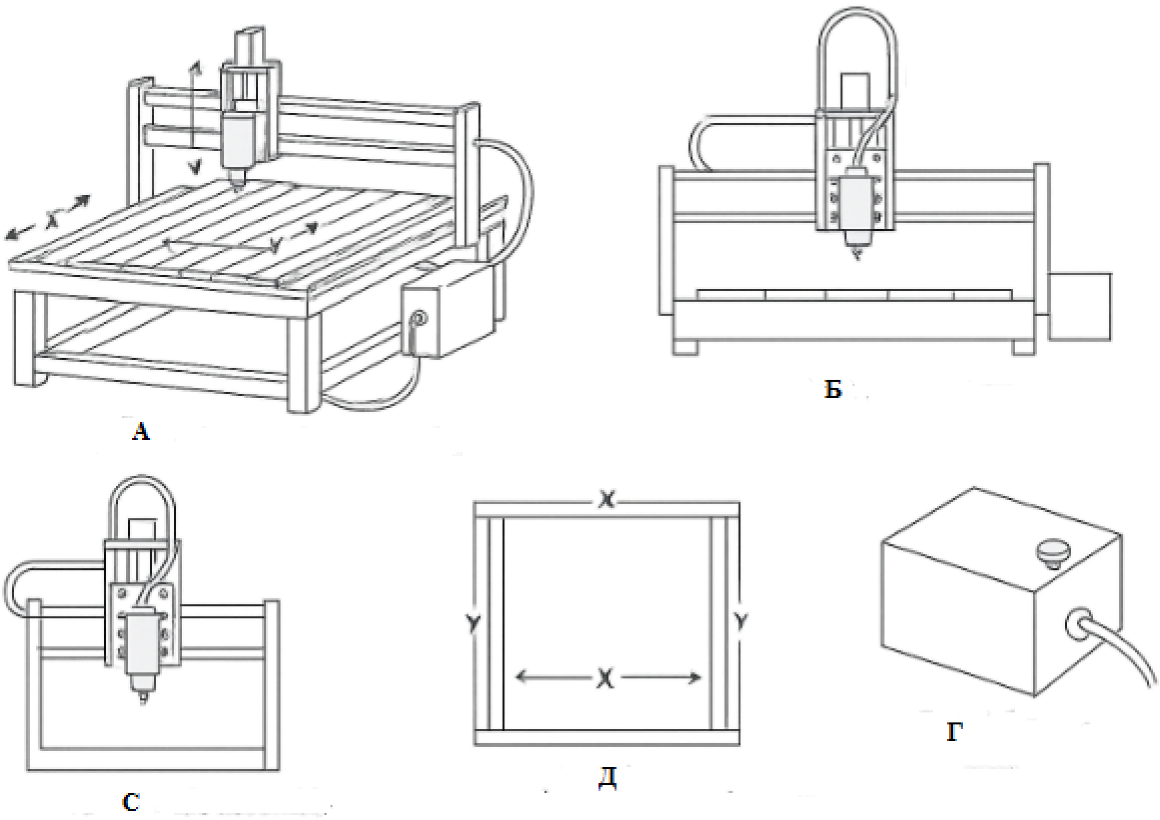

Figure 2 - Main components for component assembly in CAD, A) General view, B) Structure, C) 2-Axis speed, D) Work surface, E) Control system.

Source: [7]

Alignment issues were resolved during assembly, particularly when the motion control components were attached to the frame. Based on the Y-axis ball screw and two linear rods, they were aligned parallel to each other to prevent the moving components from jamming and to prevent damage. Parallel alignment was achieved using large gauges between the ball screw brackets and the edge of the linear rods, ensuring they were equidistant at both ends. The Z-axis has two ball screws that run up and down the bridge, holding the components for the X-axis and carriage. With two ball nuts, which also had to be equidistant at both ends, this was achieved using gauges placed above and below between the nut and the ball screw supports. Final assembly was performed on the carriage. To ensure that it was level, the brackets attached to the Z-axis ball screw nuts had to be aligned with the frame. Finally, the X-axis brackets were aligned parallel and placed at the same distance from the ball screw bracket with gauges once again.

This CNC milling machine consists of four main components: the X, Y, and Z axes, as well as the control system [9]. Each axis has its own specification, with the X axis moving from left to right, the Y axis moving from front to back, and the Z axis moving vertically from top to bottom. The X-axis moved 560 mm, the Y-axis moved 420 mm, and the Z-axis moved 400 mm. The dimensions of the machine platform are 680 mm x 670 mm x 660 mm. It is equipped with a 1000 W air-cooled spindle with a maximum spindle speed of 13,000 rpm. The machine frame is made entirely of 1020 aluminum alloy, and the machine is completely assembled from off-the-shelf equipment [10]. Each component has standard parts, including ball screws, stepper motors, linear guides, bearings, couplings, electronic components, and three-axis operating systems. Other components, including the emergency stop button, spindle, and vise, were also assembled as shown in Fig. 2, and the technical drawing of the machine design is shown in Fig. 3.

A CNC machine consists of a mini-computer or microcomputer as a control unit. CNC machining is a manufacturing technology [12] that uses computers to control mechanical equipment. Machines are programmed in a CNC language (known as G-code), which can be used to control all characteristics such as feed rate, coordination, position, and speed. In CNC machining, the computer can regulate both precision and speed. CNC machining is used in the manufacture of metal and plastic products. Activities include designing and developing prototype models for controlling CNC machines. Modern CNC systems use software applications to automate complex device design [13].

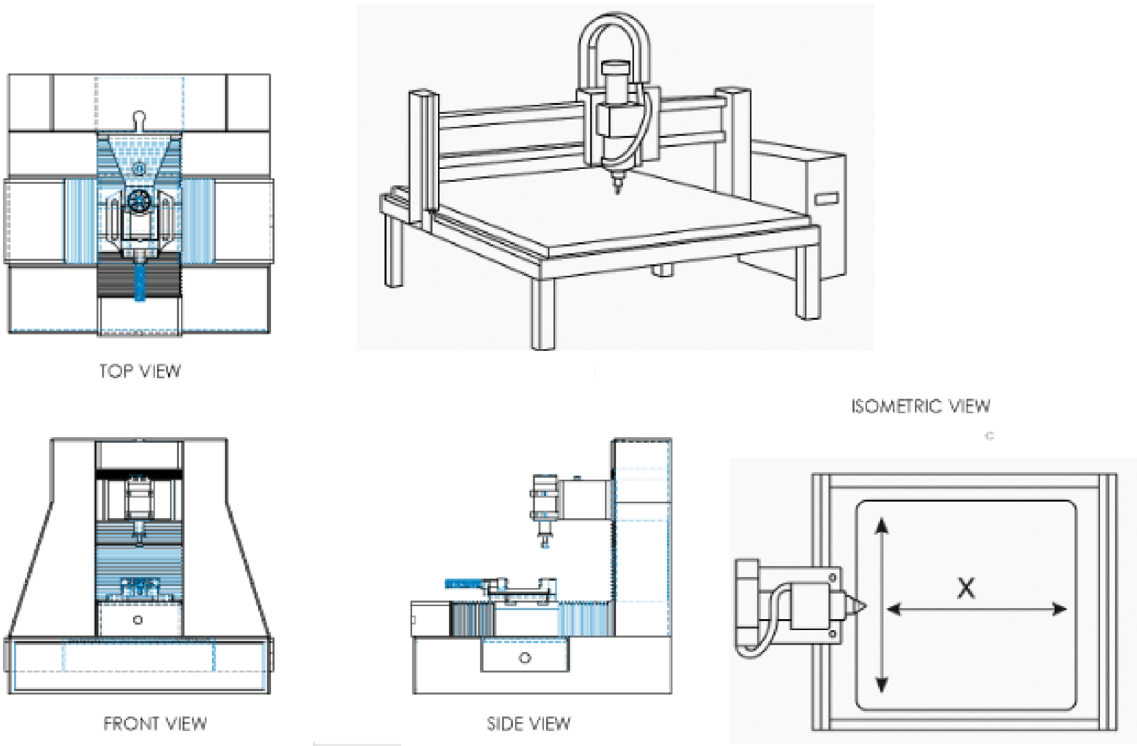

Figure 3 - Technical drawing of the CNC machine design

Source: [11]

This involves creating a code file that is analyzed to extract the commands needed to work with computer-aided design (CAD) and computer-aided manufacturing (CAM) tools. In this study, open-source microcontroller technology from Arduino is used to control the motor, and open-source software is used to execute G-code and machining applications. It is described as a tiny CNC typewriter running on an Arduino controller and a CNC shield. CNC stands for computer numerical control. The planning task is represented by G-codes, which are pre-set functions assigned to the machine's axes of motion. G-codes are also used in the CNC writing system. G-codes provide a route for the pen to move in the X, Y, and Z directions.

The combination of stepper motors and a lead screw mechanism (from a DVD drive) was placed on a plastic wood board with the appropriate orientation. Another servo motor was used on the upper side of the stepper motor. A regular handle was installed on the shaft (X-axis) of the stepper motor. A plastic wooden plate measuring 6*6 cm^2 is attached to the shaft (Y-axis) of the stepper motor, which serves as a table for writing or drawing [14].

Table 1 - Technical specifications of standard components

№	Component type	Description
1	Controller	ArtSoft Mach3
2	Stepper motor	Single Shaft Bipolar step motor
3	Stepper motor driver	Input voltage DC 12-36V Input current 1A-4A
4	High-speed motor	3000 - 13000 RPM
5	Interface connection fee	Power voltage is 5DC and supports Mach3
6	Power supply unit for motor	Input current 115 VAC, 5. 5A – 230VAC, 3.5A Output current 24V 10A

Source: [15]

Experimental Verification and Industrial Testing

The developed CNC milling machine was tested in real production conditions to assess its mechanical stability, thermal properties, positioning stability, and long-term operational reliability. Two stepper motors with lead screws are used to move the X and Y axes. A servo motor for working with wood is used for the Z axis. The stepper motors of the X and Y axes will be mounted on a wooden board, and the servo motor of the Z axis will be attached to the shaft of the stepper motor of the X axis [16]. The board mounted on the Y-axis stepper motor is used as a writing desk to which paper is attached.

For the study of finished products for each circle, which will be measured using a circularity test, a default diameter of 40 mm is used. The best result of the circularity test is 0.61, and the parameter S8000 F50 DOC 5 mm has 0.88%. The worst roundness test result is 0.64. Although the percentage error for the S1000 F200 DOC 5 mm parameter is 4.6%, it is still less than the requirements and is therefore acceptable. The results show that the surface along the round part with a low spindle speed is significantly rougher than the surface along the round part with a high spindle speed [17].

The developed CNC system demonstrates the possibility of setting up small-batch digital production with minimal capital investment. This approach contributes to:

– innovative entrepreneurship,

– the development of local production,

– technical education of the workforce,

– a culture of rapid prototyping.

Due to their small-batch nature, these machines provide greater flexibility and production efficiency while reducing capital costs. However, they are not designed for production or precision machining. In addition, they can easily replace expensive conventional machines and improve training by expanding access to understanding the operation and use of a CNC milling machine. This machine can be used in an educational institution based on machine programming, and the development system is useful for the student learning process. This machine will be a cost-effective alternative to a commercially available milling machine and will require less space for installation. The manufacturing concept has proven to be feasible for the design of small machines such as a CNC milling machine.

Conclusions

A portal-type CNC milling machine with a working area of 48″ × 48″ and a Z-axis travel of 10″ has been developed and implemented, specifically designed for high-precision woodworking, decorative panels, and prototyping.

The use of an aluminum frame, HGR20 profiled guides, and ball screws ensured high structural rigidity, geometric stability, and acceptable vibration resistance during prolonged operation.

The electrical architecture based on 48-volt GloDray drivers and a RichAuto autonomous controller has made it possible to create an interference-resistant control system without the need for a PC to be constantly present in the processing area.

Experimental tests in real conditions (wood, plastic, cycles up to 2.5 hours) confirmed the operability and reliability of the system, as well as sufficient accuracy and surface quality for decorative finishing tasks.

The total cost of building the machine (~$7,000) is significantly lower than the cost of commercial industrial CNC systems of similar size, making the proposed architecture attractive for small businesses, educational institutions, and mobile workshops.

The developed platform can serve as a basis for further improvements (integration of the 4th axis, automatic tool change, advanced diagnostics and remote monitoring tools), as well as for the serial production of affordable industrial CNC machines.

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