Design and Development of a Novel Multi-Axis Automatic Controller for Improving Accuracy in CNC Applications

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ABSTRACT
A ubiquitous device-widely used in many industrial applications is Computer Numerical Control (CNC) machinery. CNC controller constitutes the main part of a CNC machine, which performs the task of controlling and navigating the tool and implementation of industrial processes. Although there have been many controllers, designed and used, in CNC applications in recent years, most of them experience some limitations and disadvantages towing to the design techniques. This project aims to design and fabricate an innovative Multi Axis Automatic Controller (MAAC) to be used in CNC machinery, which has much superiority over the existing controllers and provides an ideal performance. The MAAC has a closed-loop control system, which can control and drive stepper motors, servo motors, DC motors, and hydraulic and pneumatic movement systems. An Improved accuracy and repeatability within rapid implementation of industrial process could be achieved by using the MAAC in different CNC applications.

KEYWORDS: CNC Controller, CNC Machinery, Closed-Loop Linear Control.

1. INTRODUCTION

In traditional methods for the production of a new product, all the production steps are conducted by human operators with machinery operated manually; however, with the advancement and creation of Computer Numerical Control (CNC) technology, automation has taken place in a variety of industrial processes. CNC prepares an automatic control of the machine tool employing the computer which represents an advanced control system directing different types of machine tools, robots, and transmission lines in industries [1]. In a CNC machine, the data is processed by a computer, allowing the processors to turn data to electrical pulses and send them to the axis driving motors [2]. A CNC machine control system uses one of the following two methods: open-loop or closed-loop. In an open-loop control system, in case of any mechanical problems occurring in the motor shaft or axes motion system, the controller continues to send pulses to the motor driver without any knowledge of the existing error that reduces the accuracy and repeatability of the CNC machine, sometimes causing the entire industrial process to halt. Backlash has some destructive effects on the implementation of industrial processes in an open-loop system and in the presence of overload; the controller cannot detect and correct the movement errors. In the case of a closed-loop control system, the encoder sends the rotational feedback of the servomotor's shaft to the controller. Therefore, in case any mechanical movement errors occur, the controller is aware of the error and has the ability to rectify it. In the open-loop control strategy, regardless of whether the feedback is transmitted from the motor shaft or not, the controller is unaware of the occurred defect and continues to run the process whenever defects occur in the axis movement systems. This tends to reduce the precision and repeatability of the industrial process and sometimes halts the process.

The prime role of a controller in the CNC machine is to receive the position signals from the computer and convert them into mechanical motion along a definite axis using the motor of the machine, thereby reaching the desired position. The controller is made of various parts; each part causes it to move a certain amount along the defined axis [3]. After receiving and interpreting the data from the CNC software, the movement command is transmitted to the motor drivers of each motor, which causes the definite parts to move along the designed routes. Either a USB or a printer port provides the necessary connection [4]. The CNC controller parts with the synchronization and integration function receive the transmitted signal and interpret it as a controlled movement of the machine's motors in the correct direction by the determined amount [5]. Recently, there have been several studies in the area of design and manufacturing for CNC machines, particularly, in designing the controller part. In 2009, a theoretical controller model with the capability to control and drive the servomotor was designed and the accuracy of the system was confirmed using simulated experimental data. The mean position error (MPE) of the system decreased, by using the theoretical model, from 2.99% to 1.22% [6].

In another study, to restore the old CNC machines, an open architecture CNC controller was designed and developed. This motion control system could retrofit the old CNC machines [7], also a reconfigurable hardware controller based on FPGA was designed to be used in the CNC machines. The experimental results show the feasibility of the proposed controller [8]. Whilst all the electronic parts of a CNC machine are already built and fully functional, the CNC machine is still designed to modify the results of the machine; in 2010, a small typed prototype CNC machine using a stepper motor was designed and built with the capability of communication via a USB port [9]. In 2012, an embedded numerical control system based on heterogeneous processor was designed and developed.
The controller has the ability to control and drive servomotors and the experimental results showed that the system had the ability and scalability to be used in CNC machinery for real time control and processing accuracy [10].

A 3-axis CNC machine model based on a programmable logic controller was designed and fabricated and the CNC model movement was provided by the use of stepper motors. The simulated model of the device was then designed. This research describes the laboratory tasks focusing on the circuit board holes being drilled using the fabricated CNC [11]. During this year, a mini CNC machine was designed and used to decrease the axial tracking error, contour error and the computational time required for online optimization with adaptive feed rate and predictive control methods [12]. A laboratory study is conducted to reduce the positioning error of a small to medium size CNC machine tool. The results show that the tuning process decreases the MPE of the CNC machine tool from 4.51% to 2.85% [13].

One of the functions of the CNC controller is to use a CNC laser cutting machine in modern industry, widely encountered in the manufacturing workshops. The best positioning accuracy of a regular laser cutting machine is about 0.025 mm; so, the minimum position error of these devices is about 2.5%, which makes it widely applicable for the metal industry [14].

2. MATERIAL AND METHODS: DESIGN AND FABRICATION OF MULTI-AXIS AUTOMATIC CONTROLLER

MAAC performs as a decision-making and controller unit in a CNC machine. The number of controllable axes and tool parts can increase to 9 as needed in the design and manufacturing of MAAC. The first prototype of the MAAC has a four channel controller to control a 3-axis CNC machine. The block diagram of the MAAC is shown in figure1. The MAAC system consists of the following units:

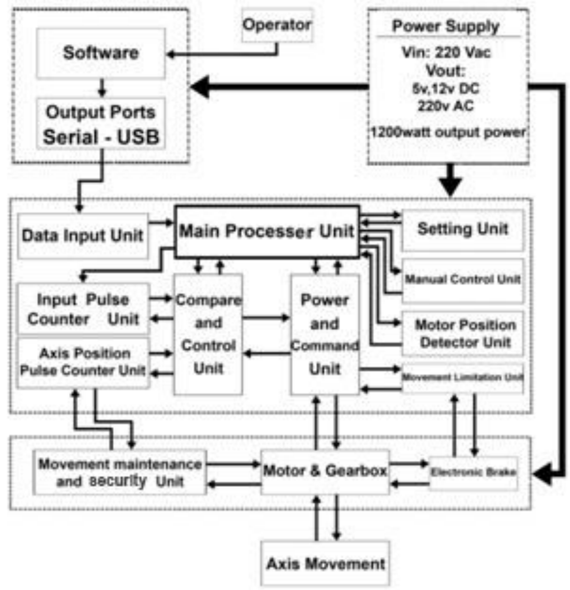

Fig. 1. The block diagram of MAAC

1. Data input Unit (DIU): DIU is a middleware between the computer and integrated circuits unit. The transmitted data packages from the device's computer are transferred to DIU via input ports and after buffering, these packages are sent to the main processer unit (MPU) and the system's circuit export movement command towards the requested point.
2. MPU: MPU forms the center of data processing and system control and all units in the system are connected via the MPU, ensuring robust two-way communication. The transmitted data packages from the computer are transferred from DIU to MPU for processing and the designated point from the NC software is diagnosed.
3. Input pulse counter unit (IPCU): Processed data packages transferred from MPU to IPCU as pulses. Following this, the pulse counting reaches a desired point. IPCU also has a display panel which shows the software requested point in real-time mode.
4. Axis position pulse counter unit (APPCU): For each requested movement step, a pulse is transmitted from the NC software to the DIU. In a similar fashion, for each movement step in each axis, a pulse is also transmitted from the movement maintenance and

security unit (MMASU) placed on each axis to the APPCU. The number of transmitted pulses from the movement of MMASU declares the current position of tool in each axis.

5. Compare and Control unit (CACU): Two different data packages are entered into CACU: data packages transmitted from IPCU that determine the requested position from the NC software in each axis, and data packages transmitted from APPCU that determine the current position of the tool in each axis. CACU compares the requested point with the current position of the tool in each axis and determines the number of movement steps to a desired position in each axis and sends that to the power and command unit (PACU). CACU controls each axis movement and determines the number of movement steps to the requested position in a real-time mode.

6. Setting unit (SU): This basic configuration allows the operator to change or set all the features of the controller so as to optimize the operation performance in a specific operation. Speed, movement steps, accuracy and the other values could be set without changing the NC software values.

7. Manual control unit (MCU): An operator can control the device and move the tool in all available directions, in each axis, to the desired position without taking part in the NC software and modify or change the operation during the process in a real time mode.

8. PACU: Incoming transmitted commands from the CACU are executed in PACU and the rotor's rotational direction and motor performance are decided via command circuits. There are two different units in a direct connection with PACU, so PACU executes the following set of transmitted commands:

- CACU: The positioning comparison results of the requested position from the NC software and the current position of the tool in each axis is determined and transferred to the command circuits.
- MCU: The transmitted signal command from the MCU are transferred to the PACU via the MPU and executed directly in a real-time mode, taking the tool to the operator requested position.

9. Motor position detector unit (MPDU): The motor shaft's rotation is the basic element of the tool movement in each axis; rotational movement transforms to a linear movement via the gearbox and the rack and pinions take the tool to the requested position. The MPDU recognizes the orientation of the motor shaft's real-time and controls the movement by sending feedback to the MPU, with an accuracy of 0.1 degrees. In this case, the controller can prevent any unwanted shaft rotation or rectify it.

10. Electronic brake unit (EBU): The EBU is installed at the motor's location in the mechanical part of the device and it has a direct and real-time connection with the PACU and the EBU. EBU blocks the rotor's shaft and does not allow the rotor to rotate in any direction for two cases: when the moving tool reaches a border or if any unwanted change is going to happen to the shaft's position.

11. Movement limitation unit (MLU): Every CNC machine has a defined range of movement that restricts the tool's operational range; MLU determines the dimensional limits of the device and prevents the tool from moving out of these defined limits. MLU has a direct connection with PACU and EBU and if the tool reaches its movement limits, the MLU stops the movement along the desired axis by sending commands to the above-mentioned units.

12. MMASU: The role of MMASU is to cause a change in the identification for a given movement. If any movement happens in each axis, the MMASU sends a pulse per each movement step to the controller such that the tool's position is reachable in a real time mode.

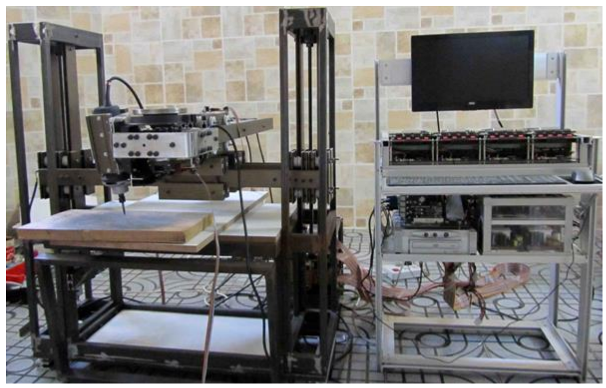

Fig. 2. The fabricated MAAC connected to a built mechanical part of the CNC machine

Figure 2 shows the fabricated MAAC connected to a built mechanical part of the CNC machine. After the design and fabrication of MAAC, it should be compared with the other similar controllers and evaluated. For this purpose, the MAAC is connected to a built mechanical part of a 3-axis CNC machine and the drilling points of the designed CAD model are operated for 20 cycles. The positioning error on each interval is measured on the manufactured part using a CMM machine. These results will be evaluated in comparison with the results of the three similar controllers for the same operational conditions. The designed CAD model that operates in the test is shown in figure 3. As shown, there are 4 drilling points in the corners of a 20 centimeter square area and the drilling point is located at the center of the square with the hole diameter being 1 millimeter.

Table 1. The LEAD SHINEST-LS-13 stepper motor specifications

Lead Shine ST-LS-13 Stepper Motor	
Technical code	57HS13
Phase	2
# of Leads	8
Step Angle	1.8 (deg/step)
Holding Torque	1.8 (Nm)
Current/phase	4 (A)
Ambient Temperature	-10 to +50 (C)
Weight	1 (kg)
Holding Torque	1.8 (Nm)
Insulation Resistance	100mΩ min. 500 VDC

The Mach3 Motion Card AKZ250 controller, smooth Stepper WRAP9 tech controller and the MC3660 Lead Shine 3-axis driver controller, which finds wide usage in CNC machinery manufacturing, are used in this test. The two types of motors used in this test for evaluating MAAC, LEAD SHINEST-LS-13 stepper motor, along with the specifications are listed in Table 1 and ZHENG Gearbox DC motor with the specifications are listed down in Table 2.

In the first phase of the experiment, all the controllers are connected to the mechanical part of a 3-axis CNC machine with Lead Shine ST-LS-13 stepper motors and a similar test is carried out for 20 cycles. In the second phase of the experiment, the MAAC alone is connected to the mechanical part of the CNC machine with the ZHENG Gearbox DC motor and a similar test is executed for 20 times. Statistical analysis was performed with descriptive tests and graphs using MATLAB R2013a (version 8.1.0.604, license number: 724504).

Table 2. The ZHENG Gearbox DC motor specifications

ZHENG GEARBOX DC MOTOR	
Rated Voltage	12 (V)
Torque	9 (Kg.cm)
Maximum Torque	11.6 (kg.cm)
Speed	160 (r/min)
Gear Ratio	59
Shaft Diameter	6 (mm)
Gearbox Diameter	39.75 (mm)
Unload Current	2.1

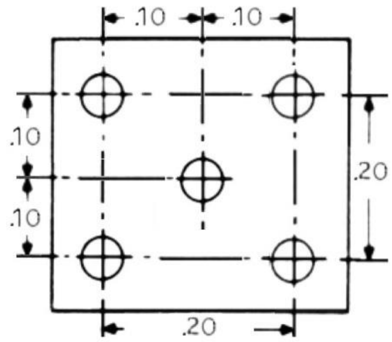

Fig. 3. The designed CAD model for the test

3. THEORY

Some of the limitations and technical issues existing in CNC machines are - the design of the controller which is mostly used for driving two main motors, the stepper and the servomotor has limitations in terms of output power and motor torque output because of their internal design and magnetic flux induction techniques. Therefore, the burden on the output motor axis has limitations that cause the mechanical part of the machine to have a limited range of movement. This makes mass production of these CNC motor types infeasible. The precision of CNC machines with the stepper and servomotor is based on the motor's precision. This means that the motor is the key determinant of the precision for the CNC. In open-loop systems, the operator circuit of the machine is working with the initiator driver pulse within the motor compartment (motors) and there is therefore no feedback; the operator circuit continues to send pulses even if there is a disturbance and this makes the system less functional with lower precision, which may in turn result in system-level failure. Regarding the design type and the technology for producing the CNC machines, there are limitations in terms of output power in the movement axis. Therefore, carrying out vast industrial constructions with a high overload is practically impossible. It is worth noting that the design method and the technology for making CNC machines has a significant influence on the price of these machines and the price is usually high. This study is conducted to design a modern controller used in CNC machines. This controller is designed optimally to reach a reduction in the limitations of previous controllers and has the following features: Counter system and power controller circuit are used to enable the CNC machine to connect to most kinds of motors and also hydraulic and pneumatic movement systems. Using the position detector systems and comparators for all axes, the error percentage in movement is reduced. This controller ensures a good construction of the fully automatic machines with variable sizes possible with multi-axis automatic controller (MAAC), increasing the industrial production rates via reduction in the operation time, reduced price for the CNC machines and reduced power consumption by using novel design.

4. RESULTS

In Table 3, the mean measured position error (MMPE) of three different tested positions for each controller by using the stepper motor in the X-axis and in Table 4, the MMPE, calculated for the three tested positions for each controller using the stepper motor in the Y axis, are summarized.

Table 3. The mean measured position error (MMPE) for three tested controller in X axis

MMPE in X axis	Mx3660 controller	Smooth controller	Mach3 controller
Position 10	0.0035	0.0980	0.1085
Position 20	0.0155	0.0210	0.0290
Position 30	0.0050	0.0480	0.9780

Table 4. The mean measured position error (MMPE) for three tested controller in Y axis

MMPE in Y axis	Mx3660 controller	Smooth controller	Mach3 controller
Position 10	0.0335	0.0235	0.1225
Position 20	0.0375	0.1005	0.0745
Position 30	0.0395	0.0470	0.0655

In Table 5, the MMPE values at the three tested positions for MAAC along both the X and Y axis are summarized.

Table 5.The mean measured position error (MMPE) for MAAC controller in both X,Y axis

MMPE in X axis	MAAC with DC motor	MAAC with stepper motor	MMPE in Y axis	MAAC with DC motor	MAAC with stepper motor
Position 10	0.0116	0.0550	Position 10	0.0149	0.0190
Position 20	0.0026	0.0375	Position 20	0.0164	0.0345
Position 30	0.0022	0.0280	Position 30	0.0070	0.0130

5. DISCUSSION

We evaluated and compared the results of the 20 tests on the designed controller with the other three controllers. It can be deduced from Table 3 that the MX3660 controller has the lowest position error amongst the three points in the X-axis with a value of MPE = 0.80% and according to the results in table 4, the MX3660 controller again has the minimum position error of all the three points with a value of 3.69%. The MPE values for the MAAC using the stepper motor along the X and Y axis are 0.40% and 0.22%, respectively.

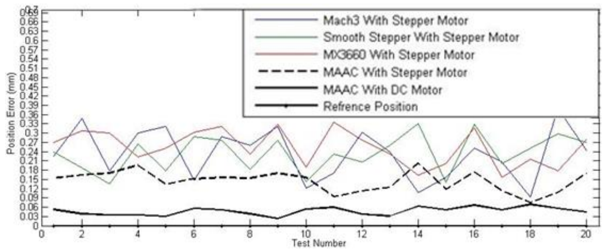

Fig. 4. The measured errors of each controller in X axis

Also, the MAAC's MPE values calculated using the DC motor for X and Y-axis are 0.54% and 0.13%, respectively. Therefore, we may confidently infer that the MAAC with stepper motor has the lowest position error when compared to the other controllers and the MAAC with the DC motor has the minimum MPE in testing. The measured errors of each controller along the X and Y axis can be seen in Figures 4 and 5.

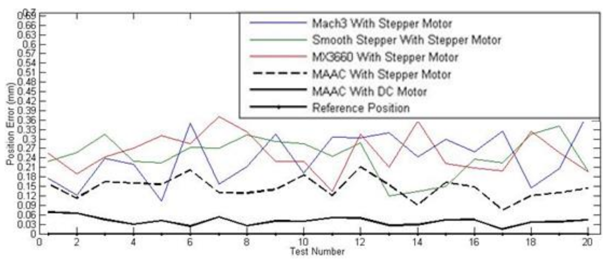

Fig. 5. The measured errors of each controller in Y axis

We observe that the MAAC with a stepper motor has the minimal measured error of all the controllers with the stepper motor. However, the MAAC with the DC motor has the minimal error along both axes in the tested complex.

6. CONCLUSION

For the past few years, there have been many studies concerning the fields of design, modification and optimization of CNC machines. Pre-determined type of motors can be generally controlled and driven by the designed and fabricated controllers. An important advantage of MAAC is its capability to control and drive all types of motors which are used in CNC machinery such as stepper, servo and DC motors. In addition, the hydraulic and pneumatic linear movement systems can be driven and employed in the manufacturing of the CNC machinery, by using APPCU and CACU in the MAAC. A designed CACU, MPDU and EBU in MAAC, helps to a decrease in the percentage of positional error for the same operation comparing with the other designed controllers. The MPE for MAAC using the stepper motor during the test reduced to 3.1% and the MPE using the DC motor for the test was very low at 0.91%, so it was less than that of the other three controllers used in similar tests. Therefore, the results indicate the DC motor offers a much better performance in positioning, in comparison to the stepper motors in similar machines with similar specifications. By using MAAC, the possibility of using different motor types enables us to manufacture CNC machines on a large scale and retrofit the old ones by using MAAC.

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