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Serial control of CNC machines

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In this paper a new method of the serial control of CNC machines is proposed. Actuators are controlled locally and the role of the central computer is limited to sending commands to the controller instead of sending it directly to actuators. It has been achieved with the use of the serial protocol with the use of the USB port. The taken approach leads to more reliable operation because commands are buffered and no synchronization between command stream and actuators operation is needed.

KEYWORDS: CNC machine, serial control, stepper motors, serial communication

1. Introduction

The term CNC [1] (Computerized Numerical Control) defines the numerical control of machines. This form of control is implemented using specialized computers or digital devices. The use of such a type of machine control allows to improve accuracy and efficiency. The production process can be carried out faster and the effect is repetitive. It can also allow to reduce production costs.

Two basic methods of CNC machine control are known. The simpler one is based on control in the open loop with stepper motors. In this approach there is no information or confirmation how many steps have been executed by the machine. In practice parameters of the driving motor as power, acceleration and breaking should be precisely chosen. When machine parameters are correct the machine should not loose any step [2].

Due to the increase in the popularity of stepper motors there are many stepper motor drivers (MD) available as A4988 [3], L297 [4], DRV8825 [5], DRV8846 [6]. These drivers allow to control stepper motors in a simple way. Only two signals: step (STEP) and direction (DIR) are used for control. The motor rotates by a constant angle when STEP signal is rising or falling. This small rotation corresponds to one unit shift called the step. The direction of the axis motion is controlled through the DIR signal. The changing of the state at the DIR input results in the change of the motor rotation direction.

An alternative type of control uses the feedback loop. The feedback loop supplies information about the spindle position that is generally achieved by utilizing encoders. This type of control allows to utilize the full power of the motor without reduction of accuracy [7], but a design of the controller and actuator is more complicated. The confirmation that the stepper motor has done the given step and is ready to start the next step can be achieved by the specific encoder. This encoder is works in a sequential pattern and gives one pulse per each motor step.

The control procedure of DC motors based on feedback from encoders is more difficult. We shall shortly analyse the example procedure of a single movement. It has to be assumed for simplicity that DC motors and encoders placed on each axis are identical and the motion trajectory is rectilinear. In this type of the motion the spindle shifts on the straight line from the point START to the point END. In this case the distance on each axis can be calculated by subtracting coordinates of these points. Assume that the distance on the X–axis is 100 units, and on Y–axis 50 units, so the motor driving in the X–axis should run two times faster. In order to ensure the shortest time of acceleration and braking on the X–axis, the maximum current should be supplied to the motor. While the motor is running we receive the impulses from the X–axis encoder. According to these signals, the Y–axis should generate one pulse for each two X–axis signals. The loss of synchronisation results in the incorrect movement. The problem is more acute when the control sequence starts, because the controllers like PID use the information on the error to correct the power supplied to the motor to minimize this error. In this type of machine the error results in the incorrect movement. So is highly probable that first impulse for Y–axis will be not synchronized with the second impulse of X–axis and after the few seconds of accelerating we can get a difference of several steps. Often, it must be tolerated the error that is bigger than one encoder signal, but in the machine with the small steps, for example 0.01mm, the resulting error can be accepted.

This phenomena when using stepper motors and encoders is much easier to cope with. In order to get the maximum acceleration, the STEP signal should be provided when the encoder impulse is received. The control motor of the Y–axis operates in the following manner: for every second impulse of the STEP signal given to the X–axis motor, the STEP signal is given to the Y–axis motor. In this method the error will be smaller than one step. Thus it is easier to control the machine with the stepper motor and the control is more accurate. For this reason the stepper motors are commonly used in CNC machines.

Because of the high popularity of this solution, the control software is mainly written to control stepper motors. Programs for the control of the CNC usually realize the control of stepper motors through transmission via the parallel standard port LPT (Line Printing Terminal). This port allows to change the state at the chosen pins at the same time. The LPT port is directly connected to stepper motor hardware drivers. The examples of such a control software can be Mach2 and Mach3 [8]. Moreover due to the wide availability of integrated circuits for stepper motor control, the design of a complete driver is less complicated than before. For example, to design the parallel driver of the numerical machine one only needs to use one MD, in the configuration including one driver for one axis. On other hand, the LPT port is still used to control CNC machines, but this port is not always available in modern computers. Therefore attempts are being done to implement fast serial transmission through the USB [9] port. CNC machines with the serial controller do not allow for the wide choice of the control software. It is usually necessary to use the dedicated software provided by the CNC machine manufacturer. However, the majority of CNC programs accept as the input the description of the tool movement as a G–code [10]. G–code is a standard language describing commands for CNC machines [11]. In presented approach the G–code interpreter was implemented. In Section 2 the review of stepper motors is given, and in Section 3 the implementation of the machine driver is shown. Moreover, in Section 4 the model of kinematics is considered.

2. Review of the stepper motors

The stepper motor is a type of engine that can be controlled by using the small constant movements termed steps. This type of control allows for the accurate positioning without the feedback loop. The several types of stepping motors are manufactured. The most popular is a brushless DC motor. In this type of the motor the stator consists of several windings. Supplying the current to the specific winding results in the small movement of the rotor. The motor can be run by switching the current between the individual windings and changing its sign. The schema of such a motor is shown in Fig. 1.

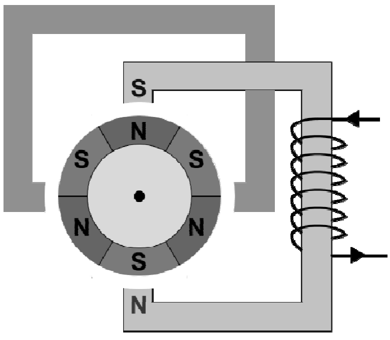

Fig. 1. The scheme of conventional stepper motor

The linear motor can be received by "unrolling" of the conventional stepper motor. The parameters are similar to those of the rotating motor, but force is received instead of torque. The scheme of linear motor is shown in Fig. 2.

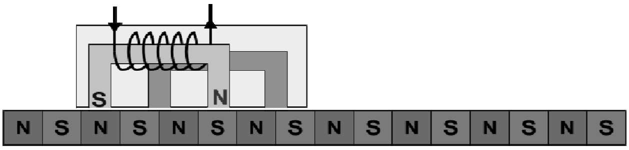

Fig. 2. The scheme of linear stepper motor

The Piezoelectric Ultrasonic Motors (USM) can be also used for the motion control using steps. These motors allow to attain high acceleration and small inertia, moreover high accuracy can be achieved. The example can be the USM from Physik Instrumente [12]. The PILine Ultrasonic Piezomotor achieves the velocity up to 500mm/s and acceleration up to 10g with the resolution up to 0.05 µm [12]. These motors have pushing and holding forces of several N. Due to their high accuracy and small size, this type of motors is utilized to build, for example XY microscope stage. It allows to transform the microscope into a specific type of the CNC machine. The other applications encompass lens control in cameras, for example, in the Canon USM Autofocus drive system [13].

The Physik Instrumente also manufactures motors using the PiezoWalk technology [12]. Such a system consists of several individual piezo actuators. The motion is realized using coordinated clamps. Each motion cycle provides the few micron movement, and this motor allows for the high frequency control, so the movement of few mm/s can be achieved. Physik Instrumente also claims that this technology allows to achieve holding and generate forces up to 600N. The cycles of the movement of the PiezoWalk motor is shown in Fig. 3.

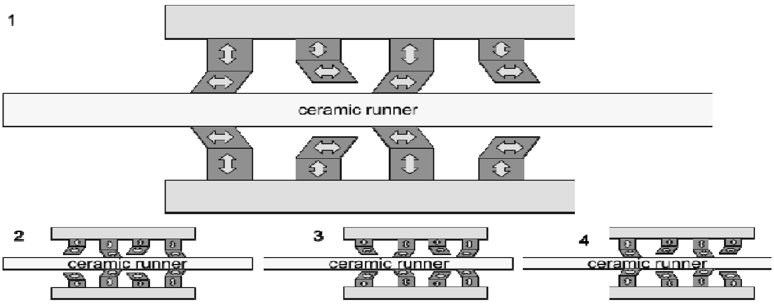

Fig. 3. Scheme of PiezoWalk operation cycles

Summarizing thus far each of the motors has its specific purpose. So there is no perfect solution for all applications. The piezoelectric motor does not contain windings and magnets, so the size of the actuator can be extremely small. It can be applied in locations where other motors would be too large. An example could be the moving of the camera lens in smartphones. But such motors are too slow to drive conventional CNC machines. In such cases the linear stepper motor with windings is a proper solution. These motors achieve high speed in the linear motion, even they can propel a projectile in the coilgun. When high reliability and rotational motion is needed, the conventional stepper motor is a good solution. But when the high rotation speed is required, for example, to drive the quadrocopter rotor, the stepper motor with the small amount of steps per rotation can be applied. However, when high accuracies are required the stepper motors with hundreds steps per one rotation can be used.

3. Comparison of control signals in CNC machines

As mentioned above for control of numerical devices like plotters, milling machines or 3D printers usually the parallel LPT port is used. This port allows to generate one control command per one clock signal. The control commands comprise information on the required motions for all axes of the machine. Because of the possibility to generate the command with DIR and STEP signals for all axes, this type of control leads to the less complicated design of the machine controller. The general limitation is that one control command contains information about the next move for one step. Also the calculation of initial values for acceleration, braking and holding speed is executed by the controlling PC computer. The other important factor is that the speed of the motion strictly depends on the speed of the commands stream. Typically, the shift of the spindle along the single axis by 1000 steps requires the transmission of 1000 commands. Additionally, the control signal sequences should be precisely synchronized with the step sequences of the stepping motor. For instance, when the delay between the issued control commands and their realization and execution is too long, an error of positioning may appear. This can happen for instance, when computer hangs for a short while. The current in windings will not be switched. Because of the inertia, the motor may rotate by a few steps forward and stop. In this case, after computer resumes its operation, the commands are sent with the speed corresponding to that of the motor being in motion. So the stream of commands may be too fast to revolve the motor, hence the motor would only oscillate and not move. For this reason, the control PC computer should not run other programs in order not to introduce additional delays, or the computer with real–time operating system should be applied.

The communication with the CNC machine controller (Fig. 8) is realized via the virtual UART port (Universal Asynchronus Receiver Transmitter). The implementation of UART is very easy due to simplicity of the serial protocol. USB–UART converters are widely available on the market. Most of these converters uses standard USB VCOM profile port that is also utilized in the designed machine. It is also possible to communicate with the designed machine controller via Bluetooth [14] VCOM profile which is compatible with the USB VCOM. Therefore, the control PC application does not require any changes.

The use of communication via the serial port requires the buffering of commands assuming that all control tasks are performed by the PC. The control commands are sent with a predetermined period and the delay has no influence on the accuracy of the positioning conversely than in the case of parallel control signals in the open loop variant of control. Moreover, the number of commands in the command stream can be significantly reduced. In this case to move the spindle by 1000 steps along the straight line only one command is needed. The same operation using the parallel control approach needs 1000 separate commands.

4. Realization of controller machine CNC

In this section we should consider the control procedure of the CNC machine. The control procedure is implemented by the program running on the computer connected with the controller. The controller is placed inside the machine. The controller consists of the 32–bit ARM microcontroller STM32F100 [15] that executes the embedded application. The outputs of the microcontroller are connected with motor windings through H–bridges DRV8835 [16], which amplify control signals. The communication between the computer and controller is realized via serial port utilizing the USB port.

The control procedure running on the PC computer executes G–code instructions. Consequently, the whole control process is a series of rectilinear moves. For every single move the procedure calculates the number of steps needed to execute the move on each axis. A single command contains the information about the distance in steps on each axis, maximum speed and acceleration values. The controller receives the command that has to be parsed. The maximum distance is chosen. The axis for this distance is called the fastest axis and should be driven with the maximum speed and acceleration. The other axes are driven relatively to the fastest axis. In order to drive motors the impulse signals on the microcontroller output are generated. These signals are amplified by the bridges directly connected with motors windings. After every move, the controller sends to the computer the information about the current position of the spindle. This approach is illustrated in Fig. 4.

In the designed CNC machine the control signals STEP and DIR were not used in the stepper motor driver. A double H–bridge DRV8835 [16] was used to provide more flexibility in the choice of motors. For example, the controller is able to control bipolar, unipolar stepper motors, DC engines and other elements of the CNC machine such as: vacuum cleaner without the modification of the hardware structure. It should be mentioned that integrated controllers of stepper motors cannot be used in such various ways. In the CNC the bridges are not permanently soldered to the main board that allows the easy exchange of the damaged bridge without soldering. The schematic diagram of controller is shown in Fig. 4.

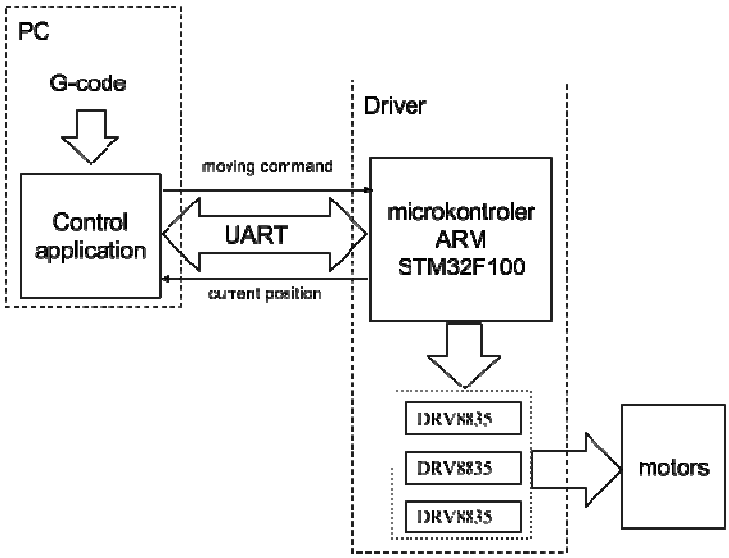

Fig. 4. Schematic diagram of working device

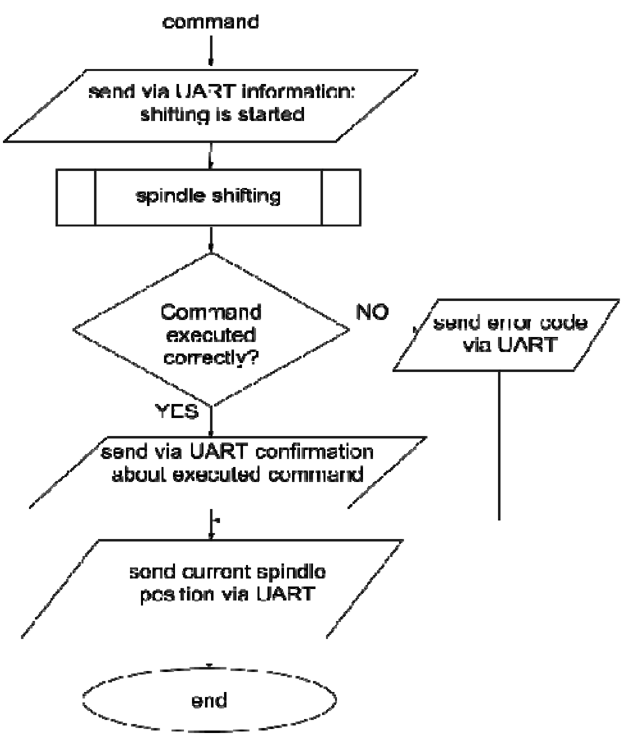

Fig. 5. Scheme of command processing in microcontroller

In Fig. 5 the diagram of the microcontroller command procedure is shown. This procedure is executed after receiving a command from the computer. The input procedure contains a command which includes information about the required motion. The procedure starts by sending to the PC the information that motion has started. It is done by sending the byte 0x61 through the UART port. Once the command is received, the current signals which control the stepper motor are generated. Finally, the spindle moves to the desired position. This process is represented by the block “spindle shifting” in Fig. 5. If the motion has been executed correctly, the feedback confirmation is sent to the PC computer. In the opposite case the suitable error code will be sent. At the end of the procedure the information about the current spindle position is sent to the PC.

5. Model of CNC machine kinematics

The control procedure is the most important factor with respect to the kinematics of the CNC machines. The model of kinematics of the designed machine is presented on Fig. 6 and 7. Fig. 7 presents guides on each axis. In Fig. 6 the moving parts are marked. The spindle can move in three planes with respect to the frame and groundwork. The frame (number 4 in Fig. 6) consists of four closed profiles. This part is fixed in relation to the groundwork. The other elements (1, 2, 3 in Fig. 6) can be movable with respect to the frame. The combination of these moves effects in the spindle motion to the destination. The motion along the Y–axis is done by moving the gate (number 1 in Fig. 6) along the frame. It causes the same shift of the elements 2 and 3 from Fig. 6 with respect to the frame. The element 2 (Fig. 6) moves along the X–axis, whereas the element 3 (Fig. 3), holding spindle, moves along the Z–axis.

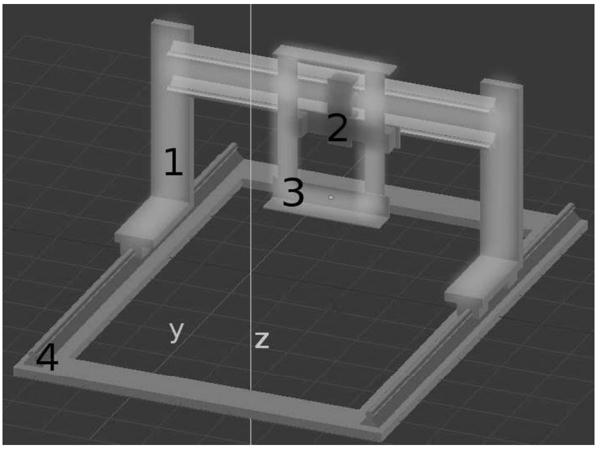

Fig. 6. Model of kinematics in the designed device

The motion of the gate (element 1 in Fig. 6) along the Y–axis is realised by the assembled guides with the frame which are marked in Fig. 7 in green and the letter “y”. The guides fastened to the element 1 (Fig. 6) are marked in red and the letter “x” (Fig. 7) and they ensure the motion of the element 2 (Fig. 6) along the X–axis. The combination of motions of the elements 2 and 4 (Fig. 6) along guides (x and y, Fig. 7) influence the motion of the spindle along the XY plane. The lifting and lowering of the spindle is realized by the element 3 (Fig. 6) and guides (marked in blue and the letter “z” in Fig. 7). This is the realization of the Z–axis. The combination of all 3 axes gives the possibility of the three–dimensional spindle control.

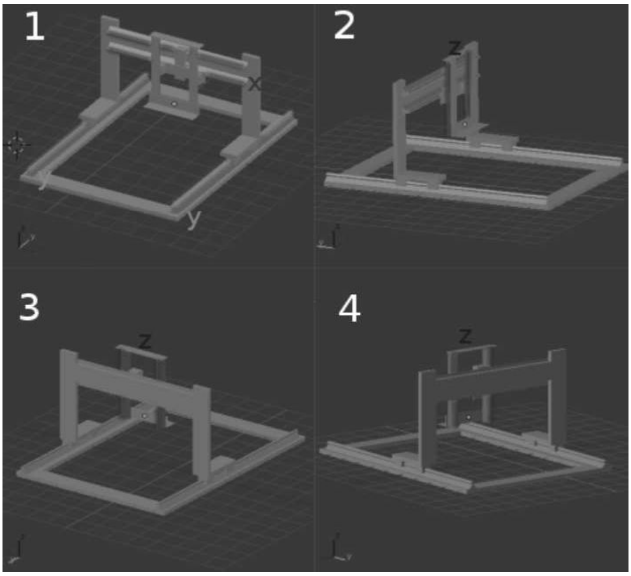

Fig. 7. Locations of each guides in built device

Table 1. Dimensions and range of moves in built device

Axis	Movement length	Min. device size	Max. device size	Accuracy
	cm	cm	cm	mm
x	80	102	102	0.1
y	43	64	64	0.1
z	25	37	60	0.1

The prototype of the elaborated device is shown in Fig. 8. It is based on the steel welded components. In order to minimize friction the linear bearings were used. The guides are made from the surface–hardened steel in the roller–shaped form of 16 millimeter diameter. The motion is carried out with the use of the trapezoidal thread forms connected with the stepper motor.

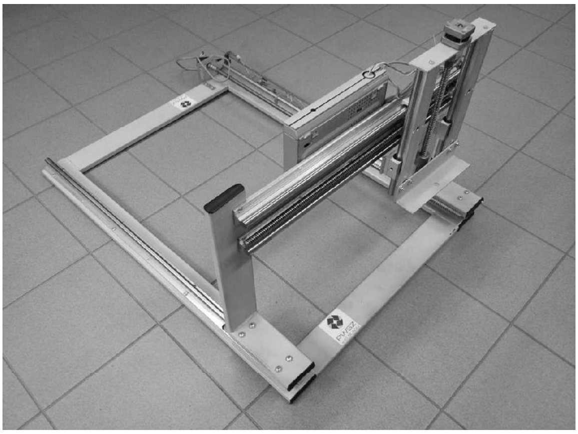

Fig. 8. The prototype of elaborated device

6. Conclusions

In this paper the design of the CNC machine with the control based on the serial communication between the computer and controller is presented. The controller can be used with any kind of motors or equipment that requires the current signals. Due to this fact a wide range of motors can be used without any changes in the controller structure. The main novelty is the application of the USB port for serial communication with the controller. This approach reduced substantially the number of commands sent between the PC computer and the controller as compared to the parallel controlling devices. There is no need for synchronization between the computer and controller. The pauses in the command stream are allowable and do not endanger the manufacturing process. A prototype of a full functional CNC machine with a controller and the PC software was realized.

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