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Application of Micro-controllers for Stepper Motors Position and Speed Control: A review

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Abstract— this paper presents an overview on stepper motors including their history, advantages, disadvantages, types, mode of excitation, drive systems, control techniques (conventional and modern control) and their application in different fields. Open loop control techniques are explained including benefits and problems. Closed loop control techniques are also analyzed and explained to show the validity of using such control algorithms. Different controllers (based on conventional or modern feedback control techniques) are also explained; such as PID controller, Fuzzy PID controller and self-tuning regulator. Different control methodologies such as filed orientated control, direct torque control that used in controlling stepper motors are briefly reviewed. The integration of controller algorithms with stepper motors in position and speed control are also included.

Keyword—Stepper motor, Position control, Variable reluctance, Hybrid, closed loop control, Driver.

1. Introduction

Stepper motors are electromechanical devices that convert electrical energy to mechanical energy in terms of rotating shaft. The input to a stepper motor is a train of pulses resulting in a step rotary motion, so it is used in open loop applications with good accuracy as it moves in distinct steps from a certain position to another known one; hence the final position of the motor shaft is known if the initial position is known. Stepper motor position is controlled by using a certain pulse sequence; this technique is called the open loop position control. In some application with a specific velocity or load torque, stepper motors may suffer from losing or slip in a step, in order to avoid this; closed loop control techniques are used to control stepper motors for better accuracy. Control techniques used in closed loop applications of stepper motors use feedback information picked up from the stepper motor position, velocity or stator parameter, this may done in sensor or sensor less techniques [1-5].

Stepper motors are used in different fields especially in control engineering applications starting from the beginning of this century until now. This is because they have great control capabilities such as high torque to inertia ratio, reliability, simple construction, brushless and many other advantages which will be discussed later. They are used widely in positioning applications in which high accuracy is needed such as military weapons, robotics, printing, Numerical Control (NC) of machine tools, automotive, medical application, aerospace and positioning application. Due to the great development of control techniques and fabrication applications, stepper motors are used extensively in position and velocity control [6-9].

A controller is used in closed loop control techniques to generate control pulses needed to start the motor and to control its operation. This controller can be achieved using microprocessor, microcontroller, PLC or even an ordinary PC. This controller can be designed with conventional or modern control techniques such as PID, genetic algorithms, fuzzy logic or neuro fuzzy. Output from the controller is a low level signal, so a drive system is needed to modify this signal to a suitable level signal, and to change the flux direction in the motor winding to control the motor operation clockwise or counter clockwise [10-12].

This paper is a review article which introduces a brief summery on stepper motors and its control among the last ten years covering all aspects. This paper is composed of three section, the first, explains stepper motor system construction and operation, the second explains Position Control Strategies and the last explains Microcontroller for Stepper Motor Position and Speed Control.

2. Stepper Motor System Construction and Operation

Stepper motor is categorized as a brushless synchronous motor that moves in specific angle with each step input. Stepper motor system consists mainly of three parts, controller (sequencer), drive system and stepper motor. Fig. 1 shows the construction of stepper motor control system [13].

2.1 Advantages and Disadvantages of Stepper Motor

Stepper motors gained their popularity and used widely because of their unique properties in controlling applications in different fields. The next paragraph summarizes the advantages and disadvantages of stepper motors [14-16]:

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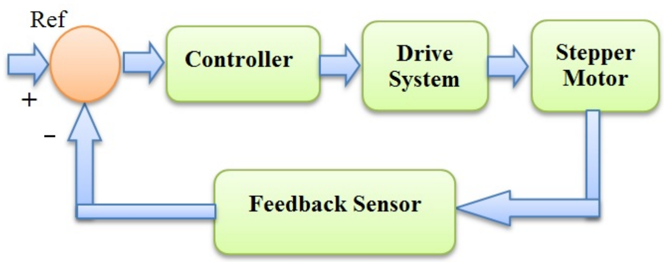


Fig. 1 Stepper motor control system

2.1.1 Advantages of stepper motors

a) Stepper motors move in steps so they have high accuracy, precise and effective in open loop applications. Stepper motors are able to operate with a basic accuracy of ±1 step, this accuracy is sufficient to remove position and speed transducers so reduces the overall cost.
b) Input to stepper motors is a train of pulses in order of 200 mA so the drive system and its interference with stepper motor are easy to accomplish in digital manner.
c) No rotor winding, so the motor has a high torque to inertia ratio especially in low speed applications.
d) The existence of winding in stator only enhances the cooling capabilities so reduces motor heating.
e) The mechanical construction of stepper motors is simple and robust, leading to high mechanical reliability.
f) Stepper motor is brushless leading to arc reduction.
g) Brushless construction has obvious advantages.

2.1.2 Disadvantages of Stepper Motor

Stepper motors suffer as any motors of some disadvantages, but less than that of other motors.

a) The existence of resonances at certain speed ranges.
b) Have high vibration and noise levels.
c) Accuracy and resolution of stepper motors depend on the motor structure and cause a problem for applications where high resolution is needed.

2.2 Stepper Motor Types

Stepper motor consists of stator and rotor, but the winding of the stepper motor is located in the stator so stepper motor is brushless motor. The stator consists of a number of poles carrying a number of windings. Each pole has one or more tooth. The number of teeth of stator and rotor are different. This magnetic structure triggers the motion of the rotor by the magnetic flux accomplished by the stator and hence describes different types of stepper motors [17-19]. The stepper motor step size is given by Eq. (1).

$$\theta_s \equiv \frac{360^\circ}{P \cdot N_r} \quad (1)$$

θ_s : step size.

P : Number of stator phase.

N_r : Number of rotor teeth.

Stepper motors are classified according to their rotor structure to three types:

a) Variable reluctance stepper motors (VRSM).
b) Permanent magnet stepper motors (PMSM).
c) Hybrid stepper motors (HSM).

2.2.1 Variable Reluctance Stepper Motors

Variable reluctance stepper motors are classified into single stack and multi stack motors, having a soft iron multi-toothed rotor and a wound stator. Stator supply is a DC voltage resulting in a magnetic flux that attracts the rotor teeth, and according to the DC input pulses the motion of the stepper motor is achieved. It is widely used because of its low cost and simple construction [20].

a) Single Stack

When a DC input is applied to the stator pole the rotor teeth will be aligned with the excited poles of the stator and by simultaneously injecting the DC input to the poles of the stator the rotor will move in the designed sequence. Fig. 2 Shows the Cross sectional diagram of a 3-phase variable reluctance step motor, (a) Stator and rotor teeth and (b) Winding arrangement [21-22].

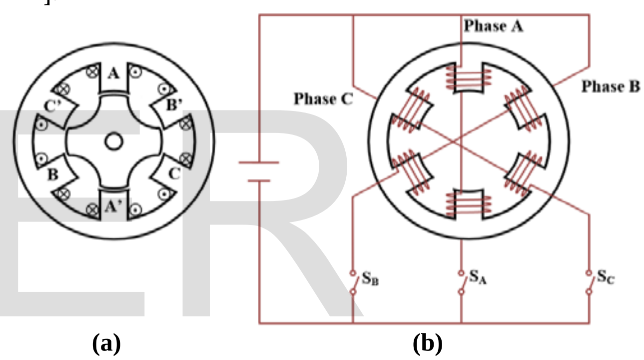


Fig. 2 Cross sectional diagram of a 3-phase variable reluctance step motor [22].

b) Multi Stack

It is an upgrade of single stack composed of multiple number of stator planes, its excitation done simultaneously from stack to another, and each stack is shifted one step from the next stack. Each stack represents one phase Fig. 3 Shows the construction of the multi stack VRSM [21-22].

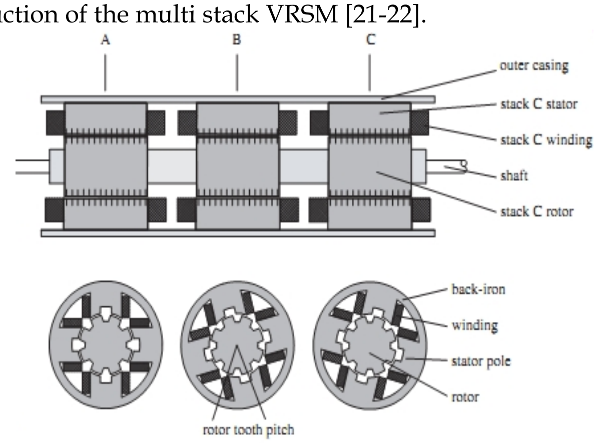
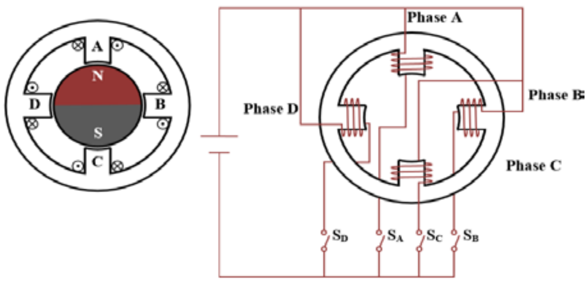


Fig. 3 Construction of multi stack VRSM

2.2.2Permanent Magnet Stepper Motor

The rotor of this type is made of permanent magnet cylindrical material and the stator has a single pole electrical phase, when one phase is magnetized the rotor moves one step. PMSM has small step and high torque to inertia ratio, so it is desired with precise and high torque application. Fig. 4 shows the cross sectional diagram of a 4-phase permanent magnet step motor, (a) Stator teeth and cylindrical magnet rotor and (b) winding arrangement [23-30].



(a) **(b)**

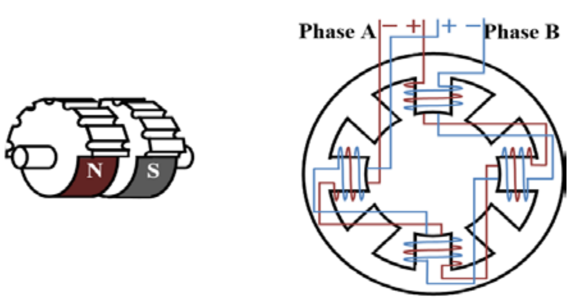
Fig. 4 Cross sectional diagram of a 4-phase permanent magnet step motor [22].

2.2.3Hybrid stepper motor

The principles of construction of VRSM and PMSM are combined together resulting in HSM construction. The rotor of HSM is multi toothed like VRSM and has a permanent magnet around its rotor. Both advantages of VRSM such as small steps and PMSM such as high static and dynamic torque are present in HSM. So, HSM is used in wide variety of applications. Fig. 5 (a) Shows the teeth and magnetic structure of the rotor of a hybrid step motor. (b) Bifilar windings of two phases of a 4-phase stator of a hybrid motor [31-38].

2.3 Stepper Motors Modes of Excitation

Stepper motor moves in rotating path but unlike other motors it moves in distinct steps. This step is defined as the step angle of stepper motor, and is calculated by Eq. (1). This angle may be ranging from 90˚ to multiple number of thousand according to the construction of stepper motor. Mechanical construction, electrical wiring of stepper motors and driving circuits are the main responsible of this step manner [39]. Different configurations for modes of excitation are:



(a) **(b)**

Fig. 5 (a) Teeth and magnetic structure of the rotor of a hybrid step motor. (b) Bifilar windings of two phases of a 4-phase stator of a hybrid motor [22].

2.3.1 Full-step excitation

a) One-phase on excitation:

In this mode a single pole is excited at a time and the rotor moves one step that's equal to the step size.

b) Two-phase on excitation:

In this mode two-phase winding is excited simultaneously at a time so the rotor moves with full step as the one-phase on excitation but takes the intermediate position between the stator phases [39].

2.3.2Half-step excitation

In this mode, a special sequence for phase excitation is implemented by switching between one-phase on excitation and two-phase on excitation so the rotor moves with half of the step size, this method gives an accurate position than full-step excitation [40].

2.3.3Micro step excitation

Micro-step excitation can be achieved by continuously varying the stator winding currents (magnitude and direction) in a special manner to divide one step to smaller values (one step can be divided into 256 times). Step size in full step excitation may reach 1.8 degree; this may cause oscillation at low speed or motor can reach resonance at high velocity range and hence micro stepping improve positioning resolution and motion stability as shown in Fig. 6. In the beginning micro stepping is carried out with a fixed rate or pulses per second in open loop application. Stepping frequency remains fixed and converted into discrete sin and cosine to actuate the motor [41-45]. Stepper motor is used in fine tracking for reference position when speed is changed in real time in the critical applications. To improve the performance of micro stepping, closed loop is used, as current is decreased due to back-EMF and have phase lag due to the phase inductance.

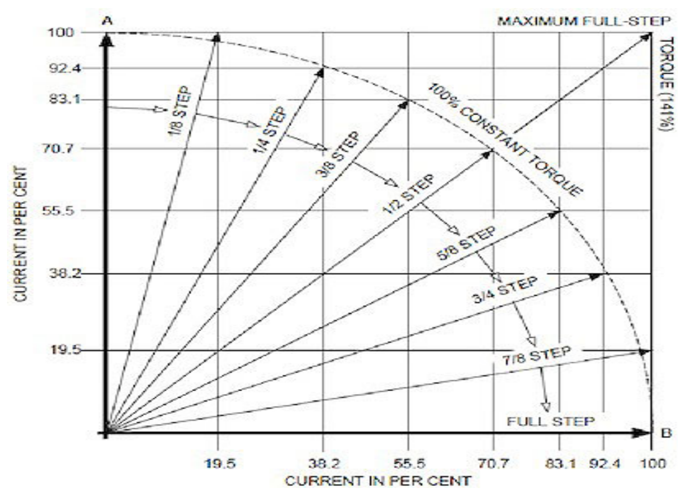


Fig. 6 Micro stepping technique

2.4 Stepper drive types

The output from controller (200mA) is not sufficient to rotate stepper motor, so a drive circuit is used to power the motor. Drive circuits also change the current and flux directions in phase winding independently, in order to rotate the motor. Drive systems are divided into two types [46]

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a) Unipolar drive.
b) Bipolar drive.

a) Unipolar drive:

The current in this drive type has one direction and this is achieved by center tab the phase winding (unipolar 6 wire) or uses two separate winding (unipolar 8 wire) per phase. This center tap is connected to the positive supply, and the ground is alternately connected to the winding end. Unipolar drive circuit is simple and less expensive but has lower efficiency and performance as shown in Fig.7 [47-48].

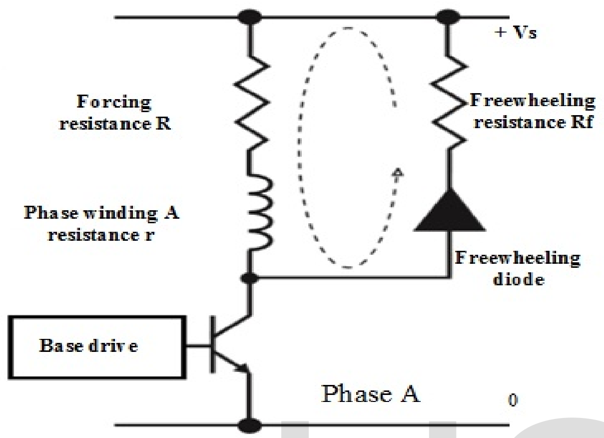

Fig. 7 One phase unipolar drive circuit configuration
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b) Bipolar drive:

Current direction in the same winding is changed by changing the polarity of the applied voltage so one winding per phase is required. This type has simple construction because no center tap is required but the driver circuit is more complicated. Bipolar drive circuit is more expensive but has high performance and high efficiency, as shown in Fig. 8 [49-51].

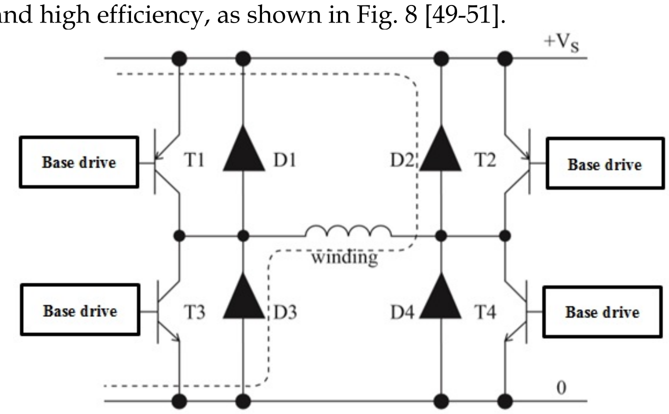

Fig.8 One phase bipolar drive circuit configuration
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3. Position Control Strategies

Stepper motors input is a train of pulses (DC pulses) with a specific sequence and a specific time intervals. This train of pulses is applied to the motor driver from the controller, which is responsible for the formation of this DC pulses without any feedback. Stepper motor driver receives these DC to energize and control the phases of the stepper motor. Stepper motors are used in open loop applications with good accuracy as it moves from a known position to another known one. However, the open loop control technique suffers from low performance capability, oscillating response due to inertia and poor behavior with system and load variations [52, 53].

A new programmable architecture called Field Programmable Gate Array (FPGA) used with micro stepping technique to improve the stepper motor system behavior. FPGA has many advantages such as reliable, fast response, programmable architecture, flexible, it can implement for complex control algorithm and cost of FPGA decreases while the density increases. Using of FPGA subdivide the motor step to a multiple number of micro step with the required resolution to improve position accuracy and smoothing the rotor rotation, but leaves the open loop control problem unsolved [54-59].

Without feedback, systems cannot detect any output problems. In stepper motor case; miss or loss in motor steps cannot be detected. In order to avoid the open loop control technique problems, closed-loop control techniques are used.

Closed loop control techniques used in stepper motor systems gives a satisfactory performance and improves its robustness. Stepper motor starts with one pulse then a train of pulses is used to control the motor. Feedback parameters in position control of stepper motor is important for closed loop applications, and this is done by two types of sensing techniques namely sensor and sensor less techniques. In sensor type, rotor position or velocity is picked up by a sensing device such as tachometer, optical encoder etc. These feed-back sensors are built in motor or even in the drive system. Sensed signal is modified with the input signal and delivered again to the controller to close the control loop. Mechanical sensors such as encoders in the past were a solution to the open loop problems but it increases the size and cost of the system so system becomes bulky. In addition, mechanical measurement for position or speed is weak in high temperature and high vibrations environment and sensors are difficult to be installed [60-63].

In sensor less type, information can be extracted from the stator circuit parameters measurement such as the winding inductance, the back EMF and the flux linkage. Back EMF is proportional to speed, by measuring the back EMF and multiplying it with certain constant speed can be obtained, the only drawback is that this type cannot be used in standstill or low velocities. Winding inductance and flux linkage can also be used to indicate rotor position. Sensor less techniques use low component and hence low price, but reliability and complexity are still problems [64-67].

Microcontrollers use different types of control algorithms such as field oriented control (FOC), direct torque control (DTC), emotional control (EMC) and model reference adaptive system (MRAS). FOC is used to enhance resonance anomalies, skipped steps and improves dynamics rather than stepping. The current drawn to the motor is controlled to maintain a specific angle between the rotor and the stator magnetic fields. Maximum torque is obtained by maintaining rotor magnetic field perpendicular to stator magnetic field. Fig. 9 shows model reference adaptive system used to drive stepper motor. DTC

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is used to eliminate the variable nature of voltage source inverter and also uses a small number of machine parameter, so DTC is better than FOC, due to its simplicity and robustness to parameter uncertainty [68, 70]. Using self-tuning regulator in controlling stepper motors speed forces the controller to adapt the motor operating conditions but this is difficult to implement in real time because it requires a large amount of floating point computations, so sampling period gets increased [71].

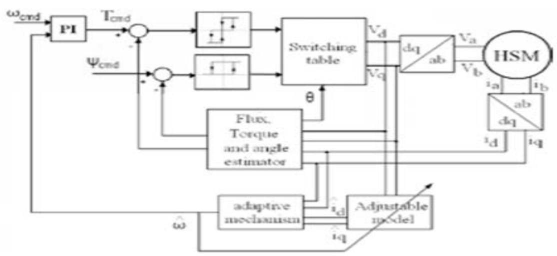

Fig. 9 Model reference adaptive system technique [70]

Using of classical closed loop control techniques such as PID gives a precise operation performance. But as a result of nonlinear characteristics and resonance problems it is difficult to carry out classical control systems with this type of motor. The response of the classical closed-loop control techniques (such as PID controller that applied to the stepper motor) to the system variation may reach to zero until applying adaptive technique. So, use of classic closed loop algorithms such as PID is weak unless the control technique is forced to adapt to the motor operating conditions. Fuzzy logic algorithm is used to the adaptation process that means; the gain of the PID controller is changed by a fuzzy algorithm to cope with the variation of the system parameter during any process.

Fuzzy PID have two types according to the construction, the first one has no explicit PID gains; instead the control signal is directly deduced from knowledge and fuzzy interference. The second type is fuzzy schedule of conventional PID gains and this is recently used widely to solve different control problems. Fuzzy PID has reduced the settling time and the overshoot value of the system response greatly from the analyzed result [72-76].

4. Microcontroller for Stepper Motor Position and Speed Control

Any closed loop control system has an essential part that is known as controller. Stepper motor controller developed from time to time, the first generation of stepper motor controllers is the stepper motor controller 1(SMC1) which used a cheap components in the implementation process. Stepper motor controller 2 (SMC2) used a semi- discrete implementation of a sensor based, field oriented control. A microcontroller is used in the design of SMC1 and SMC2. Stepper motor controller 3 (SMC3) used few number of physical components compared with SMC1 and SMC2. SMC3 used a DSP that allows complex functions to be executed with the aid of software rather than hardware. Controlling the current in SMC1 and SMC2 uses hardware approach while SMC3 controls the current using control firmware [68].

4.1 Application of Microcontroller in Position Control

Examples of position controllers will be illustrated to indicate the validity of stepper motor in position control systems. Arduino ATMega 2560 was used by Parmar et al., to control the position of two stepper motors, as it is capable of both independent and synchronized control of stepper motors. They mentioned that the controller is able to smoothly control the position of the stepper motor taking into account the physical constrains such as a feedback element used to count the steps of the stepper motor efficiently. Parmar et al, results have shown that Arduino ATMega 2560 has a high resolution as well as high accuracy and can eliminate the drawback of losing any steps [77]. On another hand, ATMega 16 microcontroller was used by Huy et al., to control the overall function of an interfering mobile device. Controller is used to set the accurate position of the vehicle and the rotation of the noise jammer by controlling four stepper motors for position and one stepper for the rotation of the jammer unit [78]. PIC16F877A microcontroller was used by Somesh et al., to maintain the phase current constant at any level to improve the position accuracy of the proposed system with a cost effective component [79]. Also, Yousef et al., used this controller for unipolar position control of three stepper motor using three stepping mode of excitation (wave step, full step and half step). Three ULN 2803 are used as drivers for stepper motors. Simulation by flow code and proteus was done and the experimental system was then executed. Results of all control techniques show the validity of the proposed system [80]. Fernandes et al. used Microcontroller (PIC16F877A) in a laser beam power adjustment system to control the position of the power sensor and the attenuating disk rotation. First stepper motor is used to adjust the angle and the second one is used in the maneuvering of the optical sensor [81].

PCL-838 (80c3-CPU) was used by Morar in position control of full/half five phase stepping motor by linearly accelerate and deaccelerate the motor. In addition, self-testing of the motor driver is done, whether normal or not. An up-to-date translator for the motor is used to drive the N-channel MOSFET array with a resolution of full/half mode is 0.72/0.36 degree/step. The results showed the validity of such compact and intelligent driver for a five-phase stepper motor with a small size and the precision of speed and position control. These benefits push this type of motor to operate in robotics and in automation application [82]. In addition, Morar used PCL838 microcontroller to control and test a five phase stepper motor driver. This controller was able to improve performance characteristics such as low response and high oscillation in two phase stepper motor. The driver used solves the problem of complexity and high cost. Constant current chopping technique was used, in order to have high velocity, torque and high efficiency [83]. PLC was used by Sarhan to control stepper motor drive for numerical control (NC) positioning system. Full stepping, half stepping and micro stepping is achieved by the PLC controller. Sarhan results showed that micro stepping is the best solution for precise control of NC positioning system [84].

Microcontroller PIC18F14K50 with a java program was used to control 3 A TB3-axis HY-TB3DV stepper motor drivers with USB in order to control the position of a 2D (two dimensional) stepper motor in forward and reverse operation. Slow and steady starting, stopping and reversing the motor operation, all are discussed [85] (Ghazali, 2015). Atmel 85c51 microcontroller was used by Chakraborty et al., to control the position of stepper motor to overcome loss or slip in steps of stepper motor. This microcontroller is interfaced with ADC 0804 (driver) for setting the position of the stepper motor angle by driving the steps of the stepper motor, reading the output of the position sensor, count step value and then display [86]. Ledshine Mikrostep Drive ND2282PBF controller was used by Wargula et al., to analyze the dynamic feature of 2-phase stepper motor (WOBIT 110BYGH601) while stopping and starting with and without load [87]. Another microcontroller with a specific program algorithm was used by Przeniosło et al., to emphasize the processor overhead minimization. Uses of closed loop controller results in great wasting in the overall system time, a specific program used to ensure the stability and optimization of the system time without any feedback [88].

4.2 Application of microcontroller in speed control

In the field of speed control stepper motors have newly gained a great consideration as AT89S51 microcontroller used by Ruifeng et al., to control the speed and the rotation of the motor. Microcontroller and its programming algorithm show a high reliability and a strong stability [89]. ATmega16A microcontroller was used by Bhale et al., to control the speed of a stepper motor. Output current from microcontroller is not sufficient to drive the stepper motor so Darlington transistor ULN2003 is used to drive the stepper motor. In fact, stepper motor is used to adjust the distance between two sphere apparatus. From previous results it was showed that stepper motor driven by microcontroller has a precise acceleration and deceleration results compared to IC555 driver [90]. Furthermore, Microcontrollers SMC147-S-2 and STM32 were used by Kuklaa et al., for determination of the torque characteristics of a stepper motor. Investigation stated that 'the higher the rotational speed, the lower the torque of the stepper motor [91]. EZMC36I controller is used by Ming et al., to control the speed and position of stepper motor in real time depending on C++ program software and good accuracy is achieved [92].

CONCLUSION

This paper discussed in details stepper motor basics and different controller types used in control stepper motors. Using stepper motor with closed loop control techniques improves position and velocity tracking performance. Different types of control algorithm are illustrated to show benefits over classical types of stepper motor. From the previous explanation and collection of information we conclude that stepper motor is an efficient choice in control application espicially in positioning control applications due to its simplicity, low coast, simple drive system, precise open and closed loop applications, high accuracy and torque in low speed.

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