IMPLEMENTING TRAPEZOIDAL VELOCITY PROFILE FOR PRECISE CONTROL OF STEPPER MOTORS USING ESP32 AND A4988 STEPPER DRIVER WITH NEMA17

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Abstract - This paper presents a comprehensive study on the implementation of a trapezoidal velocity profile for precise control of stepper motors using an ESP32 microcontroller, an A4988 stepper driver, and a NEMA17 stepper motor. The primary objective of this research is to achieve accurate and smooth motion control by generating a trapezoidal velocity profile, encompassing acceleration, constant velocity, and deceleration phases. The methodology involves a detailed explanation of the hardware setup, the algorithm for trapezoidal profile generation, and the incorporation of an inverse displacement function-based delay mechanism according to current step(pulse). Experimental results demonstrate the successful realization of the desired velocity profile and validate the effectiveness of the proposed delay control approach. The significance of this study lies in its contribution to enhancing the precision and performance of stepper motor applications, with potential implications in robotics, automation, and various other fields requiring precise motion control.

Keywords - Trapezoidal Velocity Profile, Motion Control, AS5600 Magnetic Encoder, Pulse Based Velocity Control

I. INTRODUCTION

Stepper motors are widely used in a variety of applications, including robotics, industrial automation, 3D printing, and CNC machining. They offer precise and controlled rotational motion, making them ideal for accurate positioning and synchronization tasks. The development of advanced control techniques is essential to harness the full potential of stepper motors.

Traditional stepper motor control methods often exhibit limitations in terms of smoothness and precision, leading to performance degradation and energy wastage. The trapezoidal velocity profile control system is a promising solution to these challenges, enabling enhanced accuracy, repeatability, and energy efficiency. The trapezoidal profile encapsulates acceleration, constant velocity, and deceleration phases, resulting in seamless and accurate motion profiles. This profile also minimizes wear and tear on mechanical components and optimizes energy consumption, making it a compelling choice for demanding applications.

This study aims to design and implement a trapezoidal velocity profile control system for the NEMA17 stepper motor using the ESP32 microcontroller and A4988 stepper driver. An inverse displacement function-based delay mechanism is integrated into the control system to minimize synchronization delays. This paper presents a comprehensive study that bridges the gap between theory and implementation, showcasing the successful integration of the trapezoidal velocity profile and the simple delay mechanism to achieve precise control over the NEMA17 stepper motor.

A. Aim

The aim of this research is to develop and implement a simple, precise, and efficient trapezoidal velocity profile control system for the NEMA17 stepper motor using the ESP32 and A4988 stepper driver.

B. Objectives

The specific objectives of this research are to:
Design and implement a trapezoidal velocity profile control system for the NEMA17 stepper motor using the ESP32 and A4988 stepper driver.
Develop an inverse displacement function-based delay mechanism to minimize synchronization delays.
Evaluate the performance of the control system in terms of accuracy, repeatability, and energy efficiency.

C. Motivation

The motivation for this research stems from the need for precise and efficient stepper motor control in a variety of applications. Traditional control methods often exhibit limitations in terms of smoothness and precision, leading to performance degradation and energy wastage. The trapezoidal velocity profile control system offers a promising solution to these challenges, enabling enhanced accuracy, repeatability, and energy efficiency.

Additionally, the proposed approach using an inverse displacement function-based delay mechanism is simple enough to calculate with the computing power of most microcontrollers. This makes it a practical and scalable solution for a wide range of applications.
Overall, this research aims to contribute to the development of advanced stepper motor control techniques that can meet the increasing demands of modern engineering applications.

II. LITERATURE REVIEW

The field of stepper motor control has witnessed substantial research aimed at optimizing motion control strategies and enhancing precision. A comprehensive survey of existing literature reveals a diverse array of techniques employed for stepper motor control, ranging from open-loop control methods to more intricate closed-loop approaches[1]–[4].

Velocity profiling plays a pivotal role in achieving smooth and accurate motion control. Numerous studies have investigated the merits of employing velocity profiles, such as trapezoidal, triangular, and S-curve profiles, to attain optimal acceleration, deceleration, and steady-state motion. These profiles have demonstrated their effectiveness in reducing overshoot, minimizing settling time, and improving overall system stability[1].

Notably, recent research has focused on leveraging modern microcontrollers for stepper motor control, with the ESP32 standing out as a popular choice due to its computational capabilities and built-in peripherals. Various investigations have demonstrated successful implementations of ESP32-based control systems, showcasing its potential for real-time motion control applications.

Moreover, the A4988 stepper driver has garnered attention for its capability to regulate current to the motor windings efficiently, enabling precise torque control. Studies have explored its integration within control systems, highlighting its role in achieving fine-grained motor control and reducing power consumption.

However, despite the strides made in stepper motor control, challenges persist in the successful implementation of trapezoidal velocity profiles. Previous attempts have highlighted issues related to synchronization between profile phases, non-uniform acceleration, and difficulties in handling abrupt changes in velocity. Additionally, limitations in achieving accurate motion under varying loads and environmental conditions have been identified[1].

While existing literature provides valuable insights into stepper motor control and velocity profiling, gaps remain in the seamless integration of the trapezoidal velocity profile with robust delay mechanisms to address the identified limitations. This paper seeks to build upon these findings by presenting a novel approach that combines the benefits of the trapezoidal profile with an inverse displacement function-based delay, thereby advancing the precision and efficiency of stepper motor control using the ESP32, A4988 stepper driver, and NEMA17 stepper motor.

The foundation of our trapezoidal velocity profile control system rests upon a carefully designed hardware architecture, consisting of the ESP32 microcontroller, the A4988 stepper driver, and the NEMA17 stepper motor. This section presents a comprehensive breakdown of the system's components, their interconnections, and the communication protocol governing their interaction.

III. HARDWARE

The ESP32, renowned for its computational prowess and wireless capabilities, serves as the brain of our control system. Its dual-core architecture enables efficient multitasking, making it well-suited for real-time motion control applications. The A4988 stepper driver is chosen for its ability to regulate current to the motor windings accurately, facilitating precise torque control. The NEMA17 stepper motor, with its widespread compatibility and reliability, completes the hardware trio.

A. Interconnections and Wiring Diagram:

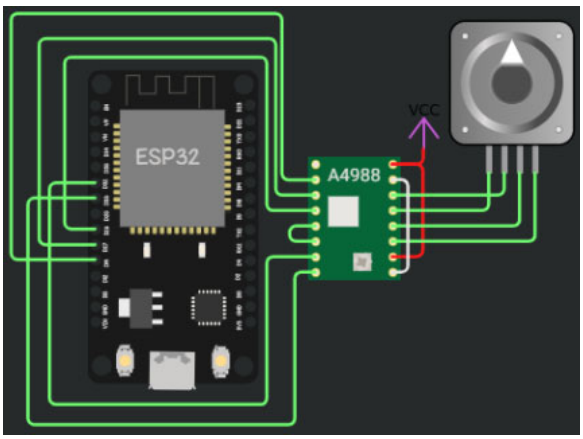


Figure 1: Wiring Schematic for ESP32, A4988, and NEMA17 in the Wokwi Online Simulator

The interconnections between these components are orchestrated to ensure seamless data exchange and control. The ESP32 interfaces with the A4988 stepper driver through a set of GPIO pins, allowing it to transmit control signals and receive feedback. The stepper driver, in turn, regulates the current to the coils of the NEMA17 motor, dictating its motion.

To illustrate these connections, a comprehensive wiring diagram is provided in figure 1, outlining the pin-to-pin correspondence between the ESP32 and the A4988 stepper driver, as well as the connections between the stepper driver and the NEMA17 stepper motor. This meticulous arrangement ensures a clear and organized hardware setup, laying the groundwork for precise motion control.

B. Communication Protocol:

The communication protocol governing the interaction between the ESP32 and the A4988 stepper driver is designed to facilitate efficient data exchange and synchronization. The ESP32 generates control signals in accordance with the trapezoidal velocity profile algorithm and transmits them to the A4988 stepper driver. These control signals encompass step pulses and direction signals, directing the stepper driver to execute the desired motion.

In summary, the system architecture is meticulously designed to harmoniously integrate the ESP32, A4988 stepper driver, and NEMA17 stepper motor. The hardware setup is fortified by a well-defined communication protocol, enabling the seamless transmission of control signals and the execution of the trapezoidal velocity profile. This synergy forms the bedrock upon which precise motion control is realized, paving the way for the subsequent implementation of the inverse displacement function-based delay mechanism. Furthermore, the efficiency of the system is also observed by using AS5600 magnetic encoder.

IV. TRAPEZOIDAL VELOCITY PROFILE GENERATION:

The heart of our control system lies in the generation and execution of the trapezoidal velocity profile, a crucial element in achieving smooth and precise motion control. This section delves into the algorithmic intricacies behind the profile generation, shedding light on the steps taken by the ESP32 to orchestrate the acceleration, constant velocity, and deceleration phases.

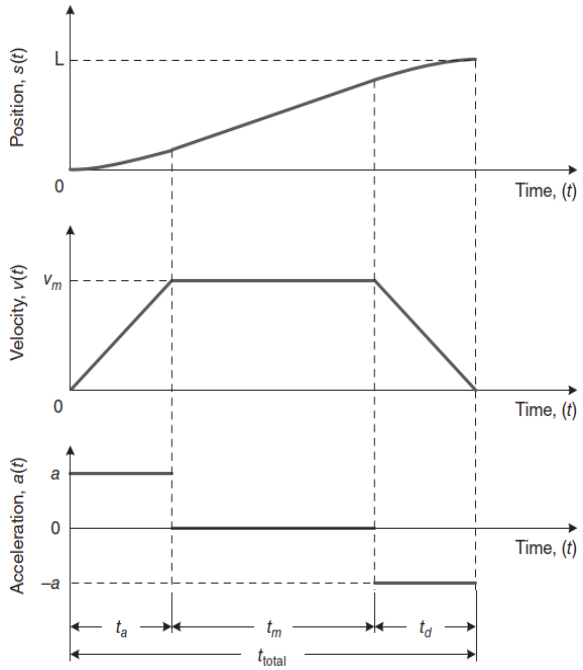


Figure 2. Trapezoidal velocity profile and associated position and acceleration[5]

A. Trapezoidal Profile Algorithm:

The trapezoidal profile generation algorithm primarily relies on calculating the number of pulses (steps) necessary for the stepper driver to traverse a given distance, along with determining the time intervals between consecutive pulses. This is accomplished by employing geometric principles to compute the total distance traveled, which involves summing the areas of two triangles and a rectangle beneath the velocity curve, as illustrated in Figure 1 [5]. The distance can be calculated using the following equation:

$$L = \frac{t_a v_m}{2} + t_m v_m + \frac{t_d v_m}{2} \quad (1)$$

Consequently, the distance (expressed in steps) required to accelerate to the desired velocity v_m can be represented as:

$$s_a = \frac{t_a v_m}{2} \quad (2)$$

The acceleration phases can be described by the following equation, which relates displacement to time:

$$s(t) = \frac{1}{2} at^2 \quad (3)$$

The equation representing the relationship between displacement and time is given by:

$$s(t)^{-1} = t(s) = \sqrt{\frac{2s}{a}} \quad (4)$$

By subtracting the times for adjacent steps, it is possible to calculate the delay time between them. Based on this premise, a lookup table of delay times can be generated. This table can then be used to drive the stepper motor in accordance with the table for acceleration. Similarly, the table can be employed in reverse to decelerate the motor.

During the constant velocity phase, the delay time remains constant and is determined by the velocity.
The step-by-step procedure for the trapezoidal profile generation algorithm is shown in figure 3.

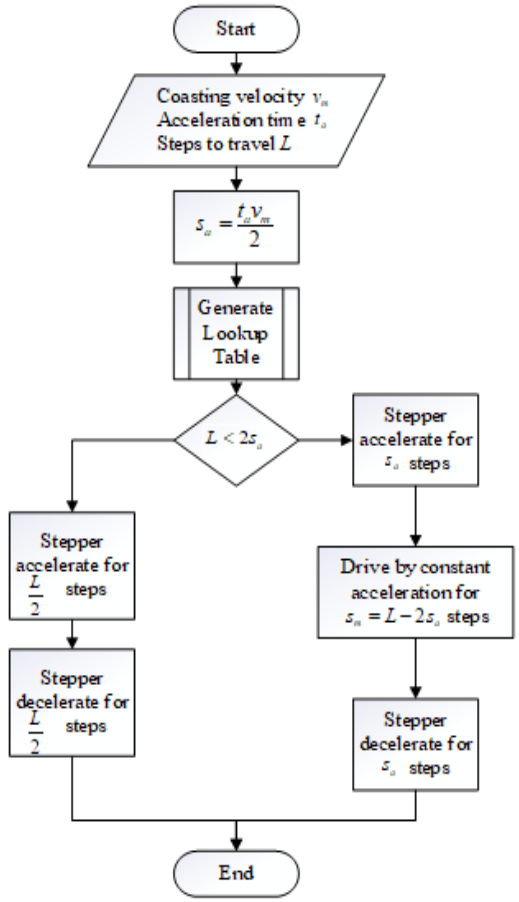
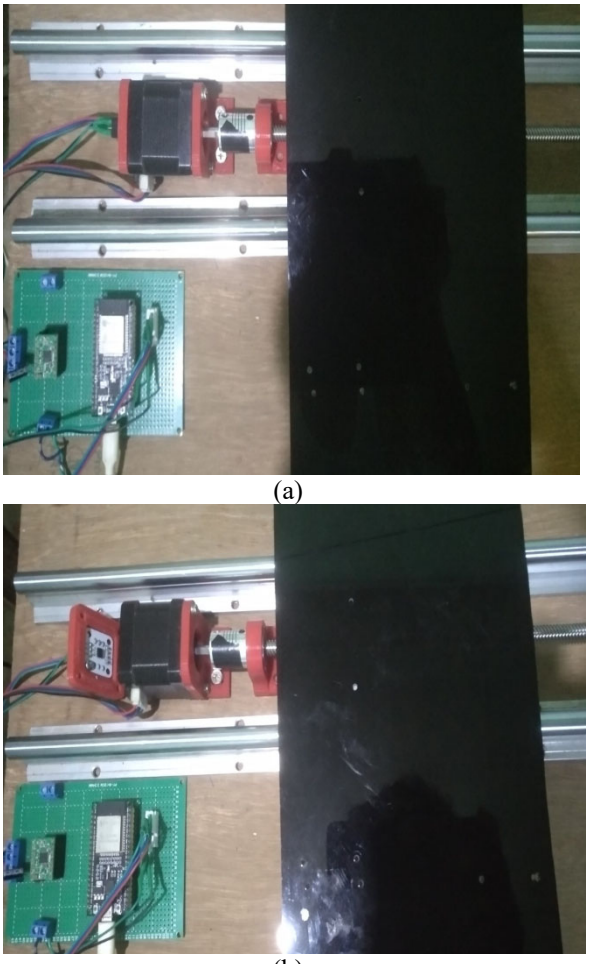


Figure 3: Flowchart depicting the Trapezoidal Profile Generation Algorithm

V. EXPERIMENTAL INVESTIGATION FOR PRECISE STEPPER MOTOR CONTROL

In pursuit of achieving precise control over stepper motors, a comprehensive series of experiments aimed at elucidating the influence of different speeds and accelerations on motor performance was conducted. The comprehension of these factors is of paramount importance in the optimization of motion control across a spectrum of applications.



(a)

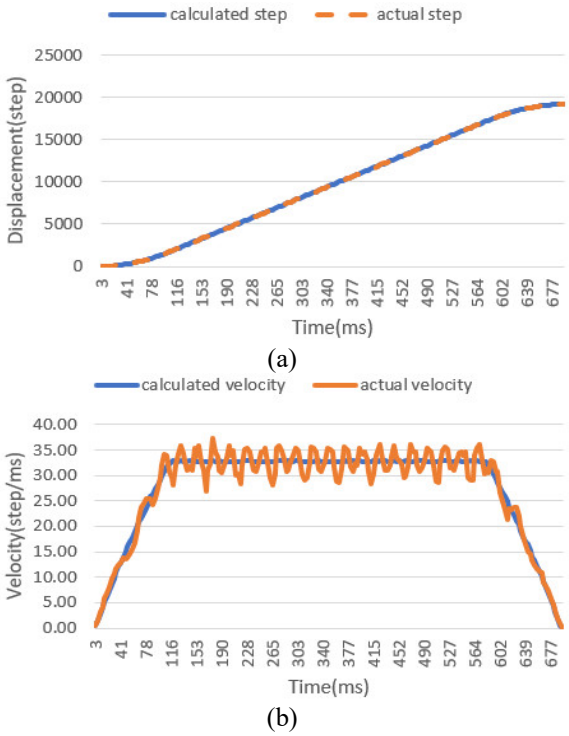
(b)

Figure 4: Experimental Configuration for Monitoring Displacement Utilizing the AS5600 Magnetic Encoder

Figure 4 depicts the experimental configuration utilized in our study. The system is identical in both images within the figure; however, in the second image, the AS5600 was disassembled to provide a clearer view of its attachment and its ability to sense the rotation of the stepper motor's rotor.

During the experiments, the acceleration time was consistently set to 120 milliseconds, and a 2 kg weight was placed on the table to simulate a load during the driving tests. The stepper motor was subjected to test drives at speeds of 160 mm/s, 180 mm/s, and 200 mm/s, covering a distance of 100 mm.

VI. RESULTS AND DISCUSSION

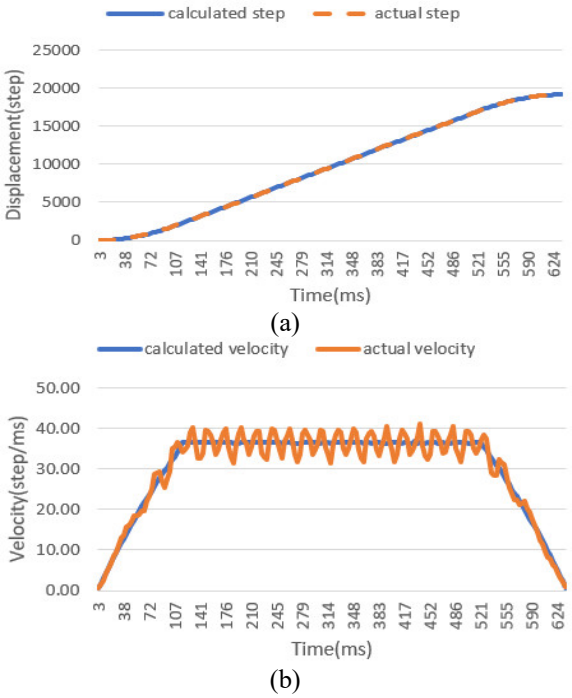


(a)

(b)

Figure 5: Comparative Analysis of Calculated and Actual Displacement and Velocity at a Coasting Velocity of 160 mm/s (32 step/ms)

Following a series of tests encompassing various acceleration times and coasting velocities, our findings reveal that step losses are sporadic, with a maximum deviation of 3 steps. Notably, at coasting velocities exceeding 200 mm/s, initial slipping was observed.



(a)

(b)

Figure 6: Comparative Analysis of Calculated and Actual Displacement and Velocity at a Coasting Velocity of 180 mm/s (36 step/ms)

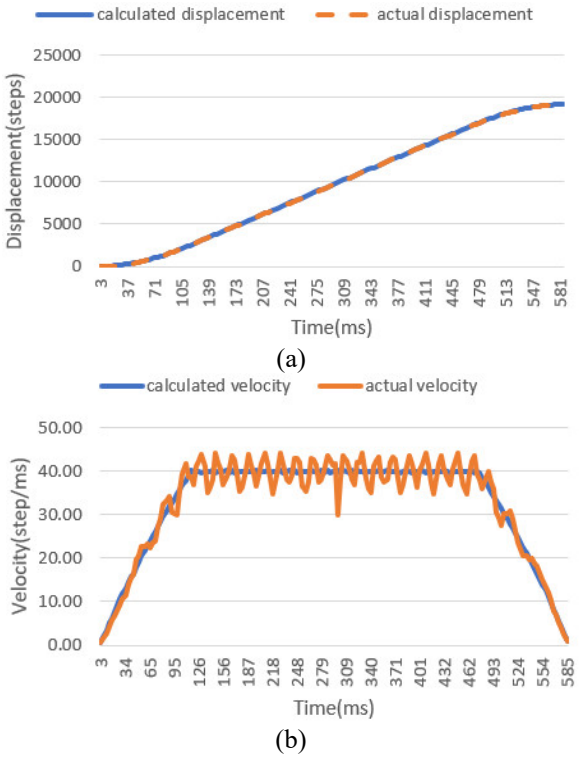


Figure 7: Comparative Analysis of Calculated and Actual Displacement and Velocity at a Coasting Velocity of 200 mm/s (40 step/ms)

VII. CONCLUSION

In conclusion, the velocity profile generating algorithm presented in this study is marked by its simplicity and efficiency, rendering it a valuable asset for precise stepper motor control. The algorithm exhibits commendable positional accuracy, ensuring precision across various motor control applications. Moreover, the smooth operation of the sliding mechanism stands as a critical factor in optimizing performance. It is noteworthy that transitioning from a lead screw to a ball screw mechanism holds the potential for achieving significantly improved results. The adoption of a ball screw promises enhanced speed capabilities, thus opening doors to further advancements in motor performance and broader applications.

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