SmartLabel: A 3D-Printed Custom Label Maker

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1 Introduction

This project focuses on creating a label maker using an ESP32 microcontroller. The system integrates stepper motors for two-axis movement and a servo motor to control the pen's position, allowing it to draw lines, shapes, and letters on tape or paper. This label maker system is a great introduction to automation, motion control, and embedded systems. It offers a hands-on approach to building a simple plotter and can be expanded for more complex projects like CNC machines or automated drawing systems.

2 Working Principle

The label maker operates based on principles of classical mechanics, electromagnetism, and control systems. Classical mechanics explains how the stepper motors move the screw and rotate the tape, translating motion to specific positions. The stepper motors and servo motor rely on electromagnetism to convert electrical energy into precise mechanical motion. A gear system connects the servo motor to the pen, translating the servo's rotational motion into linear movement. This mechanism allows the pen to move closer to or further from the tape. Control systems coordinate the movements of the motors and servo, while the microcontroller manages the timing and synchronization of all components, ensuring the pen and tape accurately.

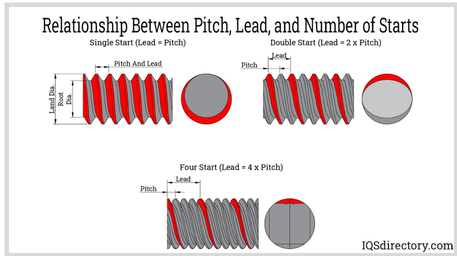
2.1 Moving the Base through the Screw with the Stepper Motor

A stepper motor rotates a screw, which moves a base along the screw using the lead screw principle. This mechanism converts the rotary motion of the screw into linear motion through its threaded design. The amount of linear motion per revolution depends on the screw's pitch (the distance the nut moves for one full rotation of the screw).

2.1.1 Lead Screw Principle

A lead screw is a mechanical device used to convert rotational motion into linear motion. It consists of a screw (with helical threads) and the base moves along the threads when the screw is rotated. The rotation of the screw moves the base linearly along the axis of the screw.

- **Pitch of the screw** is the distance that moves a nut for each complete revolution of the screw. It is a key parameter that defines the screw's movement per rotation.
- **Lead** is the distance the nut moves for each full turn of the screw. The lead may be different from the pitch if the screw has multiple threads.
- **Screw's threads** are usually angled, and the nut engages with the threads as the screw rotates, causing linear motion. The mechanical advantage of the screw can be increased by increasing the number of threads or by using a larger pitch.



2.1.2 Kinematics Analysis of Position

The kinematics of the base's position is governed by the relationship between the rotational motion of the stepper motor and the linear motion of the lead screw. The position of the base, $x(t)$ assumes an idealized system , can be expressed as:

$$x(t) = p \cdot N(t)$$

where:

- $x(t)$: Linear displacement of the base as a function of time.
- p: Pitch of the screw (distance the nut moves per full revolution of the screw).
- $N(t)$: Number of rotations of the screw as a function of time.

For a stepper motor with S steps per revolution, and a time step Δt for each motor step:

$$N(t) = \frac{t}{\Delta t} \cdot \frac{1}{S}$$

Substituting $N(t)$ into the position equation, we get:

$$x(t) = p \cdot \frac{t}{\Delta t} \cdot \frac{1}{S}$$

Simplifying:

$$x(t) = \frac{p}{S \cdot \Delta t} \cdot t$$

where:

- t: Time elapsed.
- Δt: Time taken for one step of the motor.
- S: Number of steps per revolution of the motor.

This equation shows the linear relationship between time t and the displacement $x(t)$, where the slope is determined by the pitch p, steps per revolution S, and the time step Δt.

1. **Distance per Step**
   The distance moved by the base for each step of the motor is given by:

$$\Delta x = \frac{p}{S}$$

   where:

- Δx: Linear displacement per motor step.
- p: Pitch of the screw.
- S: Steps per revolution of the motor.

2. **Total Displacement After N Steps**
   The total displacement after N steps is:

$$x_{\text{total}} = N \cdot \Delta x$$

   Substituting Δx, we get:

$$x_{\text{total}} = N \cdot \frac{p}{S}$$

   This equation shows that the total linear displacement is directly proportional to the number of motor steps N.

2.1.3 Forces

To move the base, the stepper motor must generate sufficient torque to overcome both the frictional forces and the load force. The forces acting on the system include:

1. **Frictional Force (F_{friction})**
   Friction occurs between the threads of the screw and the nut attached to the base. The frictional force is given by:

$$F_{\text{friction}} = \mu \cdot N$$

   where:

   - μ: Coefficient of friction (dimensionless).
   - N: Normal force (force pressing the nut and screw together, often proportional to the weight of the base and any additional load).

2. **Driving Force (F)**
   The force needed to move the base is related to the torque τ generated by the stepper motor. The relationship between torque and linear force is:

$$F = \frac{\tau}{r}$$

   where:

   - τ: Torque generated by the stepper motor (in Nm).
   - r: Radius of the screw thread (distance from the center of the screw to the point of contact with the nut).

3. **Net Force (F_{net})**
   The net force moving the base is the difference between the driving force F and the frictional force F_{friction}:

$$F_{\text{net}} = F - F_{\text{friction}}$$

   For motion to occur, the driving force F must be greater than the frictional force F_{friction}, i.e.,

$$F > F_{\text{friction}}$$

2.1.4 Torque and Power

The stepper motor generates a torque τ to overcome friction and move the load. The required torque can be calculated as the sum of the torque needed to overcome friction and the torque needed to move the load:

1. **Required Torque**

$$\tau = F_{\text{friction}} \cdot r + F_{\text{load}} \cdot r$$

   where:

   - F_{friction}: The force required to overcome friction.
   - F_{load}: The force required to move the weight of the base (load).
   - r: The radius of the screw thread.

2. **Power Output**
   The power tells us how quickly rotational energy is being transferred by the motor.Power P delivered by the motor is the product of the torque and the angular velocity ω of the screw:

$$P = \tau \cdot \omega$$

   where:

   - P: The power output in Watts.
   - ω: The angular velocity in radians per second.

2.2 Adjusting the Pen with the Servo

On top of the base is a servo motor, which controls the position of the pen. The servo can adjust the pen's position (closer to or further from the tape) based on the input signal. The servo achieves this by rotating a shaft, which is connected to a set of gears. The gears translate the rotational motion of the servo into a vertical displacement of the pen, enabling precise positioning.

2.2.1 Rotational to Linear Motion And Forces

The servo motor converts rotational motion into linear motion to control the vertical displacement of the pen. The system's behavior is determined by the geometry of the lever, the torque provided by the servo motor, and the gear system connecting the servo to the pen.

1. **Vertical Displacement of the Pen**
   The rotational motion of the servo motor is transferred through a lever arm of length ℓ. The vertical displacement d of the pen is determined by the rotation angle θ of the servo motor:

   $$d = \ell \sin(\theta)$$

   where:

   - ℓ: Length of the lever arm.
   - θ: Rotation angle of the lever (in radians).

2. **Force Exerted by the Pen**
   The force F applied by the pen onto the tape depends on the torque τ generated by the servo motor and the lever arm's length ℓ:

   $$F = \frac{\tau}{\ell}$$

   where:

   - τ: Torque produced by the servo motor.
   - ℓ: Lever arm length.

2.2.2 Pressure on the Tape

The pressure P, defined as the force per unit area applied by the pen on the tape, depends on the cross-sectional area A of the pen tip. Using $F = \frac{\tau}{\ell}$, we can express the pressure as:

$$P = \frac{F}{A} = \frac{\tau}{\ell A}$$

where:

- A: Cross-sectional area of the pen tip.
- P: Pressure exerted on the tape.

2.2.3 Gear Ratio and Pen Displacement

A gear mechanism is a system of interlocking gears used to transfer motion and torque between machine components. Gears are toothed mechanical elements that mesh with each other to transmit rotary motion, change the direction of rotation, and adjust speed or torque.

1. **Gear Ratio**
   The gear ratio is determined by the number of teeth on each gear. If one gear has more teeth than the other, the output gear will rotate more slowly but with more torque, and vice versa.

$$\text{Gear Ratio} = \frac{\text{Number of Teeth on Driven Gear}}{\text{Number of Teeth on Driver Gear}}$$

2. **Direction of Rotation**
   When two gears mesh, they rotate in opposite directions. If the driving gear turns clockwise, the driven gear will rotate counterclockwise.

3. **Vertical Displacement**
   The servo is connected to a gear system, and the pen's vertical displacement depends on the gear ratio. If the servo rotates by θ_{servo}, and the gear ratio between the servo and pen is $\frac{N_{\text{pen}}}{N_{\text{servo}}}$, the vertical displacement Δy_{pen} is given by:

$$\Delta y_{\text{pen}} = \frac{N_{\text{pen}}}{N_{\text{servo}}} \cdot \theta_{\text{servo}}$$

The connection between the servo motor and the pen through the gear system ensures smooth translation of rotational motion into linear motion. This mechanism allows for precise control of the pen's position relative to the tape, enabling accurate labeling.

2.3 Rotating the Tape with Stepper Motor

The stepper motor controls the movement of tape by rotating a roller, the motion is discrete and is governed by the stepper motor's steps.

2.3.1 Displacement per Step

The linear displacement of the tape depends on the radius of the roller and the angle by which the stepper motor rotates it. The relationship is:

$$\text{Displacement per step} = r_{\text{roller}} \times \Delta\theta_{\text{motor}}$$

where:

- r_{roller}: Radius of the roller.
- $\Delta\theta_{\text{motor}}$: Angle the stepper motor rotates (in radians) per step.

Since the stepper motor has discrete steps, each step corresponds to a fixed angle of rotation, typically:

$$\Delta\theta_{\text{motor}} = \frac{2\pi}{S}$$

where S is the number of steps per revolution of the motor.
Therefore, the displacement of the tape per step is:

$$\Delta x = r_{\text{roller}} \times \frac{2\pi}{S}$$

2.3.2 Total Displacement After N Steps

After N steps, the total displacement of the tape is:

$$Y_{\text{total}} = N \times r_{\text{roller}} \times \frac{2\pi}{S}$$

where:

- N: Number of steps the motor has taken.
- r_{roller}: Radius of the roller.
- S: Number of steps per revolution of the motor.

This equation describes the total movement of the tape in linear distance.

2.4 Analysis Of Entire System

In the system, the motion of the pen is determined by a combination of translational and rotational movements:

- **Y-Axis (Base Movement):** The first stepper motor drives the base via a screw mechanism, resulting in linear movement proportional to the number of steps taken by the motor.
- **X-Axis (Tape Movement):** The second stepper motor drives the tape, moving it in discrete steps determined by the motor's movement .
- **Z-Axis (Vertical Pen Movement):** The servo motor and gear mechanism control the vertical motion of the pen, moving it closer to or further from the tape surface.

The overall position of the pen at any time can be described as:

$$P_{\text{pen}} = (X_{\text{total}}, Y_{\text{total}}, Z_{\text{pen}})$$

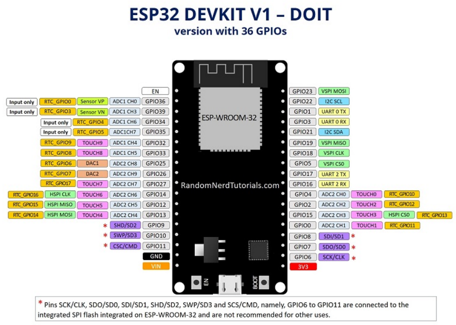
where:

- X_{total}: Position of the base along the X-axis.
- Y_{total}: Position of the tape along the Y-axis.
- Z_{pen}: Vertical position of the pen along the Z-axis.

3 Components

3.1 Esp32 Microcontroller

The ESP32 microcontroller is a highly capable platform for IoT, embedded systems, and automation projects. Below are aspects of the ESP32:



3.1.1 Core Features

- **Processor**
  - Dual-Core Tensilica Xtensa LX6:
  - Can operate in single-core or dual-core mode.
  - Clock speed: Up to 240 MHz.
- **Memory**
  - RAM: Typically 520 KB of SRAM.
  - Flash: External flash memory up to 16 MB for program storage.
  - EEPROM: Emulated in flash for non-volatile data storage.
- **Wireless Capabilities**
  - **Wi-Fi**
    - IEEE 802.11 b/g/n standards.
    - Dual-mode (Station and Access Point).
  - **Bluetooth**
    - Bluetooth 4.2 and BLE (Bluetooth Low Energy).
    - Dual-mode support enables energy-efficient wireless communication.

3.1.2 Hardware Peripherals

- **GPIO**
  - 34 GPIO pins:
    - Digital input/output.
    - Analog input (ADC, up to 12-bit resolution).
    - PWM outputs.
    - Capacitive touch inputs.
- **Timers**
  - Hardware Timers: Precise and independent timers for generating PWM signals or triggering interrupts.

- Useful for:
    - Step pulse generation in motor drivers.
    - Periodic task execution.

- **PWM**
  - Multiple channels for generating pulse-width-modulated signals.
  - Used for:
    - Motor speed control.
    - LED brightness adjustment.

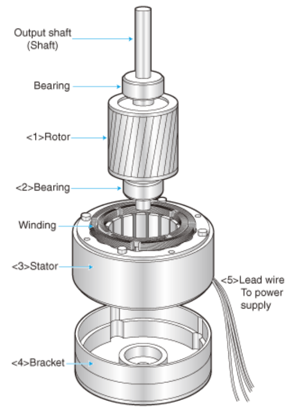
- **ADC and DAC**
  - **ADC**: Up to 18 channels, 12-bit resolution.
  - **DAC**: Two channels, 8-bit resolution.

- **Communication Interfaces**
  - **UART**: Multiple serial communication channels.
  - **I2C**: For connecting peripherals like sensors and displays.
  - **Ethernet MAC**: Requires an external PHY.

- **Interrupts**
  - GPIO pins support interrupts, enabling efficient event-driven programming.

3.2 Motors

Motors convert electrical energy into mechanical energy using the principles of electromagnetism and Lorentz force.



3.2.1 Lorentz Force

When a current-carrying conductor (such as a wire) is placed in a magnetic field, the magnetic field exerts a force on the moving charges in the conductor. In a motor, the moving charges are carried by the current flowing through the coil. The interaction between the magnetic field and the current causes the coil to experience a force, resulting in rotational motion. This force is given by the equation:

$$\mathbf{F} = q(\mathbf{v} \times \mathbf{B})$$

where:

- $\mathbf{F}$ is the force on the charged particle,
- q is the charge of the particle,
- $\mathbf{v}$ is the velocity of the particle,
- $\mathbf{B}$ is the magnetic field.

The magnetic field produced by the coil interacts with the external magnetic field (from the stator or permanent magnets), producing a torque that causes the rotor (the moving part of the motor) to rotate.

3.2.2 Electromagnetic Induction and Faraday's Law

This law states that a changing magnetic flux through a coil induces an electromotive force (emf) or voltage in the coil.The law is mathematically expressed as:

$$\mathcal{E} = -\frac{d\Phi_B}{dt}$$

Where:

- $\mathcal{E}$ is the induced emf (voltage),
- Φ_B is the magnetic flux through the coil,
- $\frac{d\Phi_B}{dt}$ is the rate of change of magnetic flux.

3.2.3 Torque Generation

Torque is the rotational equivalent of force. It is the force that causes an object to rotate around an axis. The force applied to the coil causes it to rotate, creating mechanical work. The torque (τ) generated by an electric motor can be described by the following equation:

$$\tau = n \cdot B \cdot I \cdot A \cdot \sin(\theta)$$

Where:

- n is the number of turns in the coil,
- B is the magnetic flux density (strength of the magnetic field),
- I is the current flowing through the coil,
- A is the area of the coil (the area of the loop),
- θ is the angle between the magnetic field and the normal to the coil.

3.2.4 Mechanical Power Output

The power output of an electric motor can be described in terms of the mechanical power generated as a function of torque and angular velocity (ω):

$$P = \tau \cdot \omega$$

Where:

- P is the mechanical power output,
- τ is the torque,
- ω is the angular velocity of the rotor (in radians per second).

3.2.5 Back EMF

As the rotor of the motor spins, it cuts through magnetic lines of flux, which induces a back emf. This back emf opposes the applied voltage and is proportional to the speed of the motor's rotation. The back emf (E_b) is given by:

$$E_b = k_e \cdot \omega$$

Where:

- k_e is a constant that depends on the motor's construction and the magnetic field,
- ω is the angular velocity of the rotor.

This back emf acts to limit the current flowing through the motor as the motor speeds up, leading to a more stable operation.

3.2.6 Motor Efficiency

The efficiency of an electric motor is a measure of how effectively it converts electrical energy into mechanical energy. It is defined as:

$$\eta = \frac{P_{\text{mechanical}}}{P_{\text{electrical}}} = \frac{V \cdot I \cdot \cos(\phi)}{V \cdot I}$$

Where:

- η is the efficiency,
- $P_{\text{mechanical}}$ is the mechanical output power,
- $P_{\text{electrical}}$ is the electrical input power,
- V is the voltage,
- I is the current,
- $\cos(\phi)$ is the power factor (the cosine of the phase angle between voltage and current).

3.2.7 TMC2208 Stepper Driver

3.2.8 42BYGH809 Stepper Motor

3.2.9 MG996R Servo Motor

3.3 Linear Regulator

3.4 Boost Converter

3.5 Homing Switch

4 Mechanical Design

5 Hardware Architecture

6 Software Architecture

7 System Architecture

8 Overall Workflow

9 Challenges and Solutions

10 Future Improvements

11 References