Introduction

Problem

We are working with Argonne National Laboratory in the Advanced Photon Source. In the synchrotron beamline where they conduct x-ray diffraction experiments, countless stepper motors are used for alignment, automation, etc. However, the drivers they use are bulky, expensive, and somewhat outdated. There is also a limited number, so they have to use ports sparingly. A compact, scalable driver would be ideal, but current solutions would require a power supply for each added driver in addition to wiring for serial communication. This quickly turns into a mess of wires and unnecessary use of power outlets for an increasing number of motors.

Solution

We plan to create a driver that uses power over ethernet (PoE) to communicate with a stepper driver and to power it as well. This would allow for a neat, single cable solution. There will be an input to the ethernet port with associated magnetics, and then a circuit will separate the power and the data being transmitted. Afterward, we will use a voltage step-down circuit to input an appropriate amount of power into the stepper motor. The ethernet data will then be interpreted by an MCU that interfaces with a Motion Controller IC. This will produce step/dir signals for a half-bridge driver IC to properly drive the motor. We intend to make this module universal to stepper motors with different current requirements while being relatively low cost.

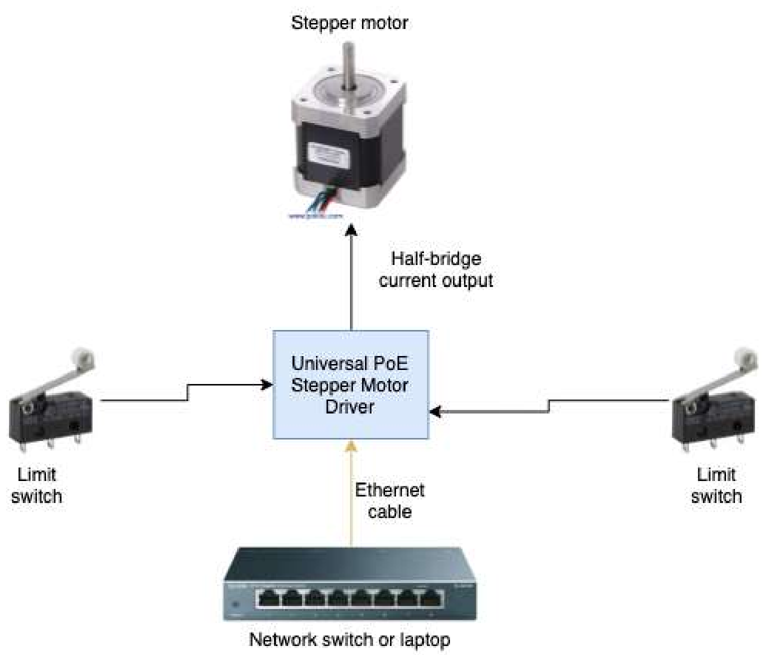

Figure 1. Simple diagram for proposed solution

High-level requirements list

1. The driver must be compatible with any bipolar stepper motor with a requirement of 3A or lower.
2. The driver must be able to control and step down the PoE power delivery to create usable power for the motors.
3. The driver must have reliable transmission of data over ethernet and interpret the commands into step/dir pulses to drive the motor.

Design

1. Block Diagram

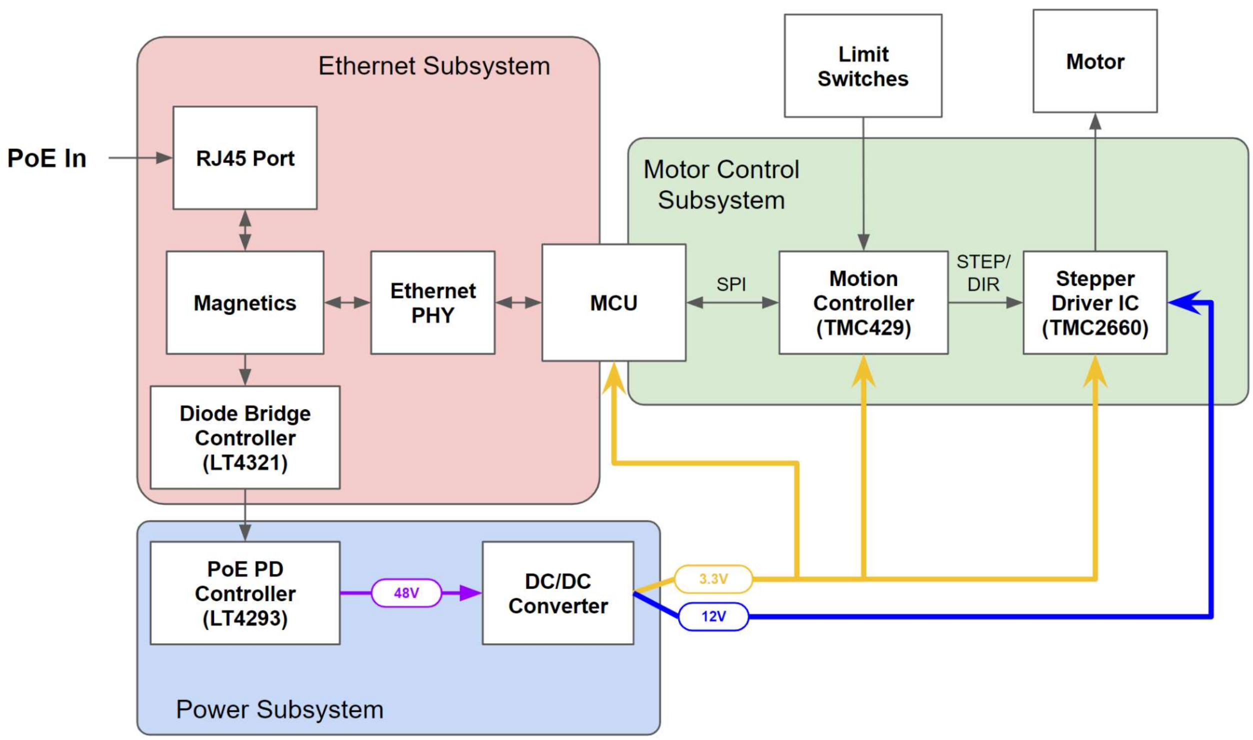

Figure 2. Universal PoE Stepper Motor Driver Block diagram

2. Subsystem Overview

Ethernet Subsystem

This subsystem is the first step after PoE input from a network switch. It handles the physical requirements for an ethernet connection and outputs digital connections that can interface with the MCU, while directing the power to the power subsystem.

Power Subsystem

There are multiple different PoE standards, and this system is what negotiates which standard is being used. It also steps down the 48V used in PoE to the DC voltages needed for all the ICs on the board in addition to the motor driver voltage.

Motor Control Subsystem

After the MCU interprets the data, it communicates with this subsystem to drive the stepper motor. This turns SPI commands into step and direction pulses which are the standard for stepper motor communication. These pulses are subsequently interpreted into a half-bridge MOSFET driver which drives the current across the two motor coils.

3. Subsystem Requirements

Ethernet Subsystem

1. The first block is the RJ45 port, which is the standard ethernet connector.
2. Next, ethernet requires supporting magnetics to operate properly, which includes a transformer.
3. The diode bridge controller IC is necessary since the PoE standard requires devices to accept any polarity, so this ensures a 48V DC output.
4. Finally, the ethernet PHY implements the physical layer of ethernet and converts the data into 3.3V outputs that an MCU can accept.

Therefore, the requirements of this subsystem is that ethernet data in the form of TCP packets must be received by the MCU, and 48V is reliably sent to the PD controller.

Power Subsystem

1. The first block in this system is the PD controller, which receives input from the diode bridge controller. This IC negotiates which PoE standard is being used, and outputs the power at 48VDC to be subsequently stepped down to a more usable voltage.
2. The DC/DC converter is the next step after the PD controller. This needs to accept a 48V input and step this down to 12V and then 3.3V for powering the stepper motor and ICs, respectively. Designing a switching regulator with these two outputs would be ideal, as it would result in maximum efficiency. The 12V output specifically needs to have high current output and relatively high efficiency, and needs to supply a maximum of 6A for the stepper motor, as outlined in the tolerance analysis.

In summary, this subsystem must be able to control the power delivery interface and efficiently step down 48V to 12V and 3.3V, with a hard requirement of 6A from the 12V output.

Motor Control Subsystem

1. The MCU first communicates with the motion controller (TMC429) with SPI. This IC is not completely necessary but recommended for high accuracy microstepping. It offloads some of the processing from the MCU and calculates the step and direction pulses and their associated ramp functions. The step/dir interface is a standard in stepper motor control, and this is input into the actual driver IC. Additionally, this accepts limit switch inputs. These are necessary to stop the motor instantly when the switch is pressed to prevent any damage that might be caused by driving the motor too far.
2. The driver IC (TMC2660) combines two normally separated systems. The first is the gate driver, which takes a step/dir input and outputs digital signals to drive MOSFET gates. The second is the MOSFET stage, which is a half-bridge arrangement of MOSFETs. The MOSFETs are able to provide enough current to drive the two coils of the stepper motor.

The total requirements of this system include being able to accept SPI commands from the MCU and convert them to step/dir pulses which are accurate enough for microstepping. Additionally, The driver IC must be able to provide up to 3A per motor phase without any heat management issues.

4. Tolerance Analysis

One critical aspect of the design is that it has enough power to drive even the most demanding motors. Therefore, it’s necessary to analyze the power requirements of the motor and other components to ensure that the PoE standard we choose is enough to power the device.

Stepper Motors

The Trinamic QSH6018 was used as a reference for the most heavy duty stepper motor that needs to be driven. From the datasheet, we can see that this has a maximum current rating of 3A per phase with a coil resistance of 1.5Ω. Since there are two phases in a bipolar stepper motor, the equation to find the maximum power draw is:

$$P_{max} = 2 * I^2_{phase, max} * R_{coil}$$

With the numbers listed above, this yields a power draw of 27W.

Due to this high power requirement, it is necessary that we use a switching regular. Doing a quick scan of Digikey, these tend to have an efficiency around 90%, so the actual current needed from PoE is 27/0.9 = 30W

ICs

There are a total of 4 ICs on the board that require a 3.3V power input. These include the MCU, Ethernet PHY, Motion Controller, and Stepper Driver IC.

We are still unsure of what specific MCU we’re going to use, but a strong contender is the STM32F107. From Table 17 of the datasheet for this device, we can extract an upper limit to current consumption at just under 50mA, which is when the device is running at max clock speed and all peripherals are enabled, resulting in a power of 165mW, although this will likely never be reached.

Next, one example of an ethernet PHY we might use is the Microchip LAN8671. PHYs tend to be relatively power hungry, with a maximum draw of 120mW in the case of this chip.

The Motion Controller IC we will most likely use is the TMC429, which has a typical current draw of 15mA, or power draw of 49.5mW.

Finally, the TMC2660, which is the H-bridge driver IC, has an operating current of 8mA, which translates to 26.4mW.

In total, the IC power draw is 165+120+49.5+26.4 = 360.9mW

Since we will be using a linear regulator for the 3.3V supply such as the LM1117, we can expect an efficiency of approximately 3.3/12 = 27.5%

Combining this with the 12V converter efficiency of 90%, the total 48V to 3.3V efficiency is ~24.8%. The adjusted power requirement for the ICs is then 360.9mW/0.248, which is just under 1.5W. This could also be improved significantly by using a switching regulator, however doing the analysis with a linear regulator gives us an upper limit on power requirements.

Conclusion

Combining the motor and IC power requirements, we arrive at a conservative estimate of 31.5W for the entire device. Since the PoE++ standard provides 60W per port, we are well within the limits of the amount of power provided. Most motors will also draw less power than the one used in this analysis, so the PoE+ standard could also be chosen in this case, which provides 30W per port.

Ethics and Safety

With regards to safety and ethics, a possible problem is the possibilities of handling high voltages. In accordance with IEEE Code of Ethics #9 [1], we must be able to prevent injuries. To prevent such injuries resulting from high voltages we will make sure to minimize contact with dangerous voltages and use the hand in back pocket rule discussed in lecture. More possible solutions will include wearing gloves, wearing long sleeved clothing or even lab coats. Ethically we must also ensure that the finished product will also be save from any hazards and in order to mitigate this we will also make sure that any open wires are insulated and that the pcb will be in a container.

References:

1. “IEEE Code of Ethics.” *IEEE*, https://www.ieee.org/about/corporate/governance/p7-8.html.