Universal PoE Stepper Motor Driver for Argonne National Lab
ECE 445 Design Document - Spring 2022

ECE 445 Design Document
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1. Introduction

1.1 Problem and Solution Overview

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 However, the drivers they use are bulky, expensive, and somewhat outdated.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.

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 is an input to the ethernet port with associated magnetics, and then a circuit will separate the power and the data transmitted. Afterward, we will use a voltage step-down circuit to input an appropriate amount of power into the stepper motor. The ethernet data is then 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.

1.2 Visual Aid

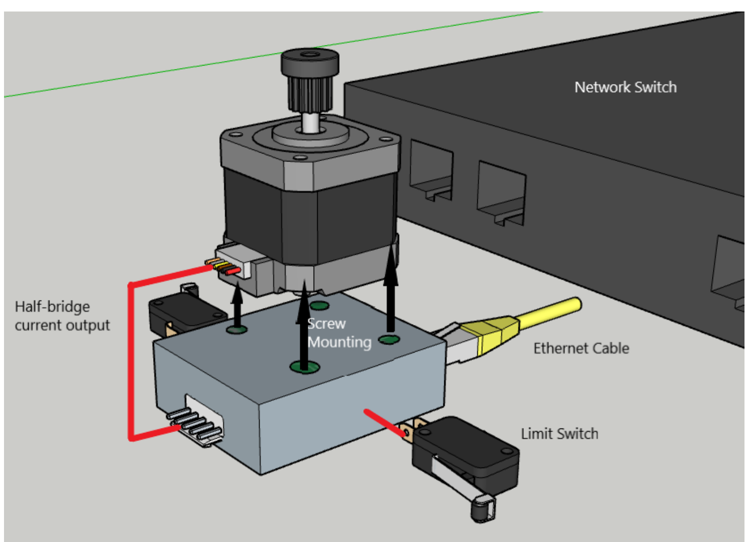

Fig. 1: Simple diagram for proposed solution

1.3 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 47.5 - 48.5 V PoE++ power delivery to 11.5 - 12.5 V and 3.0 - 3.5 V to create up to 6A of 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; reliable meaning that it does not overheat and so does not reach over 125° C as to not heat the TMC2660 chip [1].

2. Design

2.1 Block Diagram

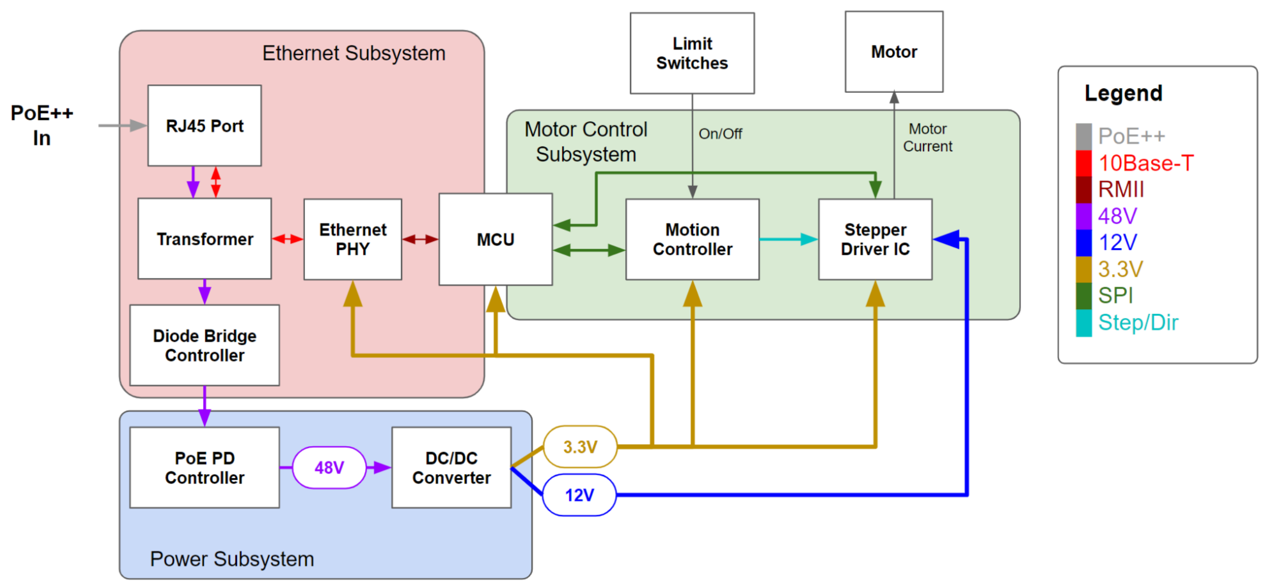

Fig. 2: Universal PoE Stepper Motor Driver Block diagram

Figure 2 illustrates the project as a whole and its subdivisions. There are three subsystems in total which are: ethernet subsystem, motor control subsystem and power subsystem. The ethernet subsystem is responsible for receiving an ethernet connection via an RJ45 port and separating between the data/commands that are input to the motor control subsystem and the power coming into the power subsystem. The power subsystem is responsible for stepping down the 48 V coming in from the ethernet subsystem to 3.3 V and 12 V output and is used to power the ethernet PHY chip, the MCU, the motion controller and the stepper driver IC. The motor control subsystem receives commands from the MCU and drives the motor accordingly and will have a limit switch to hard stop the motor if it reaches/collides with something.

2.2 Subsystem Overview

2.2.1 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.

1. The first block is the RJ45 port and transformer circuit. This is necessary because ethernet is an AC signal, so it requires magnetics to receive the signal.

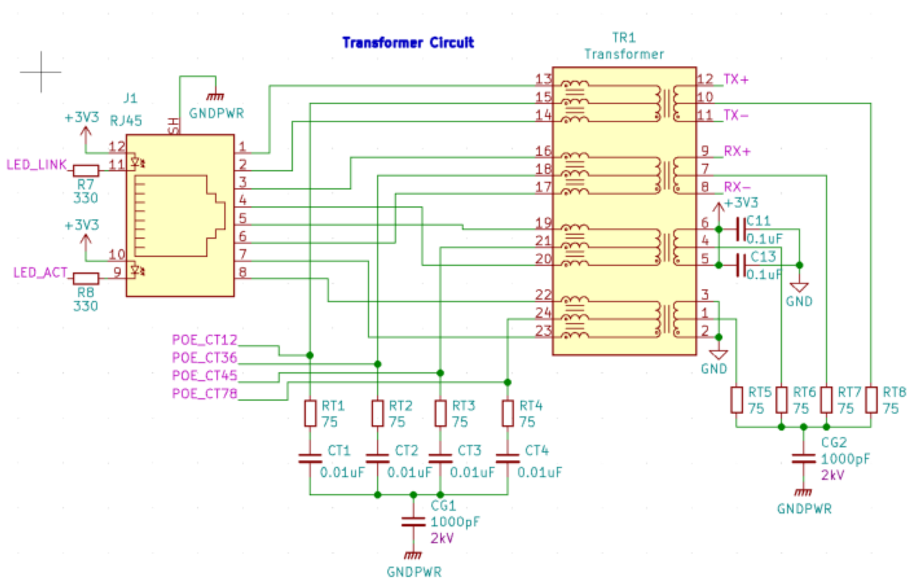

Fig. 3: Transformer Circuit

2. The diode bridge and diode bridge controller IC is necessary since the PoE standard requires devices to accept any polarity, so this ensures a 48V DC output. We are using the Analog Devices LT4321.

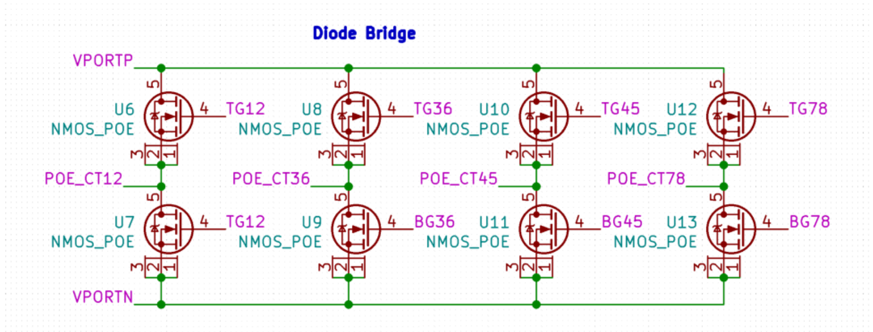

Fig. 4: Diode Bridge

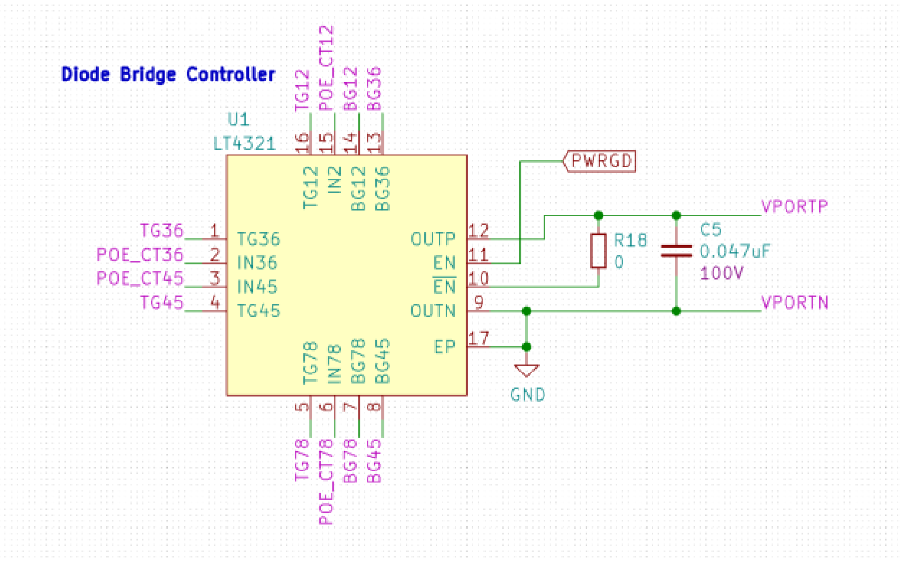

Fig. 5: Diode Bridge Controller

3. Finally, the ethernet PHY is the physical ethernet transceiver and receives and transmits the AC ethernet signal (10Base-T), and communicates with the MCU via an RMII interface. We plan to use the TI DP83848, which is a standard 10/100 PHY which we will operate in 10Base-T mode.

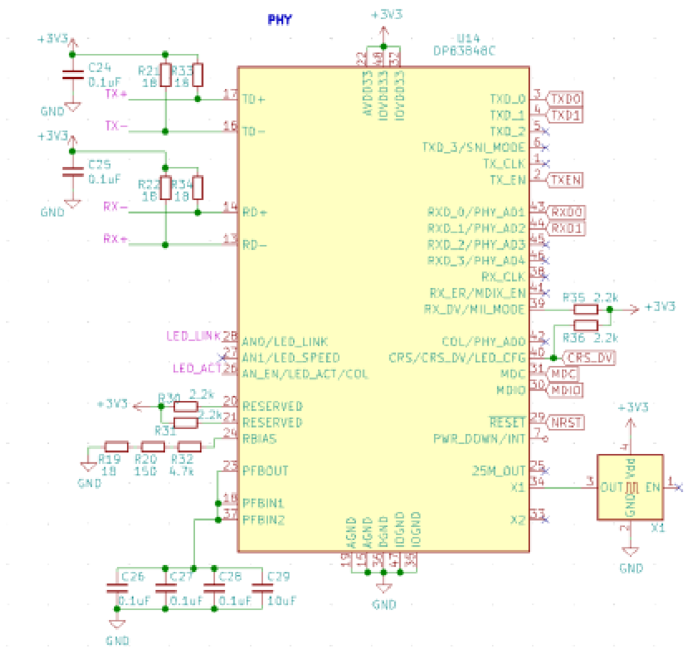

Fig. 6: Ethernet PHY

Table 1: Ethernet Subsystem Requirements and Verification Table

Requirement	Verification
The ethernet subsystem must be able to receive TCP packets accurately through the RJ45 port into the MCU.	Setup and verify IP and MAC address of external PHY chip and MCU and then send a command from laptop to turn the LEDs on the microcontroller development board on.
As the system is designed for an ethernet at a PoE standard, the ethernet subsystem must be able to output 47.5 - 48.5 V DC to the PD controller.	Firstly, plug a PoE ethernet connection then, using a voltmeter, measure the voltage of the output diode bridge and verify that it is within the range of 47.5 V - 48.5 V.

2.2.2 Power Subsystem

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

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 48 VDC to be subsequently stepped down to a more usable voltage. We are using the Analog Devices LT4293 for this.

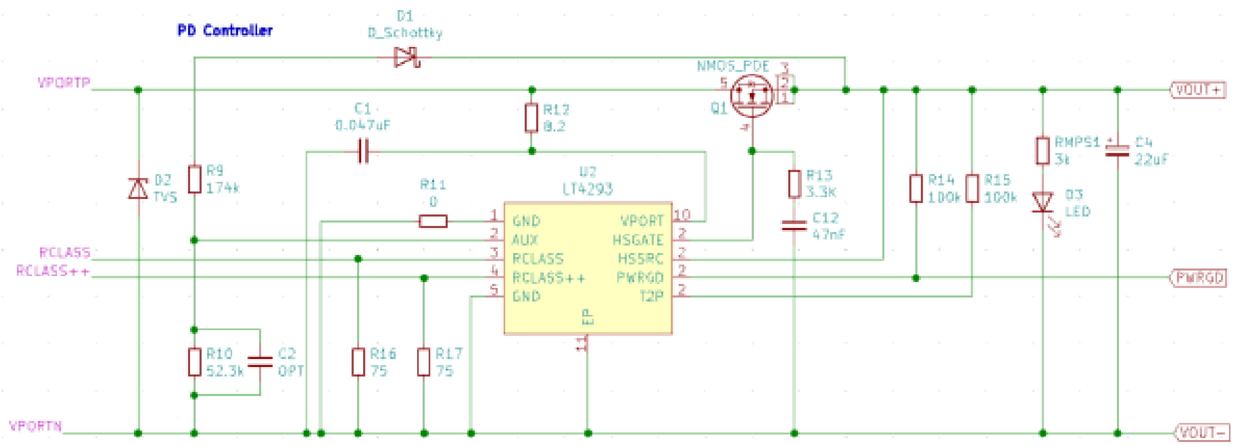

Fig. 7: PoE PD Controller

2. The DC/DC converter is the next step after the PD controller. This needs to accept a 48 V input and step this down to 12 V and then 3.3 V for powering the 0stepper 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.

Table 2: Power Subsystem Requirements and Verification Table

Requirement	Verification
The power subsystem must be able to receive a 47.5 - 48.5 VDC output from the ethernet subsystem and step it down to 11.5 - 12.5 V output with a current of 5.5 - 6.5 A.	Input a 48V DC into the PoE PD controller. Then measure that the appropriate output voltage and current of the converter should be within the range of 11.5 - 12.5 V and 5.5 - 6.5 A respectively.
Must be able to step down voltage received from the ethernet subsystem that is in the range of 47.5 - 48.5 V DC and step it down to an acceptable range of 3.0 - 3.6 V.	Input a 48V DC into the PoE PD controller. Then measure that the appropriate output voltage and current of the converter should be within the range of 3.0 - 3.6 V.

2.2.3 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.

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.

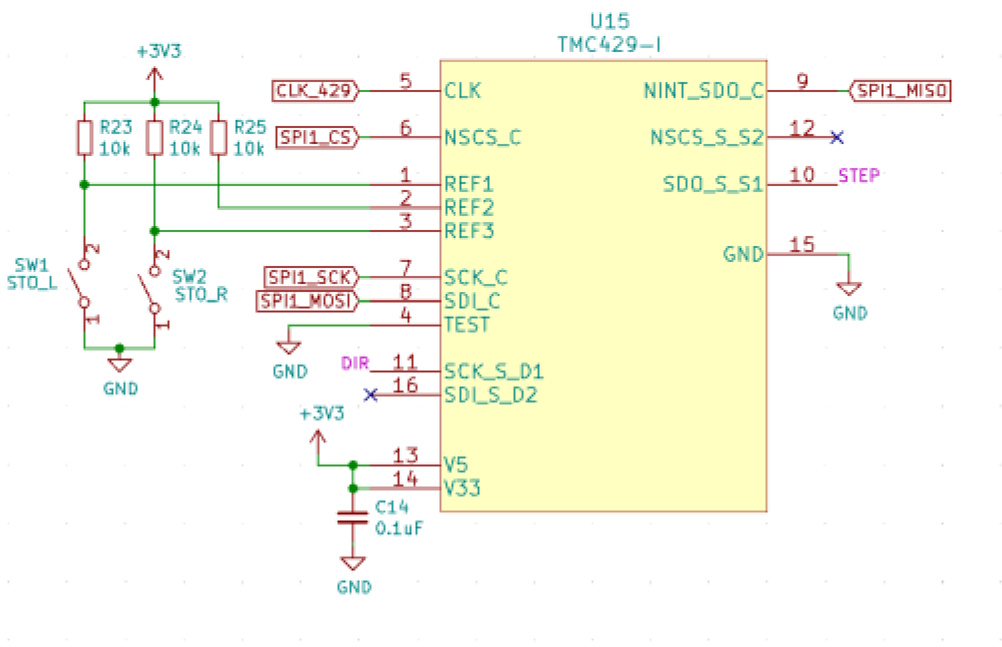

Fig. 8: Motion Controller IC

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. This chip also requires initialization on startup with an SPI interface.

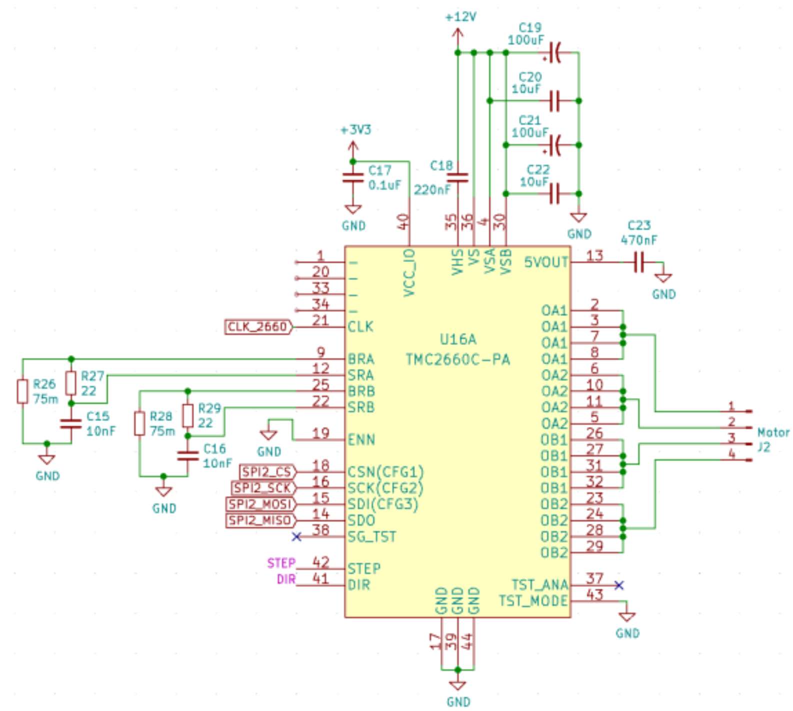

Fig. 9: Stepper Driver IC and Motor Connection

Table 3: Motor Control Subsystem Requirements and Verification Table

Requirement	Verification
Must be able to accept SPI commands from MCU and convert the commands to step/dir pulses that are accurate enough for microstepping 256 microsteps per full step.	We will print the SPI responses from the TMC429 and TMC2660 chips on a serial monitor and match them with the datasheets, as well as microstep 51200 times and see if this matches a full rotation.

Must be able to provide up to 3A per motor phase without going above 125° C.	We will be able to monitor the current provided using an ammeter and also monitor its heat using an infrared thermometer.

2.2.4 MCU

The MCU does not fit neatly into one subsystem and lies between the ethernet and motor control systems. We decided to use an STM32F407 due to support with an API written by Trinamic to interface with their motor control chips. On the ethernet side, we have an RMII interface to talk to the PHY, and on the motor control side we have two SPI interfaces for the two Trinamic ICs, as well as clock outputs for these chips.

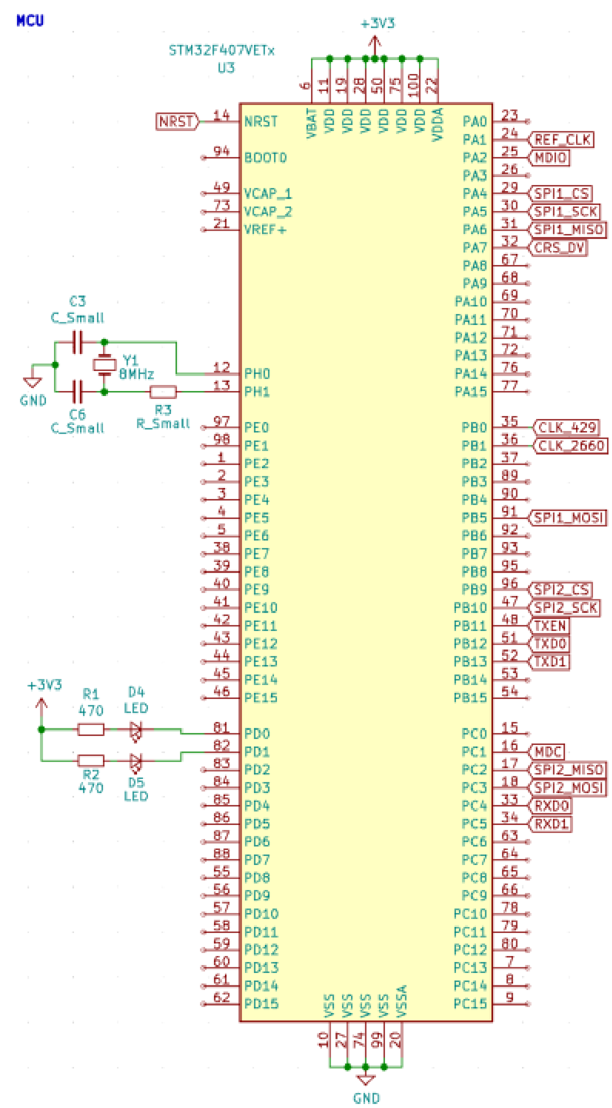

Fig. 10: STM32F407 MCU

2.3 Tolerance Analysis

One critical aspect of the design is that it has enough power to drive even the most demanding motors. Therefore, it is 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.

2.3.1 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[2], we can see that this has a maximum current rating of 3 A per phase with a coil resistance of 1.5 Ω. 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 27 W.

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 = 30 W

2.3.2 ICs

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

We plan to use the STM32F407 microcontroller. From Table 17 of the datasheet[3] for this device, we can extract an upper limit to current consumption at just under 50 mA, which is when the device is running at max clock speed and all peripherals are enabled, resulting in a power of 165 mW, although this will likely never be reached.

Next, we plan to use the DP83848 for our ethernet PHY. For 10Base-T operation, the typical current draw is 97 mA[4], which is 320 mW of power.

The Motion Controller IC we will use is the TMC429, which has a typical current draw of 15 mA[5], or power draw of 49.5 mW.

Finally, the TMC2660, which is the H-bridge driver IC, has an operating current of 8 mA[1], which translates to 26.4 mW.

In total, the IC power draw is calculated as the following.

$$165 + 120 + 49.5 + 26.4 = 560.0\, mW$$

Since we plan to use a linear regulator for the 3.3V supply such as the LM1117, we can expect an efficiency of approximately

$$\frac{3.3}{12} = 27.5\,\%$$

Combining this with the 12 V converter efficiency of 90%, the total 48 V to 3.3 V efficiency is ~24.8%. The adjusted power requirement for the ICs is then 560.9 mW/0.248, which is about 2.3 W. 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.

2.3.3 Conclusion

Combining the motor and IC power requirements, we arrive at a conservative estimate of 32.3W for the entire device. Since the PoE++ standard provides 51W of usable power 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 network switches with the PoE+ standard could also be used in this case, which provides 25.5W per port. Subtracting the IC power, which will remain constant, this leaves 23.2W for the motor. This can easily power a motor such as the Trinamic QSH4218, which is a standard NEMA17 size motor. This has a phase current of 1A and resistance of 5Ω, meaning a power draw of 10W. In summary, the PoE++ standard which we plan to use is more than capable of powering virtually any motor needed and the PoE+ standard could also be used for smaller motors. There are some locations at Argonne where PoE++ switches have not been installed yet, which is why this would be worth considering.

3. Cost and Schedule

3.1 Cost

For the labor cost, we have to first look into how much an ECE graduate makes on average. An electrical engineering graduate makes $79,714 per year and a computer engineering graduate makes an average of $96,992 per year [6]. An average between these two majors is $88,353 per year which roughly translates to $44/hr assuming 40 hrs/week and 50 working weeks/year. We estimate that for the project, each of us will work 150 hours to complete it. Therefore, for the labor cost, we can use the following formula:

$$2.5 \ * \ 150\, hr \ * \ \$44/\, hr \ * \ 3\, people \ = \ \$49,500$$

Referring to appendix A, we can calculate a total cost of the parts to be $131.61. Therefore, the grand total estimated cost of this project would be $49,631.61.

3.2 Schedule

Table 4: Project Schedule

Week	**Bryan**	**Rindra**	**Armando**
2/28 PCB Board Reviews	Finish 1st draft of PCB Layout	Research on Spec Synchrotron and TMCL compatibility.	Research eth PHY communication from ethernet to MCU
3/7 First Round PCBWay Orders	Finalize PCB and submit order	Research on how configurations are done to initialize trinamic chips.	Look into best way to program commands using spec
3/14 Spring Break	-	-	-
3/21 Second Round PCBway Orders	Start an STM32 project and write code.	Write code for initializing STM32 chips and configuring it with the motor control subsystem so that it works with spec.	Create a 3d print enclosure case. Test phy chip with rest with the rest of the board
3/28	Assemble and solder the ethernet subsystem. Also	Assemble and solder the ethernet subsystem. Also	Assemble and solder the power subsystem. Also

	start verifying it against the requirements. When finished, start connecting and assembling the subsystems.	start verifying it against the requirements. When finished, start connecting and assembling the subsystems.	start verifying it against the requirements. When finished, start connecting and assembling the subsystems.
4/4	Program the STM32 MCU. Start to debug any problems.	Program the STM32 MCU. Start to debug any problems.	Program the STM32 MCU. Start to debug any problems.
4/11	Debug	Debug	Debug
4/18 Mock demo	Mock demo, debug	Mock demo, debug	Mock demo, debug
4/25 Demonstration	Demo	Demo	Demo
5/2 Presentation	Present	Present	Present

4. Discussion of 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 [7], 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 safe 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.

5. References and Citations

1. *TMC2660 TMC2660C Datasheet - Trinamic*. https://www.trinamic.com/fileadmin/assets/Products/ICs_Documents/TMC2660C_Datasheet_Rev1.01.pdf.
2. *QMOT QSH6018 Manual. Trinamic Motion Control GmbH & Co. KG, https://www.trinamic.com/fileadmin/assets/Products/Motors_Documents/QSH6018_manual_Rev1.10.pdf.*
3. *STM32F405xx STM32F407xx - STMicroelectronics. https://www.st.com/resource/en/datasheet/DM00037051.pdf.*
4. *DP83848C/i/VYB/YB Phyter QFP Single Port 10/100 ... - Ti.com. https://www.ti.com/lit/ds/symlink/dp83848i.pdf.*
5. *Motion Controller for Stepper Motors Integrated ... - Trinamic. https://trinamic.com/fileadmin/assets/Products/ICs_Documents/TMC429_datasheet.pdf.*
6. Grainger Engineering Office of Marketing and Communications. “Salary Averages.” *Electrical & Computer Engineering | UIUC*, https://ece.illinois.edu/admissions/why-ece/salary-averages.
7. “IEEE Code of Ethics.” *IEEE*, https://www.ieee.org/about/corporate/governance/p7-8.html.
8. *STM32F405xx STM32F407xx Datasheet - STMicroelectronics*. https://www.st.com/resource/en/datasheet/DM00037051.pdf.
9. *DP83848C/I/VYB/YB PHYTER™ QFP Single Port 10/100 Mb/s Ethernet Physical Layer Transceiver Datasheet- Ti*. https://www.ti.com/lit/ds/symlink/dp83848c.pdf?ts=1645736599241.
10. *TMC429 Motion Controller Datasheet - Trinamic*. https://trinamic.com/fileadmin/assets/Products/ICs_Documents/TMC429_datasheet.pdf.

6. Appendix

Appendix A Parts List

Table 5: Parts List Table

Quantity	***Part #***	***Manufacturer***	***Description***	***Cost***	***Cost/Unit***
2	C1608X7S2A473K080AE	TDK Corporation	CAP., 0.047uF, X7S, 100V, 10%, 0603	$0.58	$0.29
30	CL21B104KACNNNC	Samsung Electro-Mechanics	CAP., 0.1uF, 25V, 0805 (decoupling)	$1.20	$0.04
1	C0805C473K1RAC7800	KEMET	CAP., 0.047uF, X7R, 100V, 10%, 0805	$0.32	$0.32
1	100SEV22M8X10-5	Rubycon	CAP., 22uF 100V 20%	$0.73	$0.73
2	CC0603JRNPO9BN200		CAP CER 20PF 50V C0G/NPO 0603	$0.20	$0.10
2	106SML050M	Illinois Capacitor	CAP ALUM 10UF 20% 50V SMD	$1.02	$0.51
3	C0805C103J5GEC7800	KEMET	CAP CER 0805 10NF 50V C0G 5%	$0.90	$0.30
1	UMK212B7224KG-T	Taiyo Yuden	CAP CER 0.22UF 50V X7R 0805	$0.15	$0.15

2	50ZL100MEFCT78X11.5	Rubycon	CAP ALUM 100UF 20% 50V RADIAL	$0.82	$0.41
2	CL31A106MBHNNNE	Samsung Electro-Mechanics	CAP CER 10UF 50V X5R 1206	$0.60	$0.30
1	CL21B474KAFNNNG	Samsung Electro-Mechanics	CAP CER 0.47UF 25V X7R 0805	$0.10	$0.10
1	CL21A106KAYNNNE	Samsung Electro-Mechanics	CAP CER 10UF 25V X5R 0805	$0.20	$0.20
0	C0805C103J5GEC7800	KEMET	CAP CER 0805 10NF 50V C0G 5%	$0.00	$0.30
1	ESW226M100AG3AA	KEMET	CAP ALUM 22UF 20% 100V RADIAL	$0.38	$0.38
1	CL21B105KAFNNNE	Samsung Electro-Mechanics	CAP CER 1UF 25V X7R 0805	$0.10	0.1
2	885342210001	Wurth Elektronik	CAP., 1000pF, X7R, 2000V, 10% 1808	$0.94	$0.47
4	C0805X7R201-103KNE-CT	Venkel	CAP, 0.01uF, X7R, 200V, 10%, 0805	$0.20	$0.05

1	PMEG10030 ELPX	Nexperia	DIODE,SCHOTTKY,100V,3 A,2-pin SOD-128,AEC-Q101	$0.50	$0.50
1	PTVS58VP1 UP-115	Nexperia	DIODE, TVS, 58V, 600W, SOD128	$0.51	$0.51
4	L171L-GC	American Opto Plus LED	LED, Green, 0805	$1.28	$0.32
4	MM3Z12VC	onsemi	DIODE, Zener,12V, 200mW, SOD-323	$1.00	$0.25
2	J1B1211CCD	WIZnet	RJ45 Port	$6.84	$3.42
1	RMCF0603JT 30K0	Stackpole Electronics	RES., 30k, 1/10W, 5%, 0603	$0.10	$0.10
2	RMCF0805F T1K00	Stackpole Electronics	RES., 1.00K, 1/8W, 1%, 0805	$0.20	$0.10
1	RMCF0805F T64R9	Stackpole Electronics	RES., 64.9, 1/8W, 1%, 0805	$0.10	$0.10
1	RMCF0805F T76K8	Stackpole Electronics	RES., 76.8, 1/8W, 1%, 0805	$0.10	$0.10
1	RMCF0805F T37K4	Stackpole Electronics	RES., 37.4, 1/8W, 1%, 0805	$0.10	$0.10

2	SWR201-NRTN-S04-SA-WH	Sullins Connector Solutions	Motor/Limit Connectors	$0.36	$0.18
11	NREC002SABC-M30RC	Sullins Connector Solutions	2.54mm 2-pin Headers	$1.21	$0.11
2	NREC003SABC-M30RC	Sullins Connector Solutions	2.54mm 3-pin Headers	$0.32	$0.16
4	PRPC002DAAN-RC	Sullins Connector Solutions	2x2 Male Headers (for PoE selection)	$0.60	$0.15
10	PSMN075-100MSEX	Nexperia	N-MOSFETs	$10.00	$1.00
4	RMCF0805FT470R	Stackpole Electronics Inc	RES 470 OHM 1% 1/8W 0805	$0.40	$0.10
1	RMCF0603FT220R	Stackpole Electronics Inc	RES 220 OHM 1% 1/10W 0603	$0.10	$0.10
1	RMCF0805FT34R8	Stackpole Electronics Inc	RES 34.8 OHM 1% 1/8W 0805	$0.10	$0.10

1	RMCF0805FT140R	Stackpole Electronics Inc	RES 140 OHM 1% 1/8W 0805	$0.10	$0.10
1	RMCF0805FT46R4	Stackpole Electronics	RES., 46.4, 1/8W, 1%, 0805	$0.10	$0.10
2	RMCF0805FT330R	Stackpole Electronics Inc	RES 330 OHM 1% 1/8W 0805	$0.20	$0.10
1	RMCF0603FT174K	Stackpole Electronics	RES., 174k, 1%, 1/10W, 0603	$0.10	$0.10
1	RMCF0603FT52K3	Stackpole Electronics	RES., 52.3k, 1%, 1/10W, 0603	$0.10	$0.10
2	RMCF0603ZT0R00	Stackpole Electronics	RES., 0, 1/10W, 0603	$0.20	$0.10
1	RMCF0805FT8R20	Stackpole Electronics	RES., 8.2, 1/8W, 1%, 0805	$0.10	$0.10
1	RMCF0603JT3K30	Stackpole Electronics	RES., 3.3k , 1/10W, 5%, 0603	$0.10	$0.10
2	RMCF0603JG100K	Stackpole Electronics	RES., 100k, 1/10W, 5%, 0603	$0.20	$0.10

4	RMCF0805FT22R0	Stackpole Electronics Inc	RES 22 OHM 1% 1/8W 0805	$0.40	0.1
5	RMCF0805FT18R0	Stackpole Electronics Inc	RES 18 OHM 1% 1/8W 0805	$0.50	$0.10
1	RMCF0805FT150R	Stackpole Electronics Inc	RES 150 OHM 1% 1/8W 0805	$0.10	$0.10
4	RNCP0805FTD10K0	Stackpole Electronics Inc	RES 10K OHM 1% 1/4W 0805	$0.40	$0.10
2	WFMB2010R0750FEA	Vishay Dale	RES 0.075 OHM 1% 2W 2010	$2.76	$1.38
0	RMCF0805FT22R0	Stackpole Electronics Inc	RES 22 OHM 1% 1/8W 0805	$0.00	$0.10
4	RMCF0805FT2K20	Stackpole Electronics Inc	RES 2.2K OHM 1% 1/8W 0805	#VALUE!	d
1	CRGCQ0805F4K7	TE Connectivity Passive Product	RES 4.7K OHM 1% 1/8W 0805	$0.10	$0.10

1	RMCF2512JT3K00	Stackpole Electronics	RES., 3.0k, 5%, 1W, 2512	$0.30	$0.30
8	RMCF0603JT75R0	Stackpole Electronics	RES., 75, 1/10W, 5%, 0603	$0.80	$0.10
				$0.00	
1	B3SL-1002P		Push button switch	$0.90	$0.90
1	7490220122	Wurth Elektronik	Transformer	$6.77	$6.77
1	LT4321HUF	Analog Devices	PoE Diode Bridge Controller	$5.11	$5.11
1	LT4293HMS	Analog Devices	PoE PD Controller	$6.15	$6.15
1	STM32F407VET6		MCU	$19.88	$19.88
1	NCP1117LPST33T3G	onsemi	3.3V DC/DC Converter (Linear)	$0.45	$0.45
1	E48SC12010NRFA	Delta Electronics	12V DC/DC Converter (Switching)	$33.39	$33.39
1	DP83848	Waveshare-Module	Ethernet PHY	$13.98	$13.98

1	TMC429-I	Trinamic	Motion Controller	$12.55	$12.55
1	TMC2660C-PA	Trinamic	Stepper Driver	$7.32	$7.32
1	SXO53C3A071-50.000MT	Suntsu	50MHz Oscillator (for PHY)	$0.52	$0.52
1	AS-8.000-20	Raltron Electronics	8MHz Oscillator (for MCU)	$0.18	$0.18

Appendix B Project Schematics

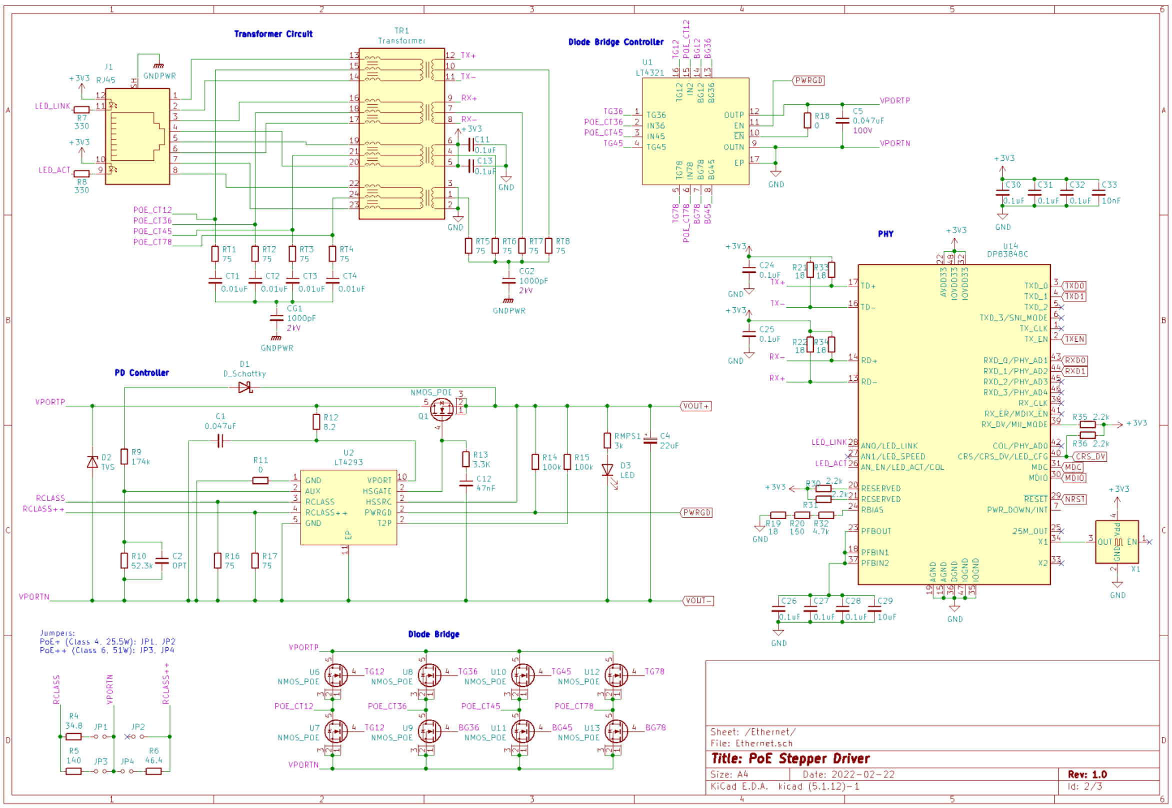

Fig. 11: Ethernet Subsystem Schematic

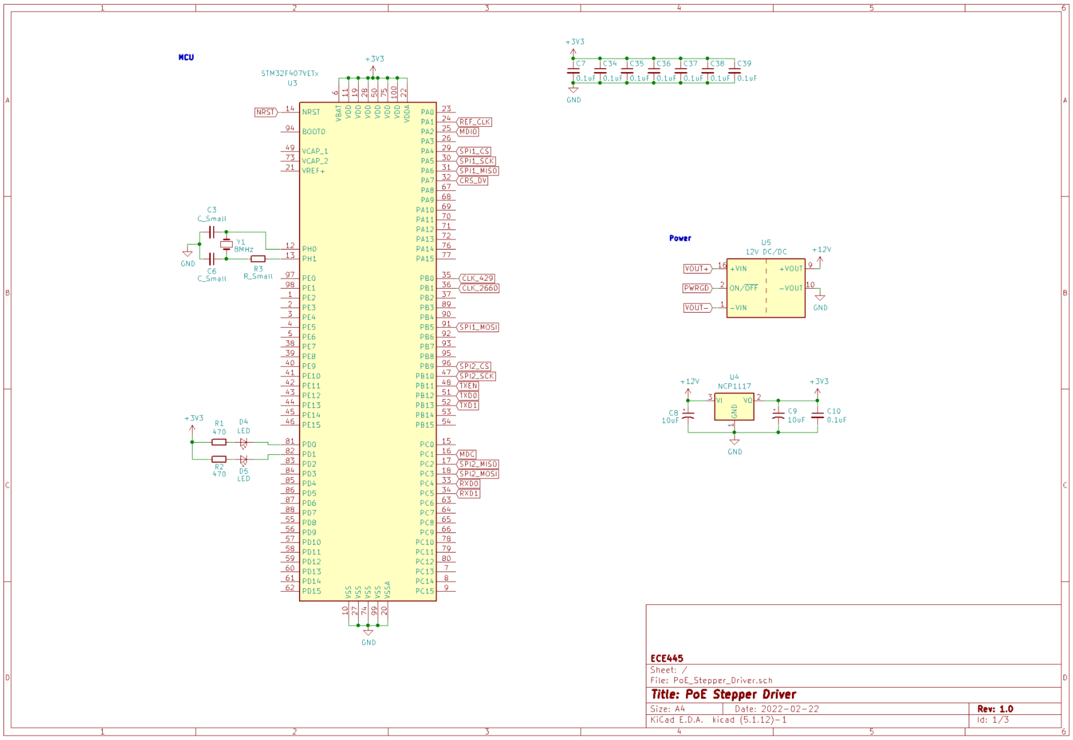

Fig. 12: Power Subsystem Schematic

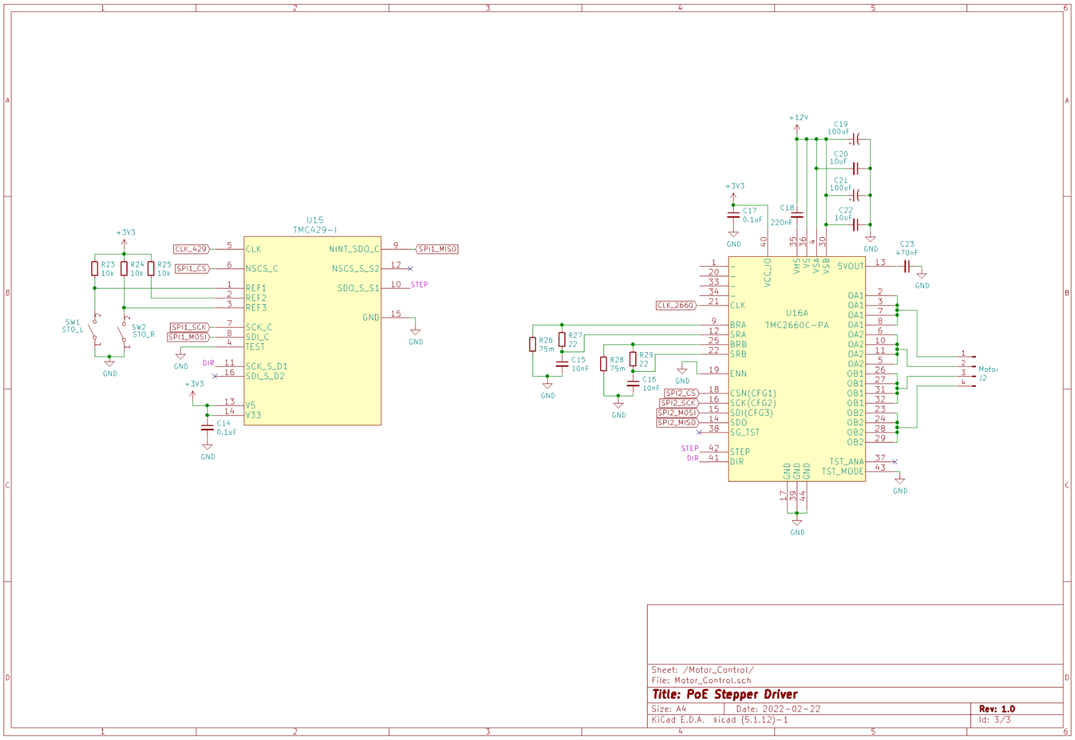

Fig. 13: Motor Control Subsystem Schematic