SCARA Robot – Hardware

White Paper **Updated – April 8, 2022**

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Abstract

In this project, we designed a fully customized power supply PCB that supplies power to all the ICs and motor driver boards, in addition to individual motor driver boards. The power supply mother board PCB consists of an Arduino Uno to act as a controller, a current booster circuit to boost the current output to support the motor, and voltage regulator ICs with smoothing capacitors to step down the voltages to desired values with minimum ripple. The Motor driver circuit consists of a power MOSFET H-bridge to drive the motor, and optocouplers to isolate the current and voltage from the PWM input side to protect the Arduino board.

In this paper, Section 1 describes the motor and optical encoder selection. Section 2 describes the resulted RCG from our component selections and design requirements. Section 3 describes the motherboard and driver circuit schematic designed and simulated in NI Multisim 14.2. Section 4 describes the Bills of Materials for the PCB.

Nomenclature

RCG	Requirements, Constraints, Goal
OTS	Off-the-Shelf
PCB	Printed Circuit Board
CAD	Computer-Aided Design
mNm	milli-Newton-Metres
CPR	Cycles Per Revolution
MOSFET	Metal-Oxide-Semiconductor Field-Effect Transistor
BOM	Bills of Materials
DOF	Degree of freedom
BJT	Bipolar junction transistor

1. OTS Part Selection

For easier calculations and design conformity, the same DCX 26L (Precious Metal Brushes) motor was chosen for the shoulder, elbow, and the plunger part (bonus DOF). The chosen motor can be found on pg. 93 of the Maxon Motor Catalogue [1] as shown in Appendix 1.

The DCX 26L (Precious Metal Brushes) motor we chose uses a 24V configuration. Such configuration was chosen as out of all configurations due to 24V one had the same maximum efficiency at 89% as all other configurations but provides the highest nominal torque of 52.3mNm with a stall torque at 384 mNm. In addition to that, the motor draws relative low current compares to other choices, allowing us to draw less current from the source and widening our PCB component selections.

For the micro controller, we choose to use an Arduino Uno board due to its high availability, high flexibility, good development tools/libraries and low cost (23$). The onboard chip ATMEGA328P supports up to 5 PWM outputs which is more than enough to support all three motors we will be running.

To allow us to sense the arm direction and movement speed to the microcontroller Arduino Uno, the US Digital E4P miniature encoder was chosen for all joints, selected from Prof. Leo Stocco's personal webpage.

The 1000 CPR model was chosen for the highest resolution and cheapest price found for our selected motor shaft. For 31.77$, it has the same price as its lower resolution counterparts (100 CPR to 800 CPR), and it is also one of the cheaper 1000 CPR options available.

2. Design RCGs

With above components selected, using data from their own datasheet, we proposed the hardware part of the design's RCG:

Specification	Requirement	Constraint	Goal
Nominal Voltage	24V±2V	24V±1V	24V
Supply Voltages	5V, 12V, 24V		All
Max Current	30A (both motor)	Max 50A	40A
Switching frequency	3kHz		Maximum
Size		140mm*100mm	Minimum
Circuit protection	Overcurrent Optical isolation		Maximum

Table 2.1: Hardware design RCGs

The above RCGs are set to make sure that our system will be able to provide correct and stable voltage to all the parts connected, able to satisfy motor's relative high current need, satisfy control system's accuracy requirements and able to perform its task for an extended period of time while able to fit into our arm design.

3. Circuit Schematic Design

3.1. Mother board/Power Supply

For our power supply board design, with the previously mentioned RCG in mind, we developed out board to have:

(1): 5V, 12V and 24V output support for all the external ICs we need. (Arduino, Motor, Sensor)

(2): 40A maximum current supplied to the motor output.

(3): Stable voltage output under high current applications. (24±0.3V under 25A, 24±1V under 40A)

(4): Safety fuses in case of current surges for each output and transformers to prevent meltdowns.

(5): LED indicators and test points for easy debugging.

(6): Different thickness traces for high/low current areas, mounting holes for installation of the board, and a slot for Arduino board.

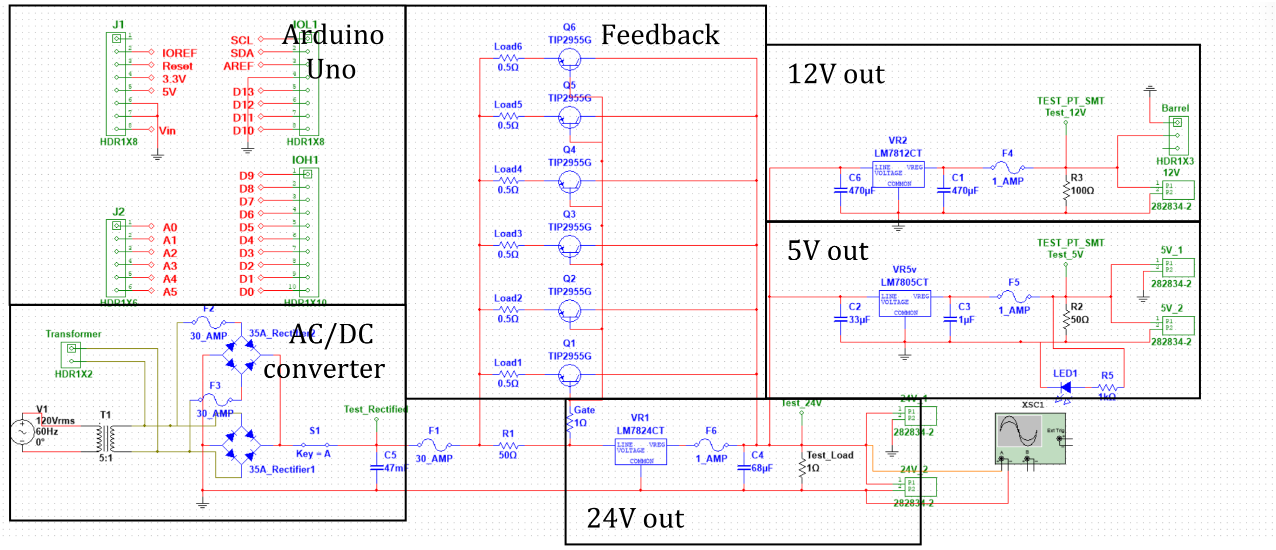


Figure 3.1: MotherBoard Circuit Schematic for Interactive Simulation

To allow the power supply unit to meet our RCG, we used 3 different voltage regulators to achieve 3 different output voltages. The IC we chose (LM78xxCT) is cheap and can with withstand up to 40V (35V for 5V to 18V model) of input voltage, while maintain a very small output noise voltage of 45µV. With the help of bypass capacitors, we are able to achieve a very stabilized DC voltage output with a maximum peak to peak voltage of ~5.2mV under 25A of load current for the 24V side, 7.1µV at 12V side and 1.7µV at 5V side [2].. The output voltage under 25A motor load's oscilloscope plot is shown below:

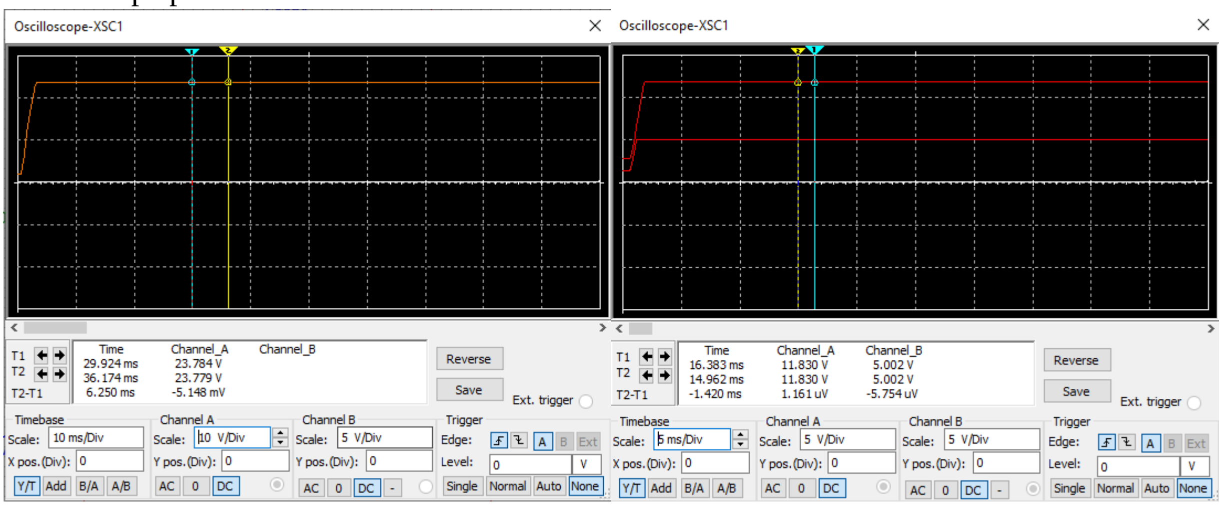


Figure 3.2: Oscilloscope readings for different output voltages

For the current side, to achieve the targeted 40A output current capability, we designed a simple Power PNP BJT feedback network to "boost" the output current under 24V conditions on the collector side. The selected power transistor TIP2955G is able to withstand 60V and 15A of continuous current and voltage, making our transistor network able to handle up to 90A of current [2]., well taking care of potential current spike, in addition to its low cost and compact form factor, it is a solid option.

Going forward, the schematic is edited to correspond parts to packages, allowing us to forward the schematic to Ultiboard 14.2 to create the PCB.

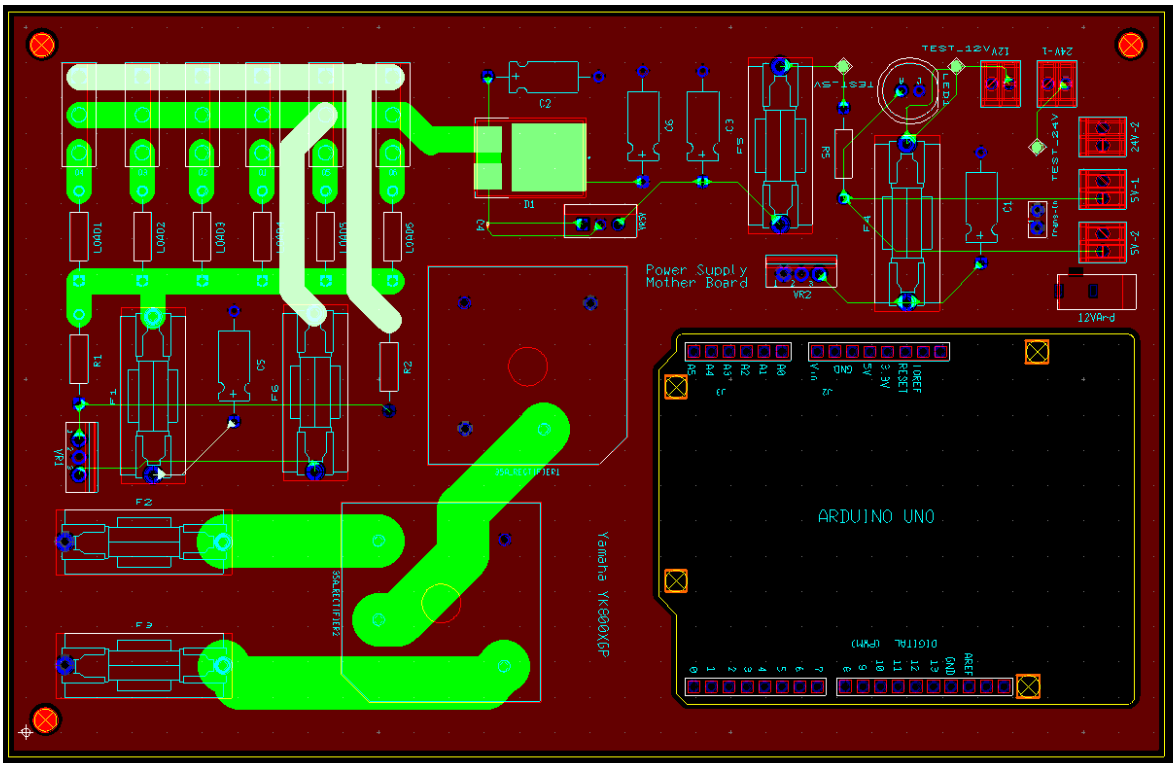


Figure 3.3: PCB Layout of the Mother Board in Ultiboard 14.2

As we can see from the figure above, we used 2 pin headers and barrel jacks to help connect our power supply circuit to motors and other ICs such as Optical sensors (5V) and Arduino Uno board (12V barrel jack). Utilizing power planes (Ground plane and a rectifier output plane) we are able to lower the connection planes to 2 layers. We have also considered about the maximum current that will flow between the pins and adjusted the trace width accordingly. The tool used to calculate trace thickness using current is shown in the Appendix below.

For the safety features, we added 1A fuses on each of the IC output side to make sure that the output current will not burn the chip, in addition to that, we have placed all the connectors on the edge of the board to reduce the risk of bending/damaging components when attempting to connect the ICs to the board. Below is our 3D rendering of the PCB design in Ultiboard 14.2:

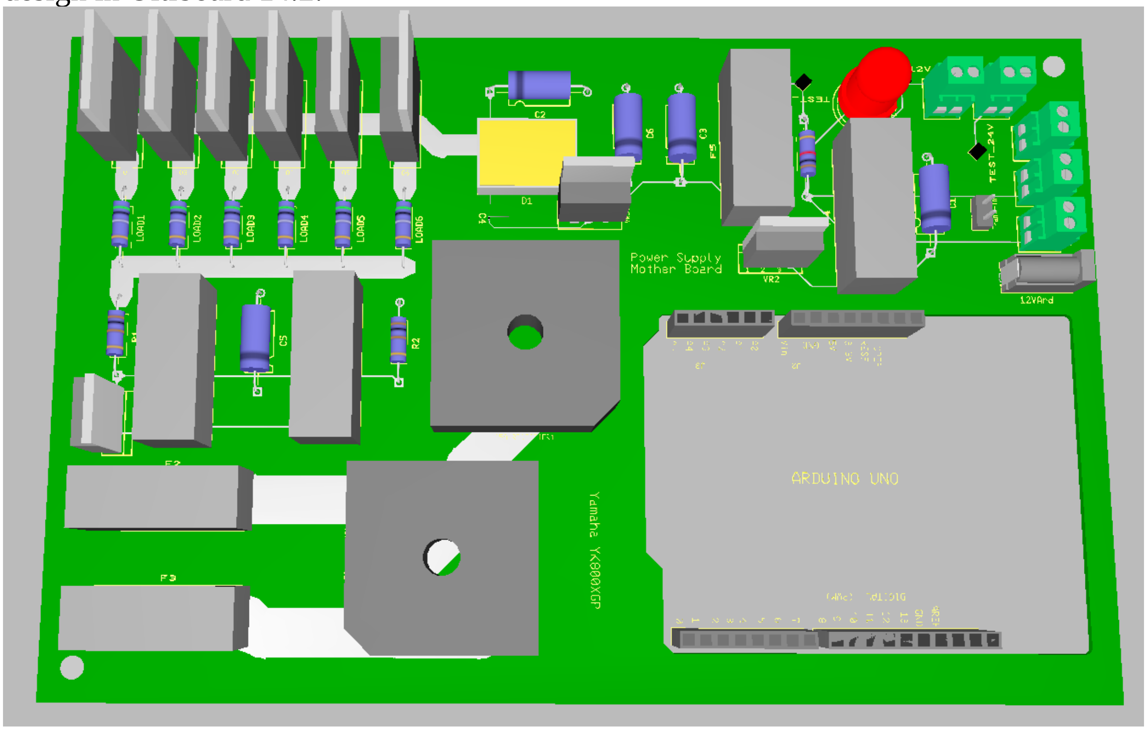


Figure 3.4: 3D Rendering of the Mother Board using Ultiboard 14.2

In addition to the safety features mentioned above, we have also added small features that allow easy testing for power users. As seen above in Figure 3.2-3.4, we added various test points at different voltage levels and an LED status indicator at the connector side to indicate the board's current status.
For the last RCG, we have arranged all of our component in a compact, but not too crowded way, to achieve a 138mm x 87mm design size to perfectly fit into the body of out arm design.

3.2. Motor driver board/Daughter board

To allow for the bidirectional use of the motor, an H-Bridge-based circuit driven by an Arduino Uno 5V PWM input was created. As the motor model for all the joints is the same, the following schematicis repeated three times for each motor.

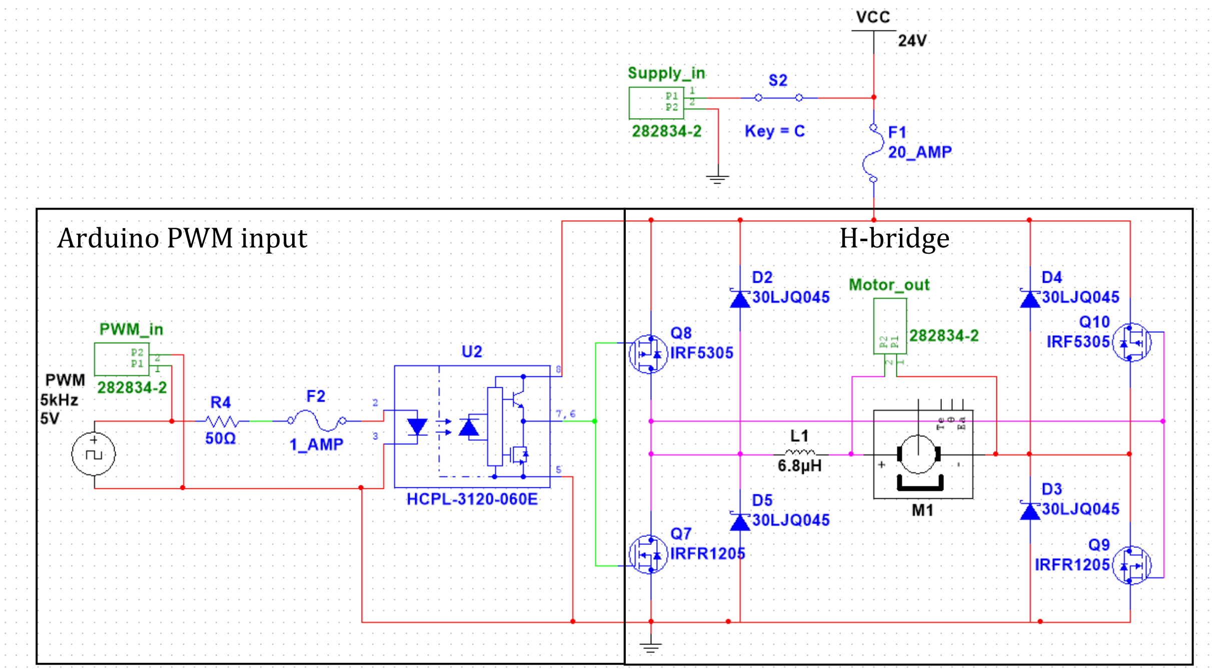


Figure 3.5: Motor Driver Circuit in MultiSim 14.2

As seen, the H-Bridge is made of two pairs of N-Channel and P-Channel power MOSFETs with 4 schotty diodes for the back EMF. To simulate a relatively correct load, a DC PM brushed motor model from MultiSim 14.2 was used, in series with an inductor to smooth out the inrush current. The motor was modelled with the specs calculated from the actual DCX26L motor datasheet, making out simulation output as accurate as real-life measurement as possible.

For the power MOSFETs, the IRF5305 and IRFR1205 are capable of handling current up to 31A (44A for IRFR1205) and can both handle 55V of voltage with a very low internal resistance of 0.06Ohms and 0.027Ohms, which gives us very minimal voltage drop to make sure that our motor is able to receive a constant voltage supply of 24V±1V to keep the motor running. The schotty diode we chose to combat the back emf (30LJQ045) is also very compact and able to withstand 30A and 45V continuous voltage and current to support long term operation of the motors[2].

As for safety features, other than the fuses we placed on the 24V input side and PWM output side to protect the H-bridge and Arduino Uno, we also added an IGBT Gate Drive Optocoupler (HCPL-3120-060E) to make sure that we have enough voltage (24V) to drive the power MOSFETs while only utilizing one 5V PWM output from the Arduino Uno. At the same time isolating the high voltage side current form the low voltage side.

Exporting the Multisim layout to Ultiboard, we re-arranged components to form out daughter board PCB as shown below:

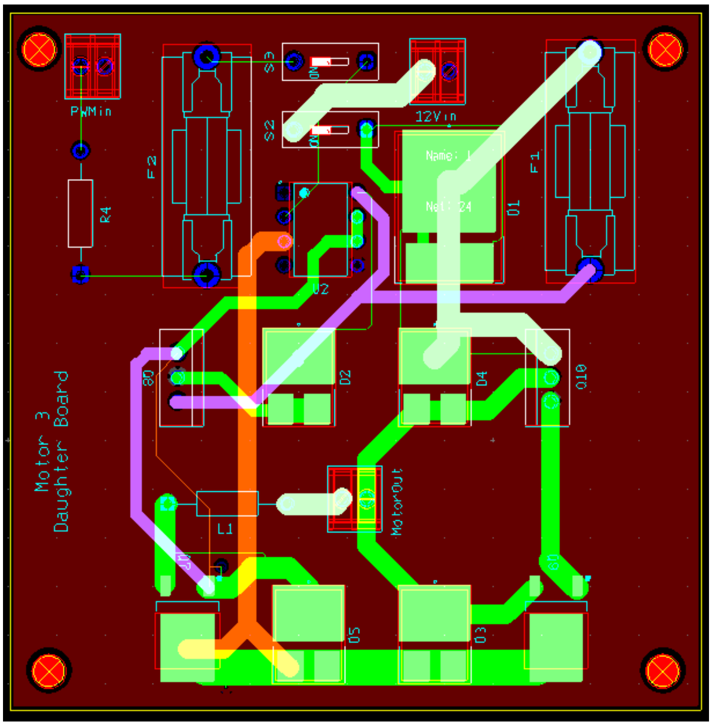


Figure 3.6: PCB Layout of Motor Driver Board in Ultiboard 14.2

As shown in Figure 3.4 above, we added 2 pin connectors for Arduino PWM input, power supply input and Motor supply output, with additional switches for testing user convenience. The detailed 3D rendering in shown below for the driver board:

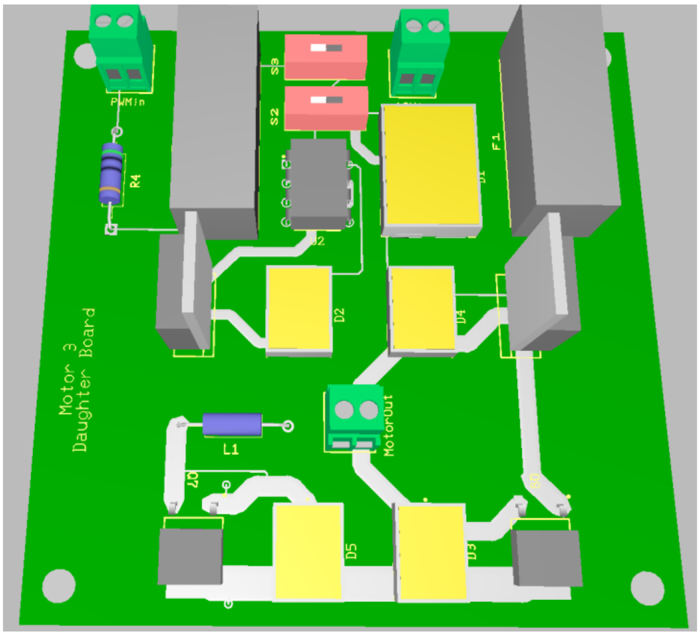


Figure 3.7: Driver Circuit PCB 3D Rendering

With the help of power planes and careful component placements similar to the Motherboard above, we are able to meet the RCG for board size with a very compact 65mm x 70mm board that can be fitted into our arm aside with the motor with ease.

To support the Simulink control system and to verify our own PCB design, the step response of the motor can be seen below:

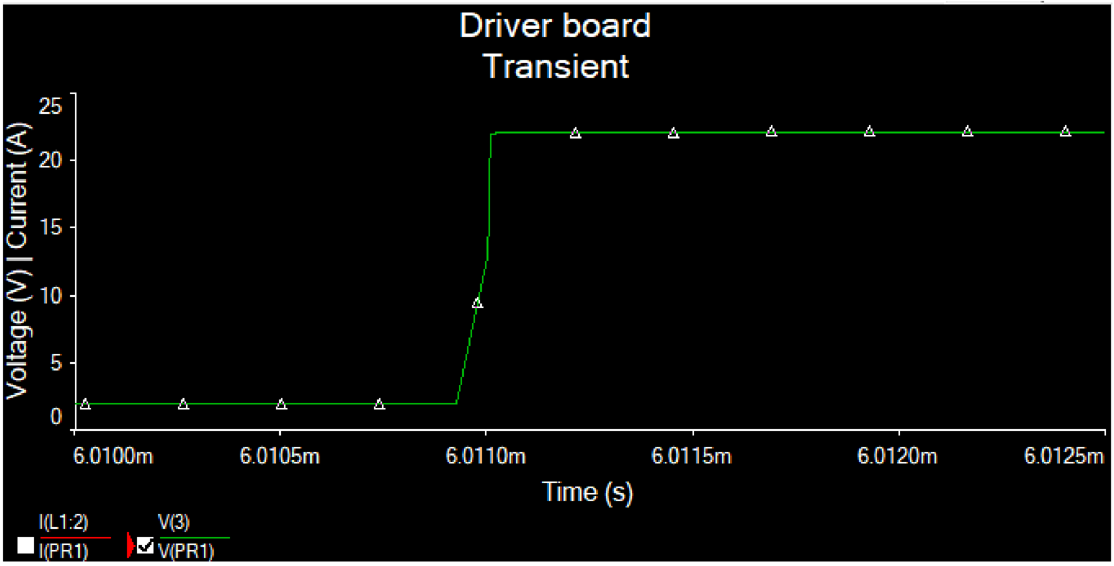


Figure 3.8: Step Response of Driver Circuit in Multisim

The process in Figure 3.1 is done for both clockwise and counterclockwise directions of the motor. With the help of Simulink, the following approximated transfer function is achieved for the step response:

$$\frac{3.829e11}{(s^2 + 1.912e05 * s + 1.676e10)}$$

Using these transfer functions, the approximated step response seen in Figure 3.2 below is achieved.

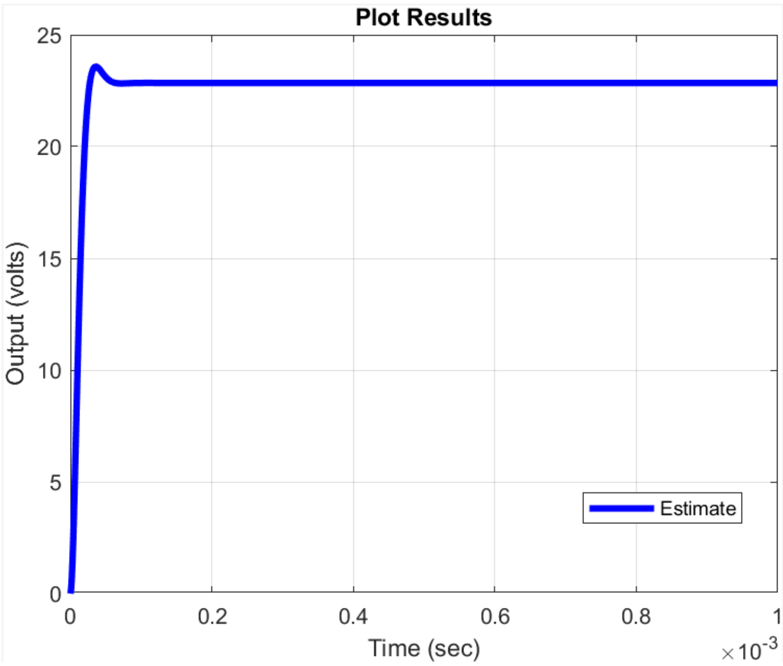


Figure 3.9: Estimated Step Response of Driver Circuit in Simulink

According to above plot, we can see that the step response settles with minimal overshoot (<1V) in minimal time (~0.05s).

4. Bills of Materials for the PCB

All prices are before tax in Canadian Dollars (CAD). Price data from *Digikey.ca*

The total cost of the BOM for 1 mother board and 3 daughter board (1 set) is $246.82.

Part	# of Components/Board pair	# of Component total	Total Price
Resistors	9	11	$3.63
Fuses	9	13	$32.17
Decoupling / Voltage Reg. Capacitors	6	6	$1.39
Optocoupler	1	3	$14.34
P-Channel Power MOSFET	2	6	$14.64
N-Channel Power MOSFET	2	6	$12.06
Voltage Regulators	3	3	$7.23
PNP BJT	6	6	$18.72
Connectors	10	16	$16.05
Schottky Diodes	4	12	$8.28
Arduino Uno	1	1	$23
E4P Optical Encoder	1	3	$95.31

References

[1] Prof. Leo Stocco. (2022). *Maxon Motor Catalogue*. Maxon Group. https://www.ece.ubc.ca/~leos/pdf/datasheets/Maxon/MaxonCat.pdf

[2] All Datasheets.com (2022). *Electronics components data search*. AllDataSheets. https://www.alldatasheet.com/

[3] Battle Electronics (2022). *PCB Trace Width Calculator.* Battle Electronics Inc. https://www.7pcb.com/trace-width-calculator.php

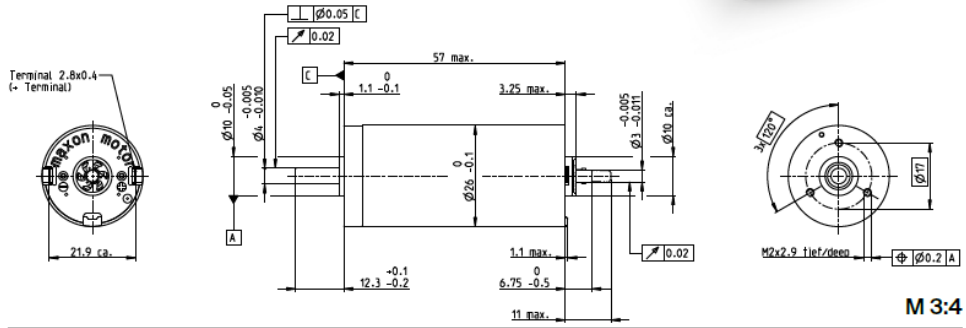
Appendix

1. Motor model used: DCX26L

DCX 26 L Precious Metal Brushes
DC motor ∅26 mm

Key Data: 18/29 W, 52.3 mNm, 5900 rpm

DCX



M 3:4

	Motor Data							
1_	Nominal voltage	V	9	12	18	24	36	48
2_	No load speed	rpm	5530	5330	5530	5330	5430	5320
3_	No load current	mA	80.5	56.8	40.2	28.4	19.5	14.2
4_	Nominal speed	rpm	5060	4690	4770	4600	4680	4570
5_	Nominal torque (max. continuous torque)	mNm	32.9	46.1	49.8	52.3	50.8	50.3
6_	Nominal current (max. continuous current)	A	2.2	2.2	1.64	1.25	0.822	0.599
7_	Stall torque	mNm	384	384	362	384	370	355
8_	Stall current	A	24.8	17.9	11.7	8.95	5.86	4.14
9_	Max. efficiency	%	89	89	89	89	89	89
10_	Terminal resistance	Ω	0.363	0.671	1.54	2.68	6.15	11.6
11_	Terminal inductance	mH	0.067	0.129	0.268	0.514	1.11	2.06
12_	Torque constant	mNm/A	15.5	21.4	31	42.9	63.2	85.8
13_	Speed constant	rpm/V	616	445	308	223	151	111
14_	Speed/torque gradient	rpm/mNm	14.4	13.9	15.3	13.9	14.7	15
15_	Mechanical time constant	ms	3.23	3.13	3.11	3.09	3.1	3.11
16_	Rotor inertia	gcm^2	21.3	21.4	19.4	21.2	20.1	19.7
	Thermal data		**Operating Range**					

2. Trace thickness calculator [3]:

Input Data

Field	Value	Units
Current (max. 35A)	35	Amps
Cu thickness	2	oz/ft²
Temperature Rise (max. 100°C)	10	°C
Ambient Temperature	25	°C
Conductor Length	1	inches
Peak Voltage	5	Volts

Results Data

Internal Traces

Trace Data	Value	Units
Required Trace Width	**2 126.57**	mil
Cross-section Area	**5 715.36**	mil²
Resistance	**0.0001**	Ω Ohms
Voltage Drop	**0.0044**	Volts
Loss	**0.15**	Watts

External Traces

Trace Data	Value	Units
Required Trace Width	**817.46**	mil
Cross-section Area	**2 197.00**	mil²
Resistance	**0.0003**	Ω Ohms
Voltage Drop	**0.0115**	Volts
Loss	**0.40**	Watts
Required Track Clearance	**24.00**	mil