Virtual Quality Control Robot – Electrical

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Abstract

A custom motor driver PCB that controls four motors in the Virtual Quality Control Robot was designed. The PCB consists of an Arduino Leonardo to act as the controller, four H-Bridge circuits to drive the four identical motors, a heatsink-integrated voltage regulator that steps the power supply input down to a 5V logic compatible with the Arduino Leonardo, decoupling capacitors to reduce noise in the transient response, five fuses across the H-Bridges, and the voltage regulator to provide overcurrent protection.

In this paper, Section 1 describes the motor and optical encoder selection. Section 2 describes the driver circuit schematic designed and simulated in NI Multisim 14. Section 3 describes the simulations performed and the linear model generated from the circuit transient response in NI Multisim 14. Section 4 describes the layout of the driver circuit PCB designed in NI Ultiboard 14. Section 5 describes the PCB CAD model exported from NI Ultiboard 14 and the PCB enclosure designed in SolidWorks 2020. Section 6 describes the Bills of Materials for the PCB.

Nomenclature

OTS	Off-the-Shelf
PCB	Printed Circuit Board
CAD	Computer-Aided Design
RPM	Rotations Per Minute
mNm	milli-Newton-Metres
CPT	Counts Per Turn
MOSFET	Metal-Oxide-Semiconductor Field-Effect Transistor
BOM	Bills of Materials

1. OTS Part Selection

For easier calculations and design conformity, the same DCX 22S (Graphite Brushes) motor was chosen for the shoulder, elbow, wrist and gripper joints. The chosen motor can be found on pg. 90 of the Maxon Motor Catalogue [1] as shown in Appendix 1.

The DCX 22S (Graphite Brushes) motor has a length of 34.2mm, a diameter of 22mm, a front shaft diameter of 3mm, and a rear shaft diameter of 2mm. The 24V configuration of the motor was chosen as out of all configurations (6V, 12V, 18V, 24V, 36V, 48V), the 24V one had the highest maximum efficiency at 86%, the highest nominal torque at 15.3 mNm, and the second highest nominal speed at 10800 rpm. The Graphite Brushes version was chosen over the Precious Metal Brushes version (pg. 89 of Maxon Motor Catalogue [1] as shown in Appendix 2) due to higher maximum efficiency (86% vs 85%), higher maximum torque (15.3 mNm vs 14.7 mNm), higher maximum nominal speed (10900RPM vs 4940 RPM), lower minimum terminal resistance (0.297Ω vs 1.02Ω), and lower cost (€129.46 vs €131.91). Additionally, motors with graphite brushes are the most effective choice for withstand high current spikes in bidirectional applications such as the Virtual Quality Control Robot [2].

To send the information on motor direction and speed to the microcontroller Arduino Leonardo, the ENX EASY 10 optical encoder was chosen for all joints from the maxongroup.com website. The 1024 CPT model was chosen for the highest resolution and cheapest price found for DCX 22S motors. For €86.64, it has the same price as its lower resolution counterparts (512 CPT and 1 CPT), and is the cheapest 1024 CPT model available (€86.64 vs €149.64 vs €139.09 vs €155.55).

2. Driver Circuit Schematic Design

To allow for the bidirectional use of the motor, an H-Bridge-based circuit driven by an Arduino Leonardo was created. As the motor model for all the joints is the same, the following schematic is repeated four times for each motor. As seen, the H-Bridge is made of two pairs of N-Channel and P-Channel MOSFETs. To simplify calculations, the motor was modelled as a resistor using its terminal resistance, meaning the current and voltage values seen in Figure 2.1 are in reference to stall current and stall torque. The Arduino Leonardo pins were modelled as step inputs for simplicity.

As additional clever features, two optocouplers were introduced in order to isolate the Arduino Leonardo from the motor, reducing noise feedback. Additionally, a decoupling capacitor was added to reduce noise incoming from the power supply and smoothen our transient response.

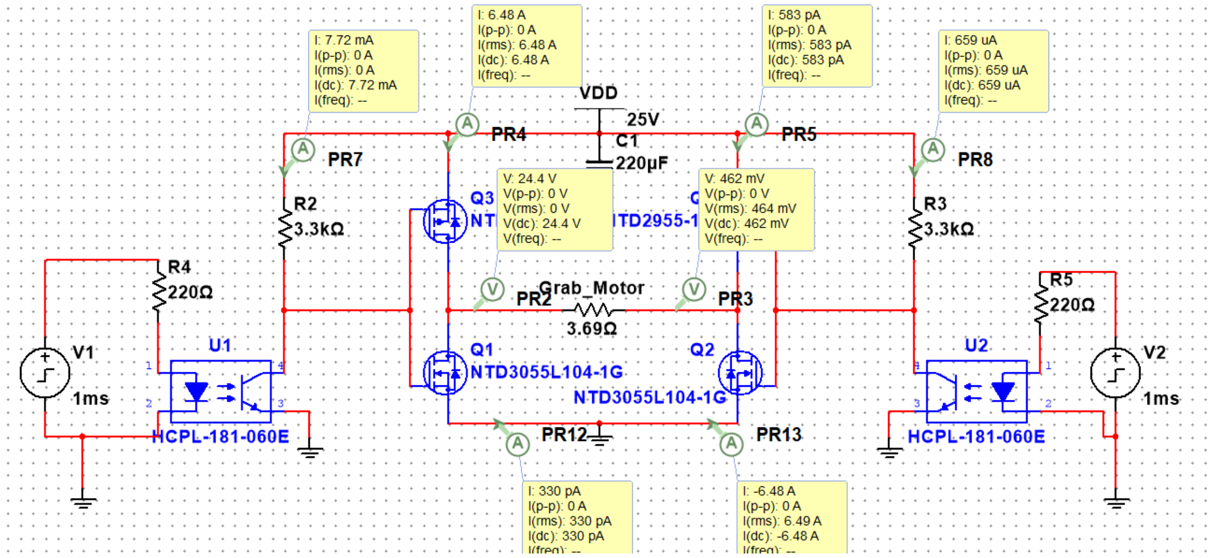


Figure 2.1: Driver Circuit Schematic for Interactive Simulation

Going forward, the schematic is edited to correspond parts to packages, allowing us to forward the schematic to Ultiboard 14 to create the PCB. The specific parts used are detailed in Section 6, titled Bills of Materials.

As shown in Figure 2.2 below, we use 2-pin headers to connect our motors and 25V power supply. As additional clever features, 10A fuses were added to each motor on top of a 1.5A fuse to the Arduino Leonardo to protect against overcurrent. Furthermore, to reduce the cost by using a one-channel instead of a dual power supply, an LM7805CT voltage regulator was integrated into the circuit to step the 25V input down to 5V used by the Arduino Leonardo.

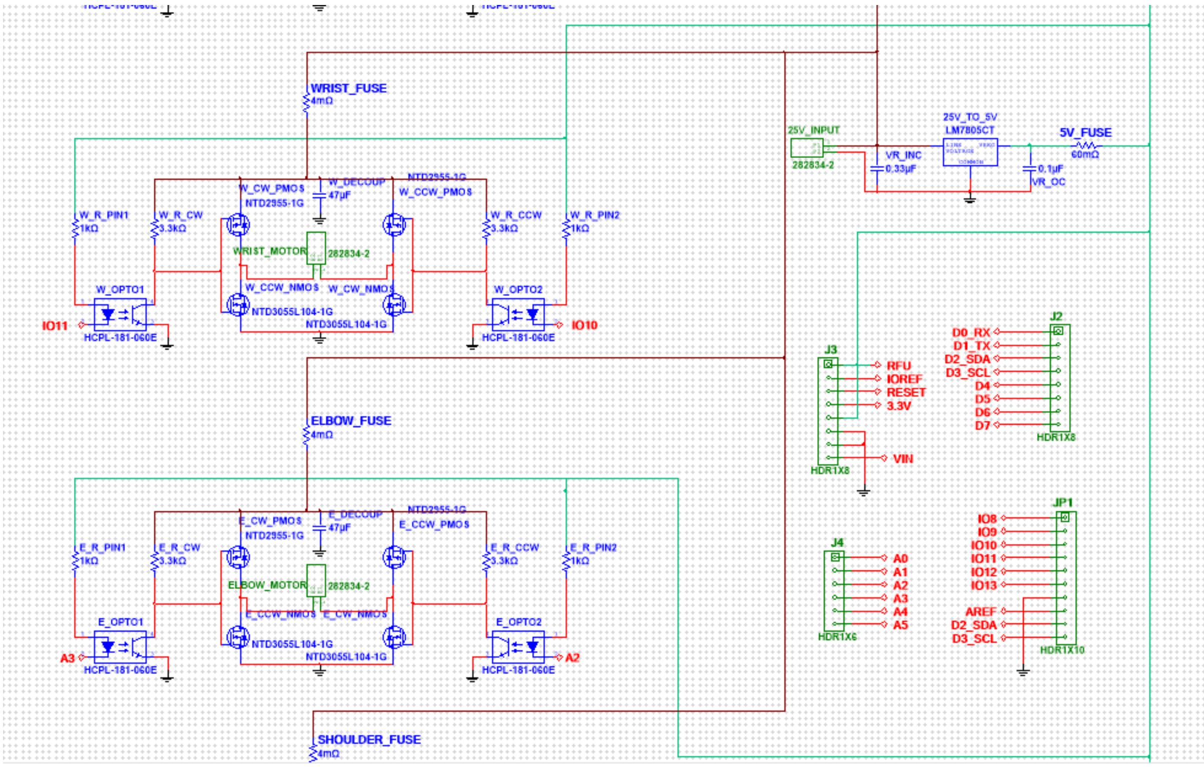


Figure 2.2: Driver Circuit Schematic for the PCB

3. Circuit Simulation and Linear Model Development

The step response of the motor can be seen below in Figure 3.1. The red (V1) and green (V2) graphs display the voltage difference between the two terminals of the motor.

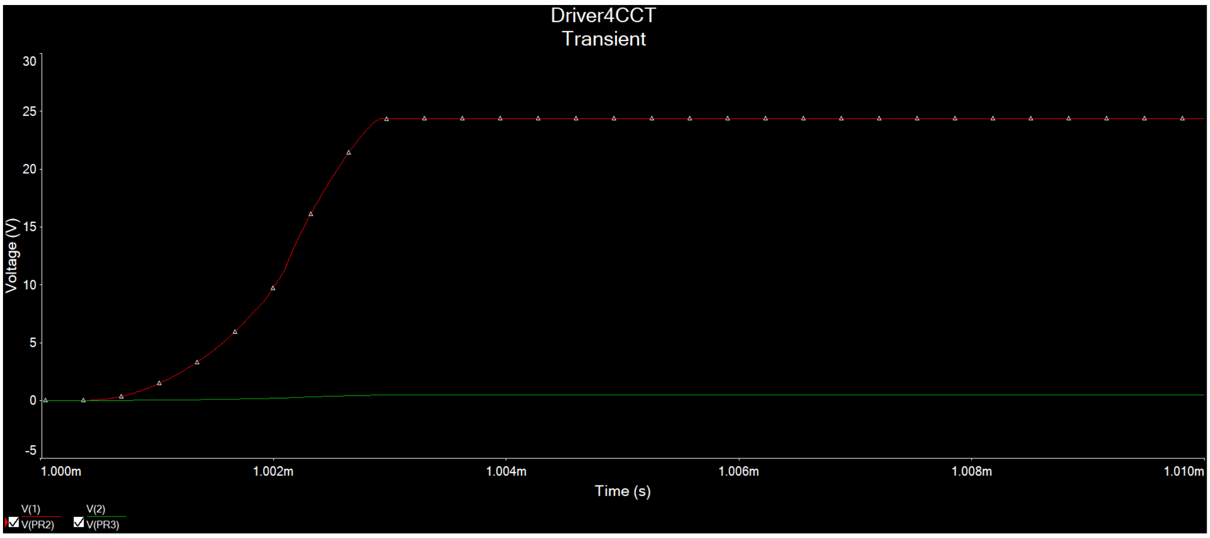


Figure 3.1: Step Response of Driver Circuit in Multisim Shown in Figure 2.1

The process in Figure 3.1 is done for both clockwise and counterclockwise directions of the motor. The respective .txt files of the graphs are then put into the MATLAB script shown in Appendix 3. The following transfer function is achieved for the clockwise step response:

$$\frac{1.433e11}{s^2 + 2.603e05\ s + 3.039e10}$$

And the following transfer function is achieved for the counterclockwise step response:

$$\frac{1.43e11}{s^2 + 2.596e05\ s + 3.034e10}$$

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

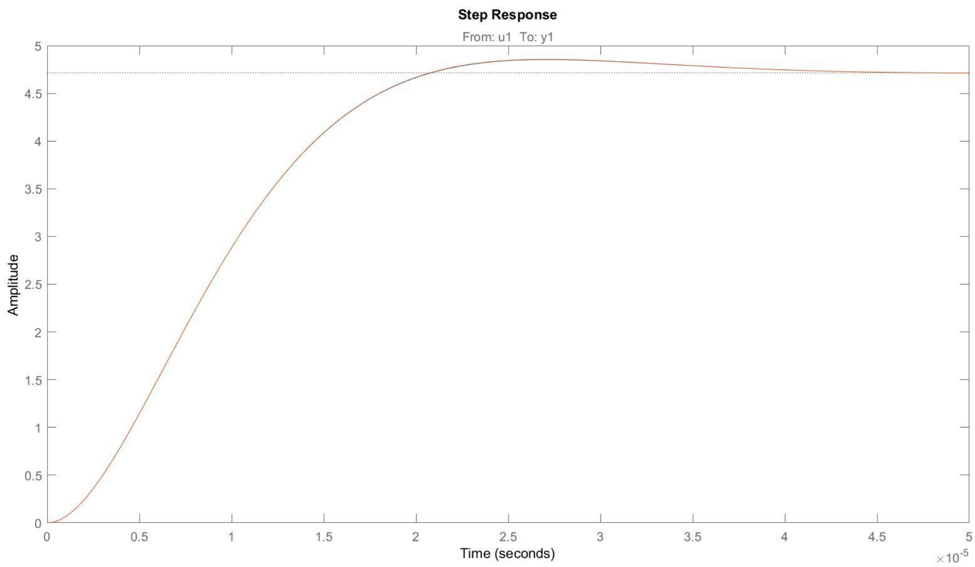


Figure 3.2: Step Response of Transfer Functions in MATLAB

As seen above in Figure 3.2, the step responses of the clockwise and counterclockwise transfer functions are highly similar and overlap in the graph. It can be seen that the step response in Figure 3.2 settles with minimal overshoot (<0.3V) in minimal time (~2s).

4. PCB Design and Layout

The PCB layout for the schematic is shown below in Figure 4.1. It is a 2 layer design that uses the bottom copper plate as the ground plane. All the components and traces are placed on the top copper plate, with only two traces running on the side of the bottom copper plate. All the components are properly named and displayed on the silkscreen for user reference.

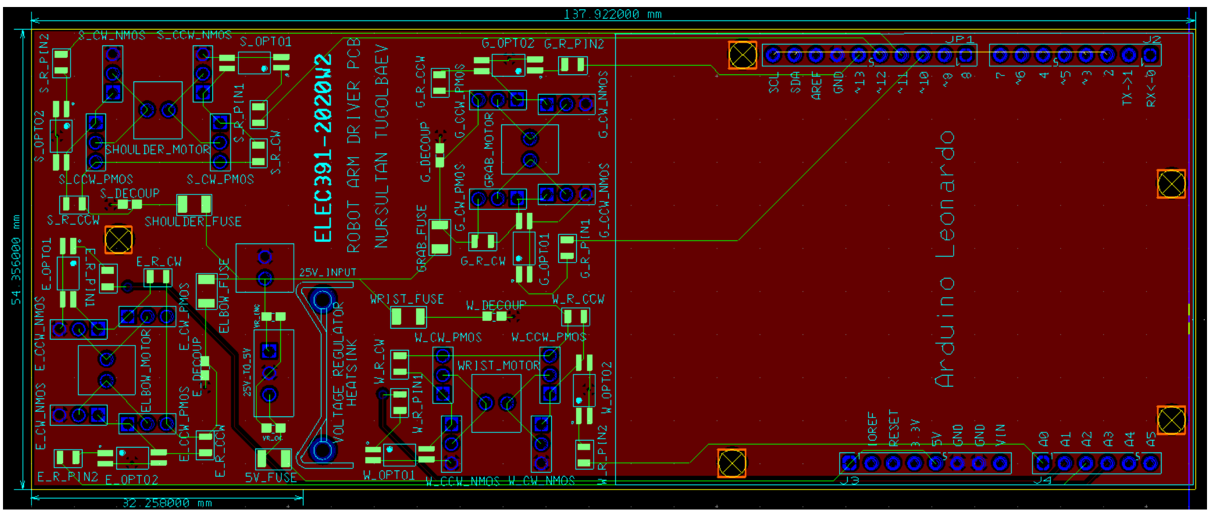


Figure 4.1: PCB Layout of the Full Driver Circuit Including the Arduino Leonardo

The PCB has dimensions of 138x55x10 mm (due to Ultiboard's restrictions, the heatsink shown in Figure 4.2 is 33mm tall, but the actual part chosen in the BOM is 10mm tall). As an additional clever feature, the Arduino Leonardo board is integrated into the PCB for a robust base, avoiding additional wiring and housing for the microcontroller. For reference, the PCB would measure 70x55x10 mm without the Arduino Leonardo.

The PCB also integrates a heatsink to keep the voltage regulator that is stepping down 20V from overheating as an additional clever design.

The 3D view of the PCB can be seen below in Figure 4.2.

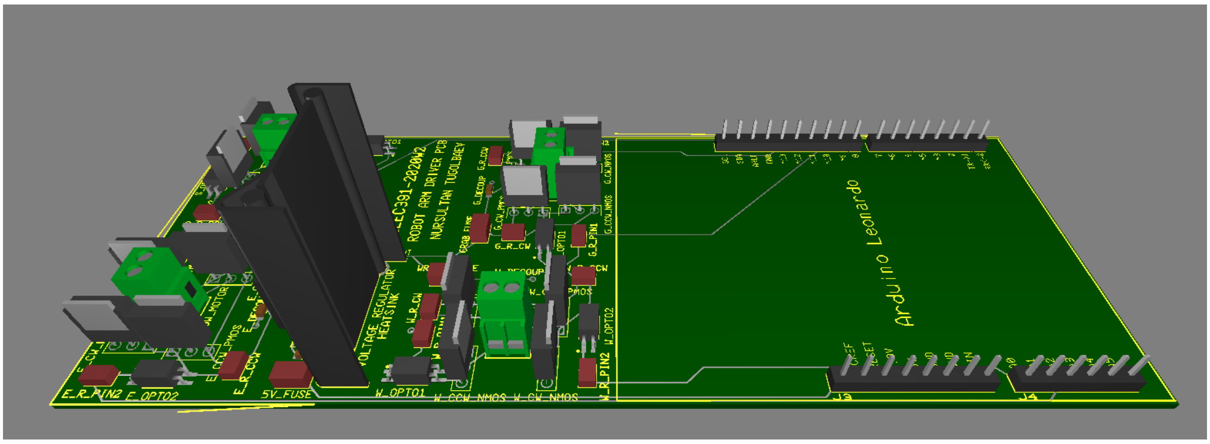


Figure 4.2: 3D View of the Driver PCB Seen in Figure 4.1

5. CAD Model and Housing

The see-through PCB housing and the exported PCB can be seen in Figure 5.1 below. The PCB housing also serves as the base enclosure for the rest of the arm as seen in Figure 5.1 and Figure 5.2. It also provides elevation to the Robot Arm by 8cm. The opening at the top of the base enclosure allows wires coming in from the encoders to connect to the Arduino Leonardo. As explained in Section 2.1 of the Mechanical Report, the wires coming in from the encoders follow the insides of the robot arms to allow for clean and simple wire management.

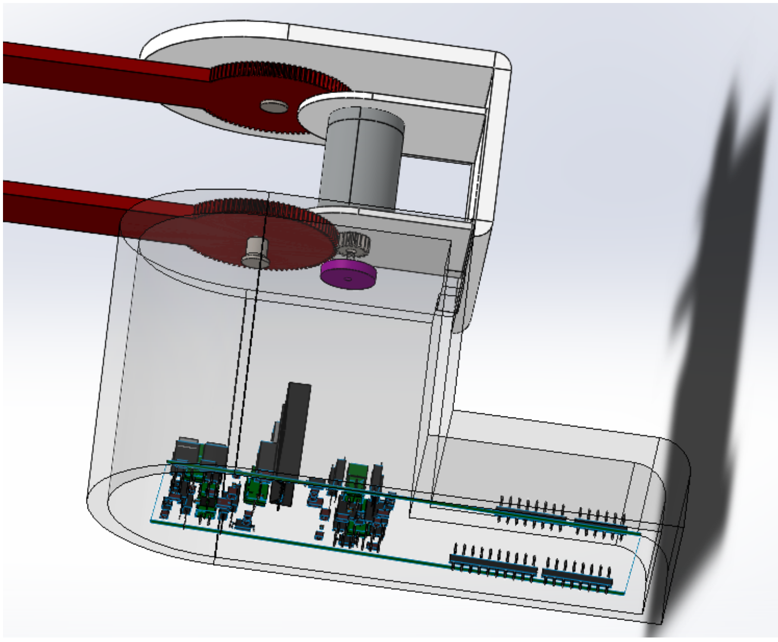


Figure 5.1: CAD Model of the Base Enclosure and Housing for PCB

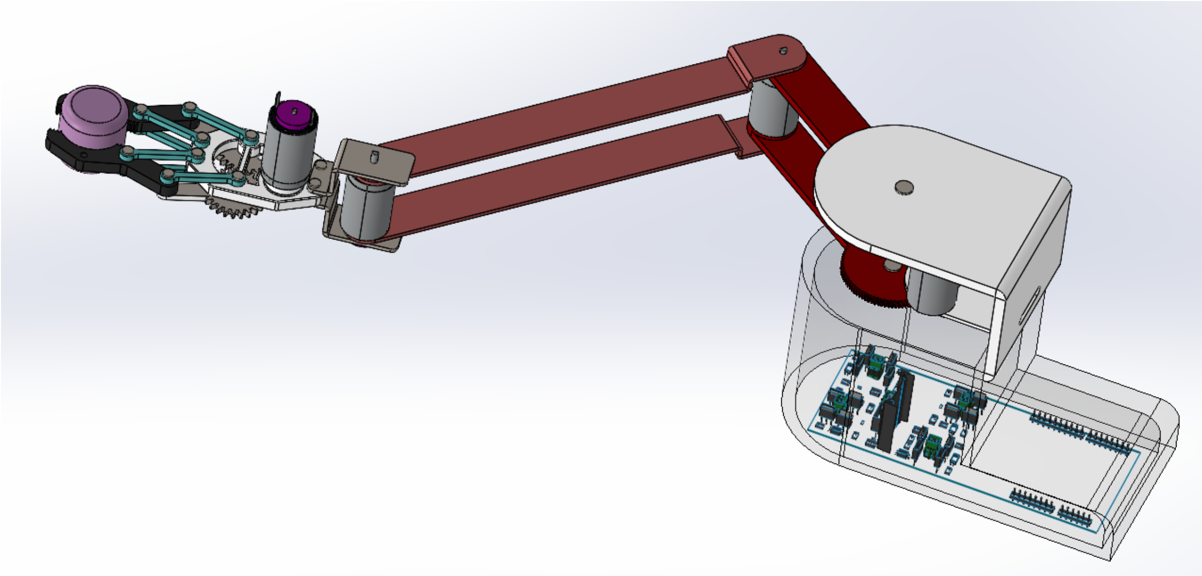


Figure 5.2: CAD Model of the Robot Arm

6. Bills of Materials for the PCB

All prices are in Canadian Dollars (CAD).

Part	# of Components	Unit Price	Bulk Price	Part Details
1kΩ Resistor	8	$0.33	$2.64	mouser.ca/link
3.3kΩ Resistor	8	$0.32	$2.56	mouser.ca/link
10A Fuse	4	$0.4	$1.6	mouser.ca/link
1.5A Fuse	1	$1.73	$1.73	mouser.ca/link
47uF Decoupling Capacitor	4	$1.39	$5.56	mouser.ca/link
0.1uF Voltage Reg. Output Capacitor	1	$0.94	$0.94	mouser.ca/link
0.33uF Voltage Reg. Input Capacitor	1	$0.21	$0.21	mouser.ca/link
Optocoupler	8	$0.6	$4.8	mouser.ca/link
P-Channel MOSFET	8	$1.34	$10.72	mouser.ca/link
N-Channel MOSFET	8	$0.98	$7.84	mouser.ca/link
Voltage Regulator	1	$2.25	$2.25	mouser.ca/link

2-Pin Connectors	5	$1.21	$6.05	mouser.ca/link
6-Pin Header	1	$0.28	$0.28	mouser.ca/link
8-Pin Header	2	$0.31	$0.62	mouser.ca/link
10-Pin Header	1	$1.39	$1.39	mouser.ca/link
Heatsink	1	$2	$2	ebay.ca/link
Arduino Leonardo	1	$24.03	$24.03	digikey.ca/link

The total cost of the BOM comes to $75.22.

The quote from JLCPCB estimates a $7.1 price for 5 pieces of PCB.

References

[1] Prof. Leo Stocco. (2020). *Maxon Motor Catalogue*. Maxon Group. https://www.ece.ubc.ca/~leos/pdf/datasheets/Maxon/MaxonCat.pdf

[2] Angelica Perzan. (2021). *Precious Metal vs Graphite Brushes*. Drive Tech by Maxon. https://drive.tech/en/stream-content/precious-metal-vs-graphite-brushes

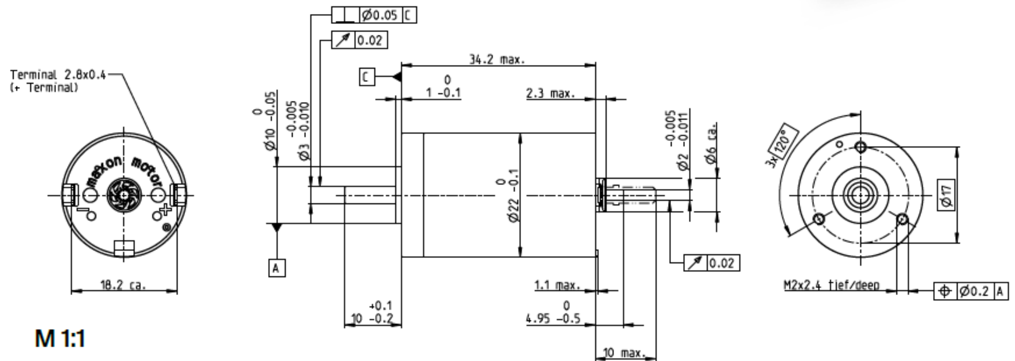
Appendix

1.

DCX

DCX 22 S Graphite Brushes
DC motor ∅22 mm

Key Data: 14/24 W, 15.3 mNm, 18 000 rpm



M 1:1

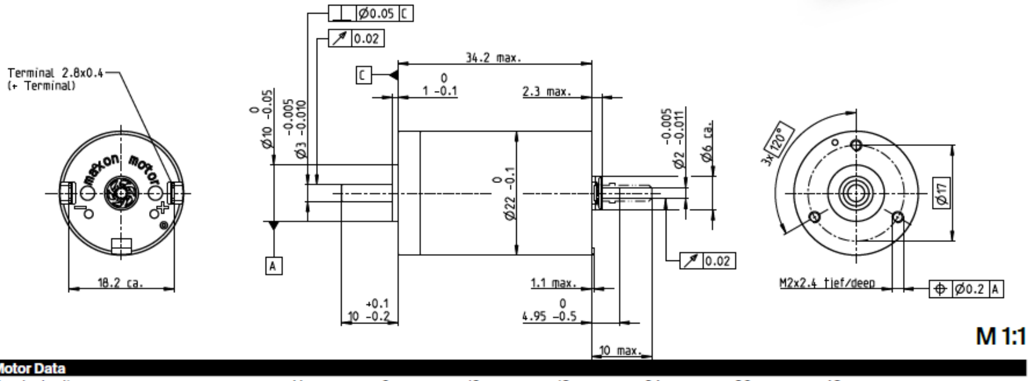
Motor Data								
1_	Nominal voltage	V	6	12	18	24	36	48
2_	No load speed	rpm	11400	12400	12400	12400	12200	12700
3_	No load current	mA	126	71.7	47.8	35.9	23.4	18.5
4_	Nominal speed	rpm	9700	10700	10800	10800	10500	10900
5_	Nominal torque (max. continuous torque)	mNm	14.4	14.6	14.9	15.3	14.8	14.0
6_	Nominal current (max. continuous current)	A	3.00	1.65	1.12	0.869	0.552	0.406
7_	Stall torque	mNm	101	108	112	120	113	104
8_	Stall current	A	20.2	11.8	8.15	6.51	4.03	2.90
9_	Max. efficiency	%	85	85	85	86	85	84
10_	Terminal resistance	Ω	0.297	1.02	2.21	3.69	8.94	16.6
11_	Terminal inductance	mH	0.017	0.058	0.130	0.231	0.535	0.881
12_	Torque constant	mNm/A	5.01	9.18	13.8	18.4	28.0	35.9
13_	Speed constant	rpm/V	1910	1040	693	520	342	266
14_	Speed/torque gradient	rpm/mNm	113	116	111	104	109	123
15_	Mechanical time constant	ms	6.23	6.12	6.08	6.07	6.22	6.01
16_	Rotor inertia	gcm^2	5.27	5.05	5.22	5.55	5.44	4.67

2.

DCX 22 S Precious Metal Brushes
DC motor ∅22 mm

Key Data: 6/10 W, 14.5 mNm, 7160 rpm

DCX



	Motor Data							
1_	Nominal voltage	V	6	12	18	24	36	48
2_	No load speed	rpm	6200	6200	6110	6340	6550	5890
3_	No load current	mA	39.2	19.6	12.8	10.1	7.09	4.55
4_	Nominal speed	rpm	4960	4670	4560	4700	4940	4240
5_	Nominal torque (max. continuous torque)	mNm	10.7	14.7	14.5	13.6	13.8	13.6
6_	Nominal current (max. continuous current)	A	1.20	0.817	0.531	0.388	0.272	0.180
7_	Stall torque	mNm	53.7	59.7	57.5	52.7	56.5	48.6
8_	Stall current	A	5.85	3.25	2.06	1.47	1.08	0.63
9_	Max. efficiency	%	84	85	85	84	85	84
10_	Terminal resistance	Ω	1.02	3.69	8.75	16.3	33.3	76.2
11_	Terminal inductance	mH	0.058	0.231	0.535	0.881	1.86	4.08
12_	Torque constant	mNm/A	9.18	18.4	28.0	35.9	52.2	77.2
13_	Speed constant	rpm/V	1040	520	342	266	183	124
14_	Speed/torque gradient	rpm/mNm	116	104	107	121	117	122
15_	Mechanical time constant	ms	6.14	6.07	6.09	5.93	6.15	6.19
16_	Rotor inertia	gcm^2	5.05	5.55	5.44	4.67	5.03	4.84

3.

```
A=importdata('Multisim_Tf_Data.txt');

Output_CW = A.data(:,1);

Output_CCW = A.data(:,2);

Input = 5.0*ones(length(Output_CW),1);

Data_CW = iddata(Output_CW,Input,1e-08);

Data_CCW = iddata(Output_CCW,Input,1e-08);

Amp_tf_CW = tfest(Data_CW,2,0)

Amp_tf_CCW = tfest(Data_CCW,2,0)
```