Task 3 - Power Management System

Okay first things first, what do we have to build?
It's basically just a robotic arm that can move around.

What do we have?

Let's see what we're working with.

Components	Quantity
Brushed DC Geared Motors	4
BLDC Motors	2
Servo Motors	3
NEMA Stepper Motor	1
Raspberry Pi 5	1
RPI Camera Module 3	1
Ldrobot D500 LiDAR Kit	1
ESP32	1

Our objective

- Schematic - Basically what goes where

- Appropriate Battery Selection

- Safety Features (including a kill switch of course)

- Power Distribution Analysis

Schematic - What goes where

Motor Specifications

We first focusing on the Torque specifications of all the motors to figure what motors to use in locomotion vs the robotic arm itself.

Components	Quantity	Rated Torque
Brushed DC Motors	4	11 kg-cm
BLDC Motors	2	0.573 kg-cm
Servo Motors	3	28.8 to 35 kg-cm
NEMA Stepper Motor (2 Phase)	1	2.9 kg-cm

Calculating that rated torque for the ECO II Series 2207 BLDC Motor was not that straightforward.

The torque of a BLDC motor can be calculated using the formula,

$$\text{Torque} = K_t \times \text{Current}$$

where K_t is the torque constant, which is related to the kV rating.

First, we convert the kV rating from RPM/Volt to the SI unit rad/s/Volt,

$$K_v(\text{SI}) = 1700 \times \frac{2\pi}{60} \ \text{rad/s/V}$$
$$K_v(\text{SI}) = 177.89 \ \text{rad/s/V}$$

The torque constant K_t is the reciprocal of K_v in SI units,

$$K_t = \frac{1}{K_v(\text{SI})} = \frac{1}{177.89} = 0.00562 \ \text{Nm/A}$$
$$\text{Rated Torque} = K_t \times \text{Rated Current}$$
$$\text{Rated Torque} = 0.00562 \ \text{Nm/A} \times 10 \ \text{A}$$
$$\text{Rated Torque} = 0.0562 \ \text{Nm} = 0.0562 \ \text{kg-cm}$$

Motor Selection

Locomotion: An obvious choice for the locomotion would be the 4 Brushed DC Geared Motors which provide enough torque for the load movement and is pretty

suitable in a 4-wheel drive configuration.

If we were to choose some other motor, say the servo motor because of its much higher torque, then we would have to make a tricycle drive which is certainly not suitable for high loads and stability.

Base joint actuator: The base motor has to overcome the frictional force and in addition, has to handle the angular acceleration of the whole robotic arm.

$$\tau_{\text{base}} = \tau_{\text{friction}} + I\alpha \tag{1}$$

where I is the moment of inertia and α is the angular acceleration at that instant about the axis.

Assuming we'll keep α minimal and proper lubrication of the motors (avoiding τ_{friction}), the torque required is quite minimal. On the other hand the precision required is massive which can only be provided by the NEMA Stepper motor. Lesser torque but the precision, boosted by software microstepping, is more suited to the base motor.

Shoulder joint actuator: Here we define some terminologies. Let the Load mass be m, link lengths be L_1, L_2, L_3, link masses be M_1, M_2, M_3, end effector mass be M_0 (including the motors for the end effector). This will be clearer to the reader by the figure below. The actuators themselves have masses A_1, A_2, A_3 and A_0 as the end effector.

Coming back to the shoulder joint actuator A_1, the maximum torque required is quite huge. It can be calculated by taking into account the maximum extension case.

$$\tau_{\text{shoulder}} = \frac{M_1 g L_1}{2} + A_2 g L_1 + M_2 g \left(L_1 + \frac{L_2}{2} \right) + A_3 g \left(L_1 + L_2 \right) +$$
$$M_3 g \left(L_1 + L_2 + \frac{L_3}{2} \right) + A_0 g \left(L_1 + L_2 + L_3 \right)$$

This is quite a huge quantity (the most torque in this whole project in fact) and can only be supported by a servo motor. The choice we make for the shoulder joint is the Pro-Range OT5330M Servo motor.

Elbow joint actuator: For the elbow joint actuator A_2, the maximum torque in maximum extension case is given by,

$$\tau_{\text{elbow}} = M_2 g \left(L_1 + \frac{L_2}{2} \right) + A_3 g \left(L_1 + L_2 \right) +$$
$$M_3 g \left(L_1 + L_2 + \frac{L_3}{2} \right) + A_0 g \left(L_1 + L_2 + L_3 \right)$$

This is lesser than the torque required in case of the shoulder joint actuator but it is still a huge quantity and can also only be supported by a servo motor. The choice we make for the elbow joint is also the Pro-Range OT5330M Servo motor.

Wrist joint actuator: For the wrist joint actuator A_3, the maximum torque in maximum extension case is given by,

$$\tau_{\text{wrist}} = M_3 g \left(L_1 + L_2 + \frac{L_3}{2} \right) + A_0 g \left(L_1 + L_2 + L_3 \right)$$

This is lesser than the torque required in case of the shoulder and elbow joint actuator but it is still a higher quantity and can also only be supported by a servo motor. The choice we make for the wrist joint is also the Pro-Range OT5330M Servo motor.

End effector actuators: These actuators dont need *that* much torque as the other joints but have to be more versatile. We may need to use it as a gripper or say as a drill-ish machine which require precision/speed at once. Considering this and also the fact that the only motors which are left are the BLDC motors, we're just gonna use the ECO II Series 2207 BLDC Motors.

Motor Controllers and Drivers

First off, our motor controller choice is pretty obvious. It's the ESP32 microcontroller. Because of its computation restrictions we can't really use it as the main driver with the object detection with lidars and camera on it, but motor driving signals are easy to compute.

On top of this, motor drivers for all the motors except the servos (which don't really require a driver) are a necessity. The schematic explaining what im talking about is given below. The COMMS go to Raspberry Pi.
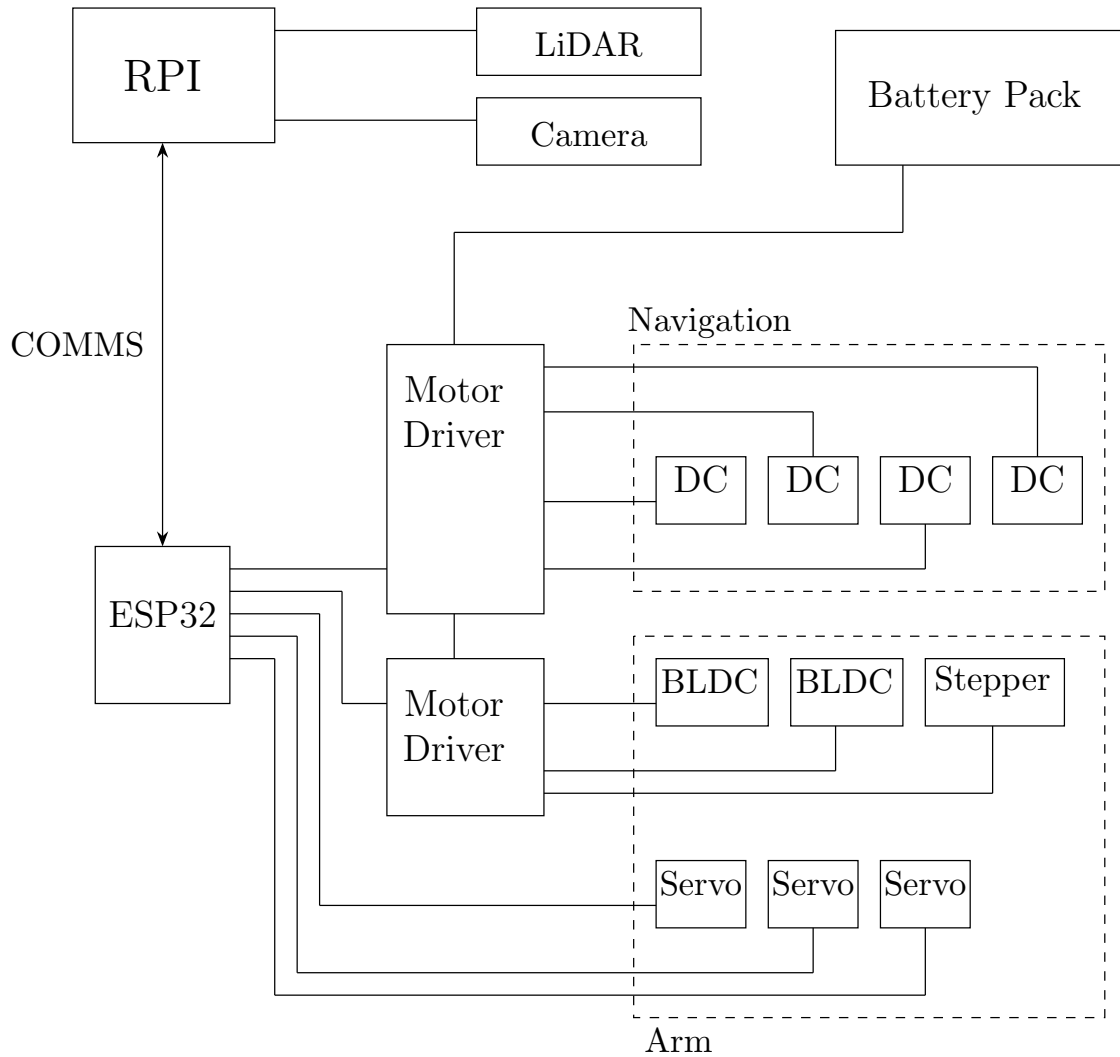
Figure 1: Overview Schematic

Battery Pack

The battery pack consists not merely the battery but the safety and protection systems in place to avoid, well, catastrophes. In place is a **BMS** (Battery management system), **Fuse** to avoid short circuits, **Fool's diode** to prevent reverse current, and a **Master Kill Switch** for turning off the whole bot. The battery pack schematic is given below.

Battery pack

Fuse

+

Battery

+

-

BMS

Current
Sensor

-
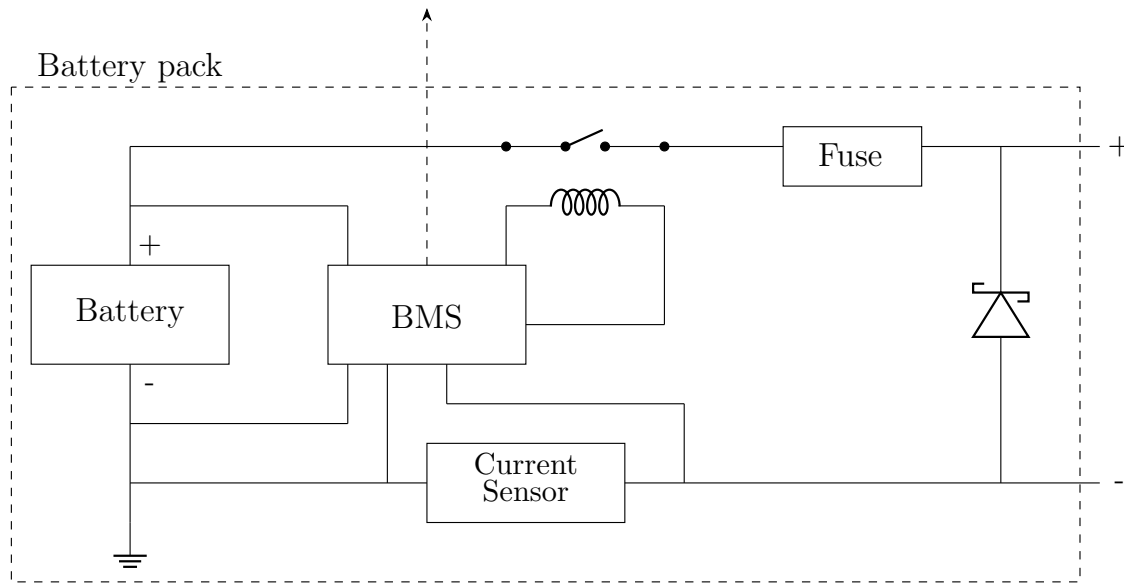
The Fool's diode will help in case of reverse currents as all the reverse current
will flow through the diode instead of the actual load. We are gonna use a Schottky
diode for this purpose due to its high reverse bias breakdown voltage (about 50 to
60 V which is more than enough).
What battery are we gonna choose? Well we haven't calculated the power specifica-
tions yet (which will we will do somewhere down the line), but one thing's sure. It's
going to be around 12 V nominal voltage battery (or we could stoop down do 11.1
V if we like 3S LiPo Batteries).

Powering the RPI and ESP32 - Voltage Regulators

Since we're using a 12 V battery, it will blow up our Raspberry Pi and ESP32
instantly. We obviously don't want that, so we use voltage regulators which in this
case, we will be using a **Buck Converter** to bring down the voltage to 5V for the
RPI, ESP32, LiDAR and Camera Modules. In addition to that, we would also need
a 7.4 V power line for the Servo motors to optimally run them for which will be using
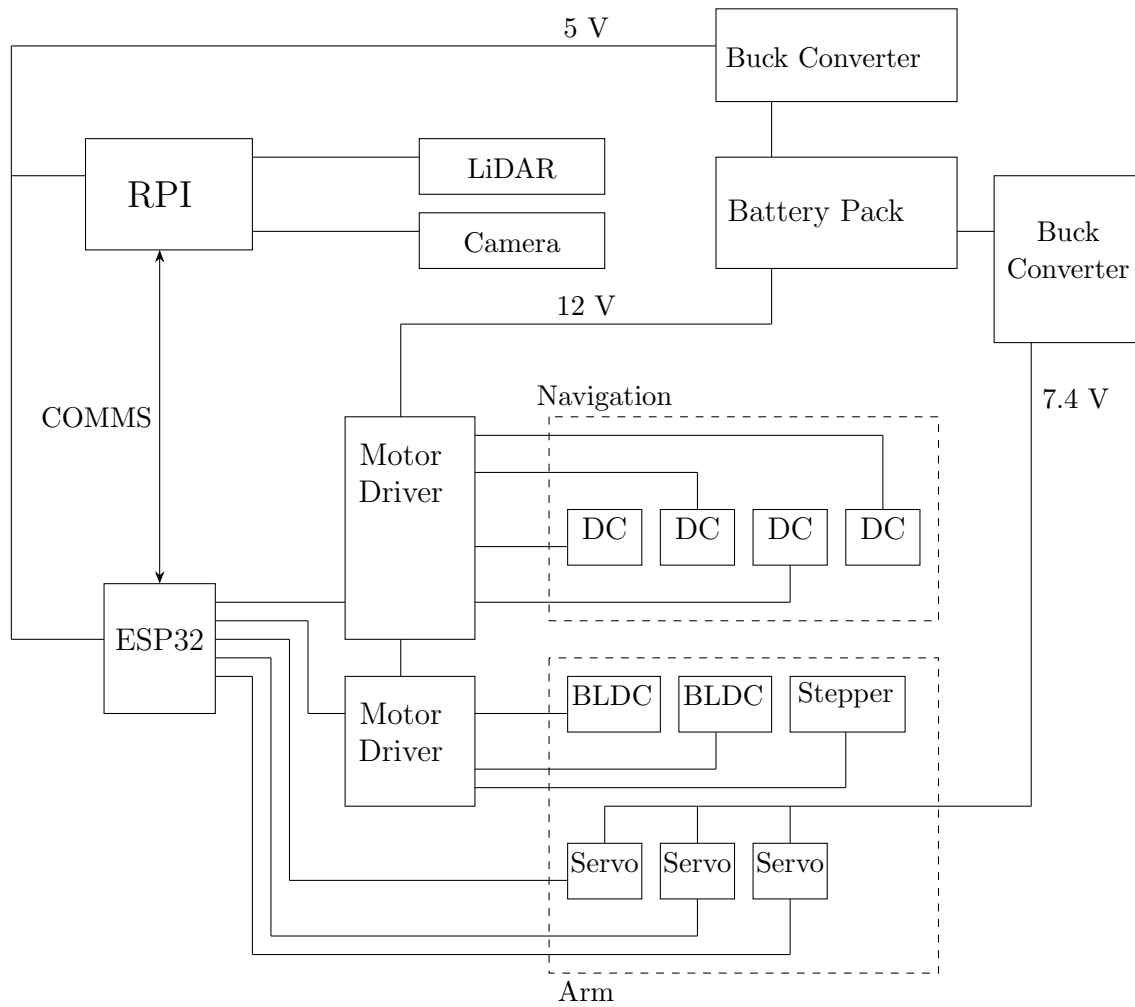a different buck converter.

Figure 2: Final Schematic

Power Distribution and Component Selection

What are the extra components we need?

1. Motor Drivers for 4× DC Motors and 2× BLDC Motors

2. Variable Buck Converters (2×)

3. Battery

4. BMS Chip (w/ Current Sensor)

5. Fuse

6. Schottky Diode

7. Master switch

Okay firstly, we have to calculate the rough power consumption estimate.

Component	Quantity	Rated Voltage (V)	Stall Current (A)
DC Geared Motor (IG45)	4	12.0	15.0
BLDC (ECO II 2207)	2	11.1-22.2	36.0
NEMA Stepper (39HY38-0504)	1	12.0	$0.5 \times 2 = 1$
Servo Motor (OT5330M)	3	4.0-8.4	3.8
Raspberry Pi 5	1	5.0	2.2
Raspberry Pi Camera Module 3	1	5.0	0.25
Ldrobot D500 LiDAR Kit	1	5.0	0.29
ESP32	1	5.0	0.3

Table 1: Component Specifications

Component	Quantity	Operating Voltage (V)	Stall Power (W)
DC Geared Motor (IG45)	4	11.1	166.5
BLDC (ECO II 2207)	2	11.1	399.6
NEMA Stepper (39HY38-0504)	1	11.1	11.1
Servo Motor (OT5330M)	3	7.4	28.1
Raspberry Pi 5	1	5.0	11.0
Raspberry Pi Camera Module 3	1	5.0	1.25
Ldrobot D500 LiDAR Kit	1	5.0	1.45
ESP32	1	5.0	1.5

Table 2: Power Requirements

$$\text{DC Geared Motors (4x)} = 4 \times 11.1 \text{ V} \times 15.0 \text{ A} = 666.0 \text{ W}$$
$$\text{BLDC Motors (2x)} = 2 \times 11.1 \text{ V} \times 36.0 \text{ A} = 799.2 \text{ W}$$
$$\text{NEMA Stepper Motor (1x)} = 1 \times 11.1 \text{ V} \times 1 \text{ A} = 11.1 \text{ W}$$
$$\text{Servo Motors (3x)} = 3 \times 4.0 \text{ V} \times 3.8 \text{ A} = 45.6 \text{ W}$$
$$\text{Raspberry Pi 5} = 5.0 \text{ V} \times 2.2 \text{ A} = 11.0 \text{ W}$$
$$\text{Raspberry Pi Camera Module 3} = 5.0 \text{ V} \times 0.25 \text{ A} = 1.25 \text{ W}$$
$$\text{Ldrobot D500 LiDAR Kit} = 5.0 \text{ V} \times 0.29 \text{ A} = 1.45 \text{ W}$$
$$\text{ESP32} = 5.0 \text{ V} \times 0.3 \text{ A} = 1.5 \text{ W}$$
$$\textbf{Total Power} = 1537.1 \text{ W}$$

That's a HUGE amount of power. Also you may notice that we have been taking 11.1 V as the operating voltage when the rated voltage was 12 V. That's because a 3s LiPo Battery has a nominal voltage of 11.1 V and peak voltage of 12.6 V, and these are the batteries we'll be using in this bot.

This rough power estimation has not taken into account the power consumed by motor drivers, the BMS, etc. has not been considered. Although they will be extremely less compared to the massive 1537 W of power.

$$\textbf{Rough Stall Current Drawn} = 1537.1/11.1 = 138.47 \text{ A}$$

Now this will affect all the materials we choose henceforth.

Battery

The battery we're going for is a Pro-Range 11.1V 5200mAh 40C 3S Lithium Polymer Battery Pack.

This pack has a three cell series combination which results in 11.1 V of voltage and a capacity of 5200mAh along with 40 C as the C rating.

$$\text{Max continous discharge current} = (\text{capacity}) \times (\text{C rating})$$
$$= 5200 \times 40 = 208000 \text{ mA}$$
$$= 208 \text{ A}$$

So this has an headroom of about 70 A which is MORE than enough. The cost of this battery is about 3653 rupees.

We have to see if this battery can even handle our continous current for atleast 5 minutes.

Component	Rated Voltage (V)	Rated Current (A)	Continous Power (W)
DC Geared Motor (IG45)	12.0	6.2	74.4
BLDC (ECO II Series 2207)	11.1	10.0	111.0
NEMA Stepper (39HY38-0504)	12.0	1	12.0
Servo Motor (Pro-Range OT5330M)	7.4	3.8	28.1
Raspberry Pi 5	5.0	2.2	11.0
Raspberry Pi Camera Module 3	5.0	0.25	1.25
Ldrobot D500 LiDAR Kit	5.0	0.29	1.45
ESP32	5.0	0.3	1.5

Table 3: Continous Power and Current Requirements

Total continous current rated current = 60.24 A @ 11.1 V.

Our battery has a capacity of 5200 mAh, so it can last 1 hour/60 minutes with 5.2 A continous current. For 5 minutes of usage, $5.2 \times 60/5$ = 62.4 A of continous current can be handled by the battery which is just enough current (about 2.16 A of headroom to spare) to run our bot for 5 minutes.

Note that we have not included the current due to the extra components, because they consume current in the order of μ A which is almost negligible.

Link for the component can be found here.

Fuse

The fuse we selected is LittelFuse Auto 200A 58VDC Fuse. This also has a headroom of about 60 A above the max discharge current. This costs about 377 rupees.

Link for the component can be found here.

Schottky Diode

We're going for an extremely cheap but useful SS34 Schottky Diode. This costs about 25 rupees.

Link for the component can be found here.

Master/Kill Switch

This switch will be in the form of a relay, because it also has to be controlled by the BMS systems. We need a relay that can handle atleast 12V DC at 150 A. Unfortunately these types of relays are pretty hard to find, and are on the expensive side.

We're going to be using the 12V 200A Car Start Relay which costs about 1493 rupees.

BMS

The BMS for our current specifications, 3S LiPo with atleast 150 A of max discharge was EXTREMELY hard to find. Hate to say it, but I had to set up a proxy server to access AliExpress. I found a 3S 150A Battery Protection Board Balance MOS High Current BMS. This costs about 1557 rupees.

Usually BMS barely take in any current, so because of lack of proper datasheets for this BMS, we're gonna assume it takes in negligible amount of current and hence consumes pretty less power (relatively).
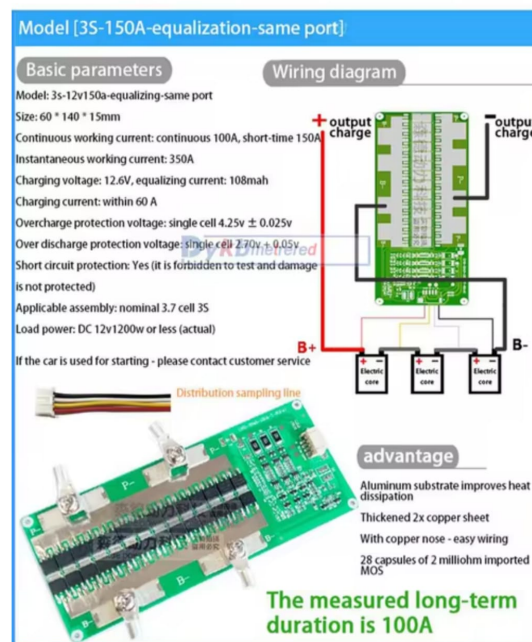
Figure 3: Data supplied by the vendor

Note that this is an unbranded BMS which could very fail mid-operation. Branded BMS are much much more expensive than what we have here, still I am gonna include one of these below.

Alternative Branded BMS

DALY SMART BMS M series BMS LFP 3S 200 A for Li-ion batteries. This costs about 7,314 rupees. This includes Wi-Fi support and consumes only microamps of current.

Link for the component can be found here.

Motor Drivers

DC Geared Motor (IG45): Total stall current for all the DC motors $= 4*15 = 60$ A. The motor driver for the IG45 Geared DC motor is the BTS7960 43A H-Bridge Motor Driver (Dual) which contains support for 2 motors in one driver. For 2 motors, stall current $= 2*15 = 30$ A which is supported by the driver. It costs around 213 rupees and we need 2 of them.

Link for the component can be found here.

BLDC (ECO II Series 2207): Stall current for this BLDC is 36 A. Motor Driver is Hobbywing SKYWALKER-40A-V2 ESC Fixed Wing which costs about 1500 rupees. We need 2 of these.

Link for the component can be found here.

Stepper Motor (NEMA16 39HY38-0504): Stall (or Rated which is the same in case of Steppers) current for this Stepper is $0.5*2 = 1$ A (there are two phases). Motor Driver is DRV8825 Stepper Motor Driver with Aluminum Heat Sink which costs about 83 rupees.

Link for the component can be found here.

Variable Buck Converters

We need two buck converters, one for the 5 V components like the Raspberry Pi and the ESP32, and other (7.4 V) for the servos.

Total maximum current for 5 V components $= 2.2 + 0.25 + 0.29 + 0.3 = 3.04$ A (15.2 W of power). Total stall current for the 7.4 V Servos $= 3 * 3.8 = 11.4$ A (84.36 W of power).

The Buck converter we are gonna use is the 200W 20A DC-DC Buck Converter Step Down Module. This costs about 377 rupees and can support 200W @ 20A which is more than enough for our bot. Also, we need 2 of these.

Link for the component can be found here.

BOM with Connectors

Component	Quantity	Unit Price (INR)	Total Price (INR)
Pro-Range 11.1V 5200mAh 40C Battery	1	3653	3653
Littelfuse 200A 58VDC Fuse	1	377	377
SS34 Schottky Diode (Pack of 2)	1	25	25
12V 200A Car Start Relay	1	1493	1493
3S 150A Unbranded BMS	1	1557	1557
DALY SMART 3S 200A BMS (Optional)	1	7314	7314
BTS7960 H-Bridge Motor Driver	2	213	426
Hobbywing Skywalker 40A V2 ESC	2	1500	3000
DRV8825 Stepper Motor Driver	1	83	83
200W 20A DC-DC Buck Converter	2	377	754
IG45 Geared Motor (with mount)	4	2660	10640
ECO II Series 2207 BLDC Motor	2	1574	3148
NEMA16 39HY38-0504 Stepper Motor	1	840	840
Pro-Range OT5330M Servo Motor	3	1889	5667
Raspberry Pi 5 (4GB)	1	6149	6149
Raspberry Pi Camera Module 3	1	3499	3499
Ldrobot D500 LiDAR Kit	1	8159	8159
ESP32 Development Board	1	354	354
XT30 Connector (IG45 to BTS7960)	4	32	128
Dupont 4-pin (Stepper to Driver)	1	12	12
Jumper Wires F-F (Driver to ESP32)	1	40	40
Jumper Wires F-F (RPI to ESP32 UART)	1	40	40
XT60 Connectors (Battery to Driver/Buck)	3	28	84
Buck to USB A Female	2	100	200
USB A to USB C (RPI Power)	1	189	189
USB A to MicroUSB (ESP32 Power)	1	99	99
130m 8 AWG Wire (Battery to Buck, Servo etc.)	1	394	394

Table 4: Complete Component List with Quantities and Prices

The connectors were selected based on the current ratings of the components. Wherever an bare connector is there it is to be used with the 8 AWG wire (upto 40 A).