# Torque Requirement Analysis for Differential Drive Robots

Q2.(A) in Mechatronics Application

## 1 Introduction

Motor selection is a critical step in mobile robot design. Motors must provide sufficient torque to overcome rolling resistance, gravitational forces on slopes, and drivetrain losses without stalling or overheating. Vishal and his team are developing two differential-drive robot prototypes: a wheel-based robot (BOTjo) and a tracked robot (BOTkuna). Although both share identical chassis dimensions, they differ in mass and drive mechanisms, which significantly affects torque demand.

This report calculates the torque requirements for both prototypes to ensure they can achieve the desired performance on uneven terrain.

## 2 Problem Description

Both robots are designed to reach a maximum speed of 5 mph and climb a ramp with a maximum gradient of 15%. The specifications are listed below.

## 3 Given Parameters

- Desired speed: $v = 5$ mph $= 2.236$ m/s
- Ramp gradient: 15%
- Gravitational acceleration: $g = 9.81$ m/s$^2$
- Factor of Safety: $FoS = 2$
- BOTjo mass: $m_w = 60$ kg
- BOTkuna mass: $m_t = 80$ kg
- Wheel diameter (BOTjo): $D_w = 8$ in $= 0.2032$ m
- Sprocket diameter (BOTkuna): $D_t = 6$ in $= 0.1524$ m
- Rolling resistance (wheels): $C_{rr,w} = 0.02$

- Rolling resistance (tracks): $C_{rr,t} = 0.08$
- Mechanical efficiency: $\eta = 0.85$

# 4 Slope Geometry

The ramp angle is obtained from the gradient:

$$\tan(\theta) = 0.15 \tag{1}$$

$$\theta = \tan^{-1}(0.15) \approx 8.53^\circ \tag{2}$$

# 5 General Force Model

The rolling resistance force is

$$F_{rr} = C_{rr} mg \tag{3}$$

The slope climbing force is

$$F_{slope} = mg \sin(\theta) \tag{4}$$

The total tractive force is

$$F_{total} = F_{rr} + F_{slope} \tag{5}$$

Each robot uses two motors, hence

$$F_{motor} = \frac{F_{total}}{2}. \tag{6}$$

Torque at the wheel or sprocket is

$$T = F_{motor} r. \tag{7}$$

Including efficiency and factor of safety,

$$T_{req} = \frac{T \cdot FoS}{\eta}. \tag{8}$$

# 6 BOTjo: Wheel-Based Robot

Wheel radius:

$$r_w = \frac{D_w}{2} = 0.1016 \text{ m}. \tag{9}$$

Rolling resistance force:

$$F_{rr,w} = 0.02 \times 60 \times 9.81 = 11.77 \text{ N.} \tag{10}$$

Slope force:

$$F_{slope,w} = 60 \times 9.81 \times \sin(8.53^\circ) = 87.9 \text{ N.} \tag{11}$$

Total force:

$$F_{total,w} = 11.77 + 87.9 = 99.67 \text{ N.} \tag{12}$$

Force per motor:

$$F_{motor,w} = \frac{99.67}{2} = 49.84 \text{ N.} \tag{13}$$

Torque per motor:

$$T_w = 49.84 \times 0.1016 = 5.06 \text{ Nm.} \tag{14}$$

Required torque:

$$T_{req,w} = \frac{5.06 \times 2}{0.85} \approx 11.9 \text{ Nm.} \tag{15}$$

# 7 BOTkuna: Tracked Robot

Sprocket radius:

$$r_t = \frac{D_t}{2} = 0.0762 \text{ m.} \tag{16}$$

Rolling resistance force:

$$F_{rr,t} = 0.08 \times 80 \times 9.81 = 62.78 \text{ N.} \tag{17}$$

Slope force:

$$F_{slope,t} = 80 \times 9.81 \times \sin(8.53^\circ) = 117.2 \text{ N.} \tag{18}$$

Total force:

$$F_{total,t} = 62.78 + 117.2 = 179.98 \text{ N.} \tag{19}$$

Force per motor:

$$F_{motor,t} = \frac{179.98}{2} = 89.99 \text{ N.} \tag{20}$$

Torque per motor:

$$T_t = 89.99 \times 0.0762 = 6.86 \text{ Nm.} \tag{21}$$

Required torque:

$$T_{req,t} = \frac{6.86 \times 2}{0.85} \approx 16.1 \text{ Nm}. \tag{22}$$

# 8 Results Summary

| Robot | Mass (kg) | Radius (m) | Torque per Motor (Nm) |
|---|---|---|---|
| BOTjo (Wheels) | 60 | 0.1016 | 11.9 |
| BOTkuna (Tracks) | 80 | 0.0762 | 16.1 |

Table 1: Torque requirements per motor for both robots.

# 9 Discussion

The tracked robot BOTkuna requires higher torque due to increased rolling resistance and weight. Including slope effects, drivetrain efficiency, and a factor of safety ensures the selected motors will not stall or overheat. BOTjo is more energy efficient, while BOTkuna offers better traction on uneven terrain at the cost of higher torque demand.

# 10 Conclusion

Torque estimation is essential before motor selection. From the analysis, BOTjo requires approximately 12 Nm per motor, while BOTkuna requires approximately 16 Nm per motor to safely achieve the desired speed and climb a 15% ramp. These values provide a baseline for selecting motors and gearboxes for both platforms. Part B: Motor Selection for Tracked Robot (BOTkuna)

BOTkuna's estimated required torque was approximately 16.1 Nm per motor (after including rolling resistance, slope force, mechanical efficiency, and factor of safety). Suitable motors must supply continuous torque at or above this value and operate within expected speed and voltage ranges.

## 10.1 Motor Selection Criteria

The tracked robot's motors must satisfy the following:

- Provide continuous torque greater than or equal to the required torque ($\approx$ 16 Nm).
- Supply sufficient power and speed to achieve the target robot velocity (5mph 2.236m/s).
- Operate at practical battery voltages (12–48V DC typical for mobile robots).
- Be compatible with speed controllers (ESC or DC drives) and allow gearing if used.

- Minimize weight, power loss, and heat generation.

Brushless DC (BLDC) motors are preferred in mobile robots for their higher efficiency, better torque-to-weight ratio, longer lifetimes, and lower maintenance compared to brushed DC motors. BLDC motors use electronic commutation to produce smooth torque and precise control, making them suitable for robotic applications. :contentReference[oaicite:0]index=0

## 10.2 Suggested Motors

The following motors are examples of DC/BLDC motors that could be considered for BOTkuna. Note that in many cases a gearbox (planetary or spur) would be used to reach the required output torque.

| Motor | Rated Torque (Nm) | Rated Speed (RPM) | Voltage (V) | Comments |
|---|---|---|---|---|
| **Frameless BLDC (example)** | 4.79 (rated) | 1000 | 48 | Peak, 21.7 Nm, suitable when used with a reduction gearbox. |
| **General DC Planetary Motor** | 2.0 | 150 | 24 | Typical small geared motor, requires high ratio gearbox (e.g., >10:1). |
| **IG50 Planetary DC Motor** | 2.0 | 150 | 24 | Mid-range torque motor combined with planetary gearbox. |
| **PGM45 Planetary DC Motor** | 0.20 | 1350 | 12 | Low torque, better suited for smaller reduction stages. |

Table 2: Examples of motors suitable for robotic drive (with appropriate gearboxes to meet output torque).

Note: Commercial BLDC motors with several Nm of continuous torque are often paired with planetary gearboxes to achieve output torque comparable to the requirement. High torque frameless BLDC motors, such as one with 21.7Nm peak torque and 4.8Nm rated torque, can be suitable when coupled with gear reduction (e.g., 4:1 or 5:1) to deliver continuous output torque beyond the 16 Nm requirement. :contentReference[oaicite:1]index=1

## 10.3 Motor Justification

- **Frameless BLDC Motor:** A robot-specific BLDC motor can deliver very high peak torque (over 20Nm) while maintaining a relatively compact form factor and good efficiency. These motors are optimized for dynamic response and low heat generation

— beneficial for tracked robots experiencing variable terrain loads. :contentReference[oaicite:2]index=2

- **DC Planetary Geared Motors:** Standard DC motors with planetary gearboxes are cost-effective and provide modular torque scaling. With appropriate gear ratios (e.g., $> 10 : 1$), they can meet the required torque output. Planetary gear systems maintain compact size while enhancing torque output.

## 10.4 Maximum Absolute Force Tolerance

The robot's maximum absolute force is the force the drive system can exert on the ground without stalling.

If a motor produces torque $T_{\text{motor}}$ after gearing, and the track sprocket radius is $r_t$, then the maximum tractive force per side is:

$$F_{\max} = \frac{T_{\text{motor}}}{r_t}. \tag{23}$$

Assuming a geared output torque of $T_{\text{out}}$ per motor:

$$F_{\text{max,total}} = 2 \times \frac{T_{\text{out}}}{r_t} \tag{24}$$

Using $r_t = 0.0762$ m and $T_{\text{out}} \geq 16$ Nm (from Part A), then:

$$F_{\text{max,total}} \approx 2 \times \frac{16}{0.0762} \approx 420 \text{ N} \tag{25}$$

This 420N is the maximum traction force the robot drive can apply before its motors stall (assuming ideal conditions). In practice, motor controller limits, slip, friction, and safety margins will lower this.

The maximum absolute force helps determine the robot's ability to accelerate and resist external disturbance forces without losing traction or stalling.

## 10.5 Conclusion

For BOTkuna, using high-torque BLDC motors with reduction gearboxes is recommended. Frameless BLDC motors designed for robotic actuation can provide high peak torque, while planetary-geared DC motors offer a cost-effective alternative when used with appropriate gear reductions. A torque capacity above 16Nm per motor, combined with a suitable control system and power electronics, will ensure the robot meets performance targets.