Torque Estimation for a 3-Axis Mobile Gimbal with 3–6 kg Payload

1. Torque Components and Estimation

The peak torque requirement for each gimbal axis can be estimated as the sum of inertial, frictional, and aerodynamic (wind) torques with an appropriate design margin:

$$T_{\text{peak}} \approx J\,(\alpha_{\text{cmd}} + \alpha_d) + b\,\omega + T_{\text{Coulomb}} + T_{\text{wind}} \tag{1}$$

where

- J : payload + frame moment of inertia about the axis (kg·m^2)
- α_{cmd} : commanded angular acceleration (rad/s^2)
- α_d : disturbance angular acceleration from base motion (rad/s^2)
- b : viscous damping coefficient (N·m·s/rad)
- ω : instantaneous angular velocity (rad/s)
- T_{Coulomb} : static friction/Coulomb torque (N·m)
- T_{wind} : wind-induced torque (N·m)

The wind-induced torque can be estimated using a flat-plate approximation:

$$T_{\text{wind}} \approx \frac{1}{2}\rho\,C_d\,A\,V^2\,r \tag{2}$$

where

- ρ : air density $\approx 1.2\,\text{kg/m}^3$
- C_d : drag coefficient (1.0–1.2 for bluff bodies)
- A : projected area normal to wind (m^2)
- V : wind/airflow speed (m/s)
- r : lever arm from axis to center of pressure (m)

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2. Example Calculations

Example 1: Moderate Mapping/Inspection Case

- Payload mass: $m = 5\,\text{kg}$
- Approx. box: $0.22 \times 0.18 \times 0.15\,\text{m}$
- Inertia about roll/pitch axis:

$$J \approx \frac{1}{12} m(b^2 + c^2) \approx 0.023\,\text{kg·m}^2$$

- Commanded accel: $\alpha_{\text{cmd}} = 600^\circ/\text{s}^2 \approx 10.47\,\text{rad/s}^2$
- Disturbance accel: $\alpha_d = 800^\circ/\text{s}^2 \approx 13.96\,\text{rad/s}^2$
- Wind: $A = 0.05\,\text{m}^2$, $V = 12\,\text{m/s}$, $r = 0.1\,\text{m}$, $C_d = 1.1$

$$\begin{aligned}
T_{\text{inertia}} &= J(\alpha_{\text{cmd}} + \alpha_d) = 0.023 \times (10.47 + 13.96) \approx 0.57\,\text{N·m} \\
T_{\text{wind}} &\approx 0.5 \times 1.2 \times 1.1 \times 0.05 \times 12^2 \times 0.10 \approx 0.48\,\text{N·m} \\
T_{\text{total, peak}} &\approx 0.57 + 0.48 + 0.1 \approx 1.15\,\text{N·m}
\end{aligned}$$

In kg·cm: $1.15\,\text{N·m} \times 10.197 \approx 11.7\,\text{kg·cm}$

Add 2× margin ⇒ **23–30 kg · cm** peak.

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Example 2: Rougher Outdoor Case (Landing in 30–60 kg·cm)

- Payload mass: $m = 6\,\text{kg}$
- Approx. box: $0.26 \times 0.22 \times 0.16\,\text{m}$
- Inertia: $J \approx 0.050\,\text{kg·m}^2$
- Commanded accel: $\alpha_{\text{cmd}} = 800^\circ/\text{s}^2 \approx 14.0\,\text{rad/s}^2$
- Disturbance accel: $\alpha_d = 1200^\circ/\text{s}^2 \approx 21.0\,\text{rad/s}^2$
- Wind: $A = 0.08\,\text{m}^2$, $V = 15\,\text{m/s}$, $r = 0.12\,\text{m}$

$$\begin{aligned}
T_{\text{inertia}} &\approx 0.050 \times (14.0 + 21.0) = 1.75\,\text{N·m} \\
T_{\text{wind}} &\approx 0.5 \times 1.2 \times 1.1 \times 0.08 \times 15^2 \times 0.12 \approx 1.43\,\text{N·m} \\
T_{\text{total, peak}} &\approx 1.75 + 1.43 + 0.2 \approx 3.38\,\text{N·m}
\end{aligned}$$

In kg·cm: $3.38 \times 10.197 \approx 34.4\,\text{kg·cm}$

With 1.5–2× margin for gusts and shocks:

$$\boxed{\text{Peak torque range } \approx 52\text{–}70\,\text{kg·cm}}$$

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3. Key Takeaways for BLDC Motor Selection

- **Continuous torque** is much lower (10–20 kg·cm for 3–6 kg payloads).
- **Peak torque** of 30–60 kg·cm is realistic for off-road or windy outdoor conditions with safety margin.
- Use **direct-drive frameless BLDC** for micro-jitter; 2–3:1 timing belt if space or cost constrained.
- Place encoder on **load side** if belts are used to avoid compliance/backlash in the loop.

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4. Quick Design Checklist

1. Compute J_r, J_p, J_y from CAD for payload + gimbal plate.
2. Decide α_{cmd} (slew profile) and estimate α_d from base IMU logs.
3. Estimate A, r, and wind speed V for outdoor/off-road use.
4. Compute peak torque using Eq. (1) and convert to kg·cm.
5. Apply 1.5–2× margin for shocks and uncertainty.
6. Select BLDC motors such that
   - $T_{\text{continuous}} \geq T_{\text{rms}}$
   - $T_{\text{peak}} \geq$ calculated peak torque