Planetary Gearbox Design for Battlebot

Task 2

Introduction

The goal is to develop a mechanically robust and efficient configuration that performs reliably under combat conditions and maintains functionality even after partial damage. I have designed this doc structurally for better understanding of the task.

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3. Material Selection for Gearbox Components
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Things to Focus On

The design approach revolves around the following core requirements:

- **Efficiency**: Optimize for minimal energy loss and smooth power transmission.
- **Post-Damage Functionality**: Ensure the gearbox continues functioning even after partial failure (e.g., loss of a planet gear).
- **Durability**: Withstand high mechanical shocks, torque spikes, and continuous operation under combat conditions.

Parameters That Can Be Changed

To meet the design objectives, the following parameters are configurable:

- Number of gear teeth in each component (sun, planet, ring)
- change the config/component without affecting the weight
- Materials used for gears, bearings, and carrier

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0 Gear System Design

Gear Ratio and Parametric Design (Based on Things to Focus)

Let:

- $N_s = n$: Sun gear teeth
- $N_r = r$: Ring gear teeth
- $N_p = p$: Planet gear teeth

Gear Ratio Equation

$$G = 1 + \frac{N_r}{N_s}$$

Targeting $G = 20$:

$$20 = 1 + \frac{N_r}{N_s} \Rightarrow \frac{N_r}{N_s} = 19 \Rightarrow N_r = 19n$$

Meshing Condition

$$N_r = N_s + 2N_p \Rightarrow 19n = n + 2p \Rightarrow p = 9n$$

Final Configuration

- Sun Gear: $N_s = n$
- Planet Gear: $N_p = 9n$
- Ring Gear: $N_r = 19n$

Since we arent specified the radii or modular Dimension ig we should critically consider this mathmatical relation to ensure the design is mathematically sound and physically constructible according to requirements. still let me assume n for best performance according to our design approach (Things to focus on mentioned above)

Selection of Sun Gear Teeth (N_s)

To meet the core design goals—**efficiency**, **post-damage functionality**, and **durability**—the number of sun gear teeth must be selected carefully to maintain a balance between mechanical performance and physical constructibility.

Target Gear Ratio: We are designing for a reduction ratio of approximately $G = 20 : 1$, using the standard planetary gear formula (ring fixed, carrier output):

$$G = 1 + \frac{N_r}{N_s} \Rightarrow N_r = 19N_s$$

Meshing Condition: To ensure correct gear engagement:

$$N_p = \frac{N_r - N_s}{2} = 9N_s$$

Selected Configuration:

- Sun Gear Teeth: $N_s = 10$
- Planet Gear Teeth: $N_p = 90$
- Ring Gear Teeth: $N_r = 190$

Justification:

- All gears have integer tooth counts that satisfy the meshing and symmetry conditions.
- Supports 3-planet configurations for enhanced torque distribution and redundancy.
- Maintains a moderate gear size, allowing the teeth to withstand high contact loads without becoming too fragile.
- Enables a compact design without compromising efficiency, making it suitable for high-impact battlebot environments.

Conclusion: Choosing $N_s = 10$ ensures that the gearbox meets the desired 20:1 reduction ratio while satisfying all mechanical constraints for durability, load-sharing, and continued operation in the event of planet gear failure.

Estimated Gearbox efficiency: 85% to 90% [due to mesh and dissipative actions]

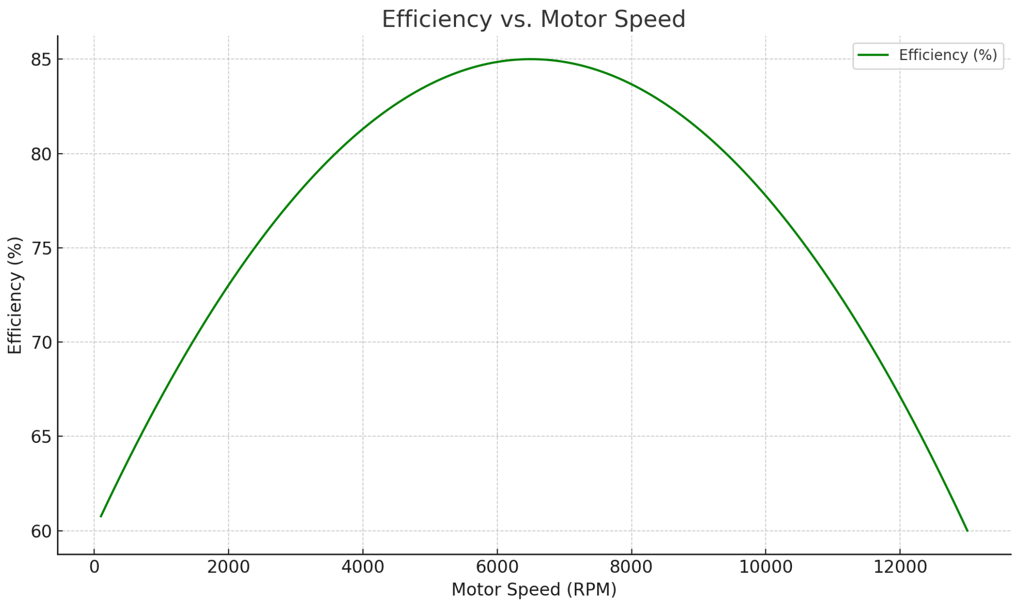

Figure 1: Efficiency vs. Motor Speed. The efficiency peaks at moderate RPMs and slightly drops at low and high speeds due to mechanical losses and dynamic inefficiencies. This graph helps in identifying the gearbox's most efficient operating zone.

Post-Damage Functionality

- Use 4 planet gears for load redundancy
- Floating carrier design to allow redistribution

Durability Design

- Double support for carrier to avoid deflection
- Root fillets and 20–25° pressure angle for strength

Comparison: 3-Planet vs. 4-Planet Configurations

Feature	**3-Planet Configuration**	**4-Planet Configuration**
Load sharing	Medium	High
Efficiency	Slightly better	Slightly reduced
Redundancy	Poor	Good
Weight	Lower	Higher
Design complexity	Simpler	More complex (tighter spacing)
Manufacturing cost	Lower	Slightly higher
Recommended for	Compact, low-medium torque	High torque, impact-heavy use

Planetary Configuration Choice

After careful evaluation of the trade-offs between 3-planet and 4-planet gear configurations, the final decision is to proceed with a **3-planet system**.

While a 4-planet system offers better load distribution and improved redundancy in case of gear failure, it introduces several drawbacks:

- Increased system weight, which negatively impacts the battlebot's agility and speed.
- Higher design and manufacturing complexity due to tighter spacing constraints between planets.
- Slightly reduced mechanical efficiency due to more internal contact surfaces.

Given that weight is a critical factor in combat robotics, where rapid maneuvering and speed are essential, the advantages of a lighter and simpler **3-planet system** outweigh the additional robustness offered by a 4-planet system.

Now we have a foundational framework to work on; we'll proceed to the next section.

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0 Gear System Design

Gear Ratio and Parametric Design

Let

Task2

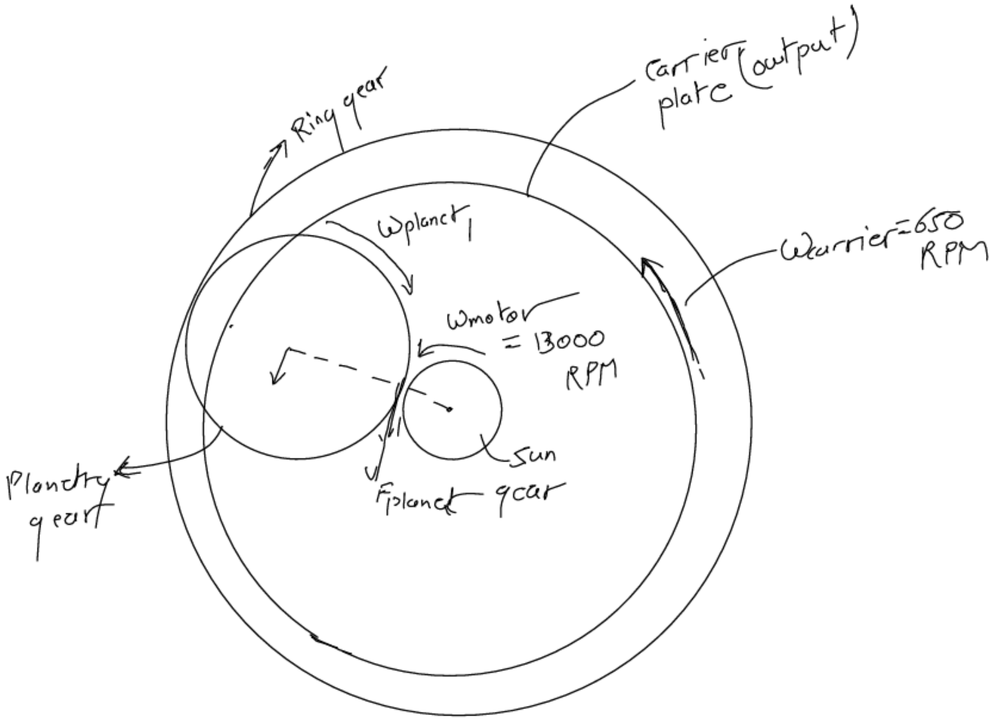

Figure 2: Basic layout of system

- $N_s = n$ – Sun–gear teeth
- $N_r = r$ – Ring–gear teeth
- $N_p = p$ – Planet–gear teeth

Gear Ratio

With the ring gear held fixed and the carrier taken as the output, the classical reduction is

$$G = 1 + \frac{N_r}{N_s}.$$

Targeting $G \approx 20$ gives

$$N_r = 19\,N_s.$$

Meshing Condition

Proper meshing requires

$$N_r = N_s + 2N_p \quad \Rightarrow \quad N_p = 9\,N_s.$$

Baseline Tooth Counts

A mathematically valid set is

- Sun gear $N_s = 10$
- Planet gear $N_p = 90$
- Ring gear $N_r = 190$

Note: with a standard module, a 10–tooth sun is small and prone to undercut. If manufacturing constraints allow, increasing N_s to ≥ 18 teeth will improve strength without altering the 20:1 ratio (change N_r and N_p proportionally).

Estimated Gearbox Efficiency 85 %–90 % (mesh and bearing losses).

Post–Damage and Durability Features

- Four planets offer the best redundancy, but the added mass motivates a three–planet layout for this combat robot.
- Use a floating carrier and generous root fillets (20–25 pressure angle) to minimise stress concentrations.

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1 Torque Analysis

System Parameters

- Motor (input) torque: $T_{\text{motor}} = 0.5\,\text{N m}$
- Motor speed: $\omega_{\text{motor}} = 13\,000\,\text{rpm}$
- Reduction ratio: $G = 20 : 1$
- Efficiency: $\eta = 0.85$
- Sun–gear pitch radius: $r_s = 10\,\text{mm} = 0.01\,\text{m}$
- Carrier pitch radius (for force check): $r_c = 15\,\text{mm} = 0.015\,\text{m}$

Output Torque and Speed (Carrier)

$$T_{\text{out,ideal}} = G\,T_{\text{motor}} = 20 \times 0.5 = 10\,\text{N m},$$
$$T_{\text{out,actual}} = \eta\,T_{\text{out,ideal}} = 0.85 \times 10 = 8.5\,\text{N m},$$
$$\omega_{\text{out}} = \frac{\omega_{\text{motor}}}{G} = \frac{13\,000}{20} = 650\,\text{rpm}.$$

Tangential Force on Sun Gear (Nominal)

The tooth load is set by the *input* torque, not the reduced output torque:

$$F_t = \frac{T_{\text{motor}}}{r_s} = \frac{0.5}{0.01} = 50\,\text{N}.$$

Force Distribution on Planet Gears

For a three–planet system,

$$F_{\text{planet}} = \frac{F_t}{3} \approx 16.7\,\text{N per planet.}$$

Design Safety Factor

A safety factor of 2 is applied to the *output* torque (worst–case shock at the wheels):

$$T_{\text{design,out}} = 2\,T_{\text{out,actual}} = 17\,\text{N}\,\text{m}.$$

The corresponding *input* (sun) design torque is $2\,T_{\text{motor}} = 1\,\text{N}\,\text{m}$.

Peak Mesh Forces (Combat Impact)

$$\begin{aligned}
F_{t,\text{peak}} &= \frac{1}{0.01} = 100\,\text{N}, \\
F_{\text{planet,peak}} &= \frac{F_{t,\text{peak}}}{3} \approx 33.3\,\text{N}, \\
F_{\text{ring,peak}} &= F_{t,\text{peak}} = 100\,\text{N}, \\
F_{\text{carrier}} &= \frac{T_{\text{design,out}}}{r_c} = \frac{17}{0.015} \approx 1.13 \times 10^3\,\text{N}.
\end{aligned}$$

Summary

- Output torque (with losses): $8.5\,\text{N}\,\text{m}$
- Output speed: $650\,\text{rpm}$
- Sun–gear tangential force: $50\,\text{N}$
- Force per planet (nominal): $\approx 16.7\,\text{N}$
- Peak sun–gear tangential force: $100\,\text{N}$
- Peak force per planet: $\approx 33.3\,\text{N}$
- Ring radial load (peak): $100\,\text{N}$
- Carrier output force (@15 mm): $1.13\,\text{kN}$

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2 Material Selection for Gearbox Components

The materials chosen prioritize a balance between mechanical strength, impact resistance, machinability, and weight control.

1. Sun Gear

- **Material**: 4340 Alloy Steel (Quenched and Tempered)
- **Properties**:
  - High tensile strength: $> 1000\,\mathrm{MPa}$
  - Excellent toughness under impact
  - Good wear resistance and heat treatable to HRC 45–50
- **Justification**: As the primary torque input gear, the sun gear must resist high tangential force and dynamic impact loading from the motor shaft.

2. Planet Gears

- **Material**: 8620 Case-Hardened Steel
- **Properties**:
  - Core ductility with surface hardness up to HRC 60
  - Good fatigue and pitting resistance
  - Well-suited for carburizing or nitriding
- **Justification**: Planet gears are under constant cyclic loading and must survive high contact pressure from both sun and ring gear teeth.

3. Ring Gear

- **Material**: 4140 Steel (Heat Treated)
- **Properties**:
  - Strong core with moderate machinability
  - Good impact resistance and internal tooth wear resistance
- **Justification**: The ring gear serves as the fixed reaction surface; it must absorb radial force without deforming or wearing unevenly under combat stress.

4. Planet Gear Pins and Shafts

- **Material**: 52100 Bearing Steel (Hardened)
- **Properties**:
  - Very high surface hardness and wear resistance
  - Withstands shear force and rotational fatigue
- **Justification**: Planet pins experience bending and shear loads; hardened bearing steel minimizes wear and extends life under extreme force.

5. Carrier Plate

- **Material**: 7075-T6 Aluminum Alloy
- **Properties**:
  - High strength-to-weight ratio
  - Tensile strength: $\sim 500\,\mathrm{MPa}$
  - Excellent fatigue resistance
- **Justification**: The carrier must remain lightweight to maintain agility, yet strong enough to hold all planet pins under torque. 7075-T6 provides structural integrity without excessive mass.

Material Selection Summary

- Gears use high-strength, impact-resistant steels with hardened surfaces.
- Pins and shafts are made from wear-resistant bearing steel.
- The carrier is a lightweight but high-strength aluminum alloy.

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3 Damaged Planetary Case Performance

Performance of gearbox under such a failure and what design strategies can counter its consequences.

Scenario: One Planet Gear Fails

In a 3-planet configuration:

- Torque is normally distributed equally: $\sim 33\%$ per planet.
- If one planet fails, the load redistributes to the remaining two.
- This doubles the torque per remaining gear: from $\sim 283\,\mathrm{N}$ to $\sim 566\,\mathrm{N}$ each (from prior analysis).

Consequences of a Failed Planet Gear

- **Load imbalance:** Uneven force vectors introduce vibrations and wobble in the carrier.
- **Increased stress:** The two remaining planet gears and pins experience double the force, which may exceed their yield or fatigue limits.

- **Tooth misalignment:** Non-uniform spacing may cause backlash, increased wear, or even binding.
- **Gear carrier deformation:** Carrier experiences eccentric torque loading, possibly leading to flexing or bearing misalignment.

Mitigation and Design Strategies

To enhance post-damage survivability:

- **Dual-Supported Carrier Pins:** Supporting bothends of the planet pins increases torsional stability and prevents pin bending after impact.
- **Use floating carrier design:** Allows planets to adapt to small misalignments post-failure.
- **Pre-stress or preload bearings:** Reduces backlash and dampens vibration under asymmetrical loading.
- **Low-Friction Coatings or Lubricants:** PTFE or MoS2-based lubricants reduce drag and wear without increasing system mass.
