Design of a 106:1 Hybrid Planetary-Cycloidal Actuator for General Purpose High-Torque Applications

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***Abstract*—High-torque rotary actuators are fundamental components in industrial automation, robotic manipulators, and heavy-duty positioning systems. While conventional multi-stage planetary gearboxes provide necessary reduction, they often suffer from excessive length and backlash. This paper presents the analytical design of a compact hybrid actuator that integrates a planetary pre-stage with a cycloidal output stage. The system delivers a total reduction ratio of 105.88:1 in a unified module. The design leverages the high-speed efficiency of planetary gears and the shock-load capacity of cycloidal discs. This study details the geometric parametrization of the cycloidal profile and analyzes the inherent mechanical benefits of the hybrid architecture, including compactness and stiffness. Furthermore, the adaptability of the mechanism is evaluated across various prime movers, including Stepper motors, BLDC motors with encoders, and standard DC drives, demonstrating its versatility for diverse high-torque applications.**

I. Introduction

In the domain of electromechanical actuation, achieving high torque density within a limited volume is a persistent engineering challenge. Applications ranging from prosthetic limbs and collaborative robot (cobot) joints to industrial rotary tables require actuators that are not only powerful but also rigid and compact.

Traditional solutions typically rely on Harmonic Drives or multi-stage planetary systems. Harmonic drives, while compact and zero-backlash, are cost-prohibitive and fragile under shock loads. Conversely, stacking multiple planetary stages increases the axial length of the motor, creating lever-arm issues in joint designs.

This paper proposes a hybrid architecture: a "Two-Stage" concentric reducer. Stage 1 utilizes a planetary gear set (4.235:1) to reduce input speed, while Stage 2 employs a cycloidal mechanism (25:1) for massive torque multiplication. This configuration allows for a theoretical reduction of 105.88:1(≈106:1) while maintaining a "pancake" form factor suitable for embedded applications.

II. Theoretical Design and Calculation

The actuator is designed as a modular unit where the output of the planetary carrier serves as the input eccentric shaft for the cycloidal stage.

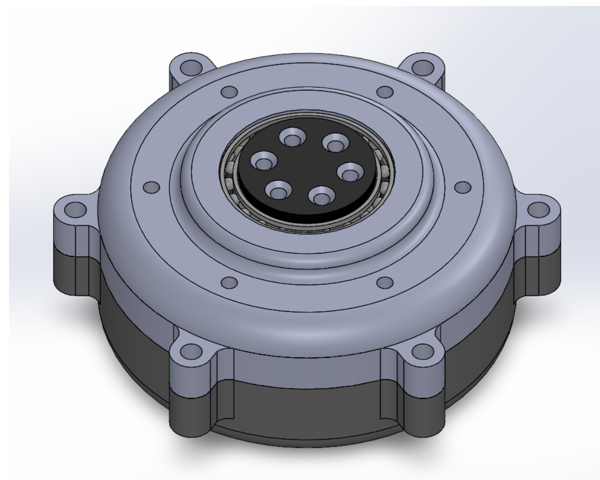

Fig. 1. Isometric view of the hybrid planetary-cycloidal actuator.

A. Stage 1: Planetary Gearbox

The first stage reduces the high-speed input from the motor. It follows a standard Type-I planetary configuration (Sun Input, Ring Fixed, Carrier Output).

- Sun Gear (N_s): 17 Teeth
- Planet Gears (N_p): 19 Teeth
- Ring Gear (N_r): 55 Teeth

The reduction ratio (R_p) is:

$$R_p = 1 + \frac{N_r}{N_s} = 1 + \frac{55}{17} \approx 4.235 \tag{1}$$

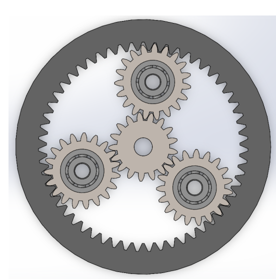

Fig. 2. Isometric view of the hybrid planetary-cycloidal actuator.

B. Stage 2: Cycloidal Drive

The second stage utilizes a single-disc cycloidal profile. To ensure smooth motion and reduce stress concentrations, the profile is generated as a shortened epitrochoid. The ”Shortening Parameter” (S), which defines the curvature of the lobes, is calculated as:

$$S = \frac{E \times Z_{pins}}{R_{pins}} \tag{2}$$

Where Z_{pins} is the number of housing pins (26) and R_{pins} is the radius of the pin circle (22.0 mm). Substituting the design values:

$$S = \frac{0.5 \times 26}{22.0} \approx 0.591 \tag{3}$$

A shortening parameter of $S = 0.591$ was selected to provide a smooth lobe profile , optimizing the mechanism for the manufacturing tolerances of additive manufacturing while minimizing the pressure angle.

The reduction ratio of this stage (R_c) is:

$$R_c = \frac{L}{P - L} = \frac{25}{26 - 25} = 25 \tag{4}$$

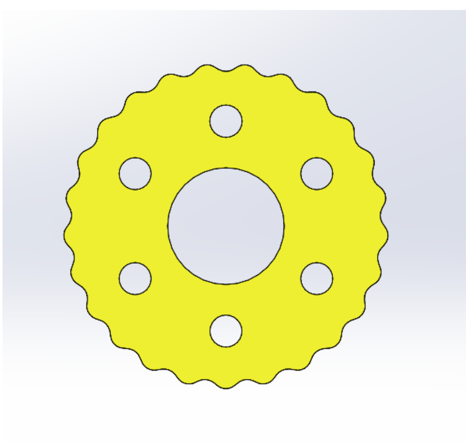

Fig. 3. Isometric view of the hybrid planetary-cycloidal actuator.

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C. Total Reduction

The total system ratio (R_{total}) is the product of both stages:

$$R_{total} = R_p \times R_c = 105.88 \tag{5}$$

III. Kinematic Inversions and Versatility

One of the distinct advantages of the proposed hybrid module is its kinematic versatility. By fixing different components of the assembly, the actuator can function in multiple modes suitable for different robotic joints. Table I details the Input-Output relationships derived from the design topology. The theoretical ratios differ slightly between inversions. For example, in Mode 4 (Wheel Hub), the housing acts as the

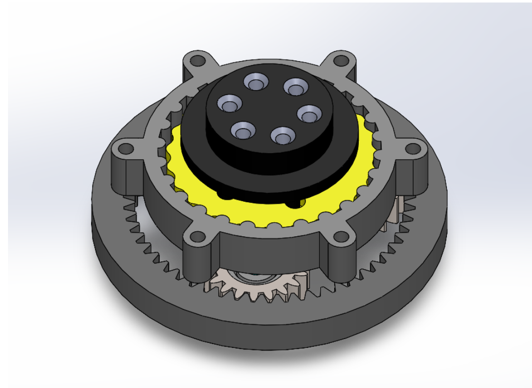

Fig. 4. Isometric view of the hybrid planetary-cycloidal actuator.

rotor, which is ideal for the rover applications, allowing the tire to be mounted directly to the spinning exterior of the actuator.

TABLE I
Kinematic Inversions of the Actuator

Mode	Fixed Component	Output	Application
1	Ring Gear	Carrier	**Standard Reducer** (Used in this paper). High torque, stable mounting.
2	Carrier	Ring Gear	**Differential Drive**. Used when the ”Output” needs to be reversed relative to input.
3	Housing (Stator)	Output Shaft	**Joint Actuator**. The standard robotic arm joint configuration.
4	Output Shaft	Housing	**Wheel Hub**. The shaft is bolted to the chassis, and the housing (wheel) spins around it.

IV. Design Specifications Summary

To facilitate reproducibility and future optimization, all geometric and kinematic parameters of the proposed hybrid actuator are consolidated in Table II.

V. Inherent Design Advantages

The hybrid Planetary-Cycloidal configuration offers distinct mechanical advantages over single-type gearboxes.

A. Shock Load Resistance

Unlike planetary gears where load is concentrated on 1-2 gear teeth, the cycloidal stage distributes the load across approximately 30% of the housing pins simultaneously. This provides exceptional resistance to shear failure during sudden impact or emergency stops, making the actuator ideal for dynamic environments.

TABLE II
COMPLETE DESIGN PARAMETERS OF THE HYBRID ACTUATOR

Stage	Parameter	Symbol	Value
Stage 1: Planetary Gearbox			
	Sun Gear Teeth	N_s	17
	Planet Gear Teeth	N_p	19
	Ring Gear Teeth	N_r	55
	Module	m	1
	Stage Ratio	R_p	4.235:1
Stage 2: Cycloidal Drive			
	Pin Circle Radius	R	22.0 mm
	Housing Pin Diameter	d_p	3.0 mm
	Eccentricity	E	0.5 mm
	Shortening Ratio	S	0.591
	Disc Lobes	L	25
	Housing Pins	P	26
	Stage Ratio	R_c	25:1
System Outputs			
	Total Reduction Ratio	R_{total}	105.88:1
	Manufacturing Clearance	c	0.15 mm
	Nominal Output Speed	ω_{out}	$\approx$ 28 RPM

B. Zero-Backlash Potential

While planetary gears inherently possess backlash due to gear meshing tolerance, the cycloidal stage acts as a ”low-pass filter” for this error. Since the planetary stage is on the high-speed input side, its backlash is divided by the ratio of the cycloidal stage (25:1) when viewed from the output. This results in high positioning accuracy at the final output shaft.

C. Axial Compactness

To achieve a 100:1 ratio using only planetary gears, two or three stacked stages would be required, significantly lengthening the actuator. The hybrid design achieves this in a short axial length, reducing the center of gravity distance when mounted on robotic arms.

VI. ACTUATION MODALITIES

The proposed gearbox is designed to be motor-agnostic. The performance characteristics shift depending on the prime mover selected:

A. Stepper Motor Integration

When coupled with a Stepper Motor (e.g., NEMA 17/23), the 105:1 ratio amplifies the motor's inherent ”holding torque.” This configuration is ideal for pick-and-place machines or camera gimbals where position holding without active feedback is required. The gearbox allows micro-stepping precision to be mechanically multiplied, achieving theoretical resolutions exceeding 0.001 degrees.

B. BLDC with High-Resolution Encoder

For dynamic robotics (e.g., Quadruped legs or Exoskeletons), a Brushless DC (BLDC) motor provides high-speed input. The hybrid gearbox reduces the typically high BLDC base speed (3000+ RPM) to a usable torque range (approx. 30 RPM). The high reduction ratio also minimizes the ”cogging” effect often felt in low-speed direct-drive BLDC motors, resulting in smoother motion profiles.

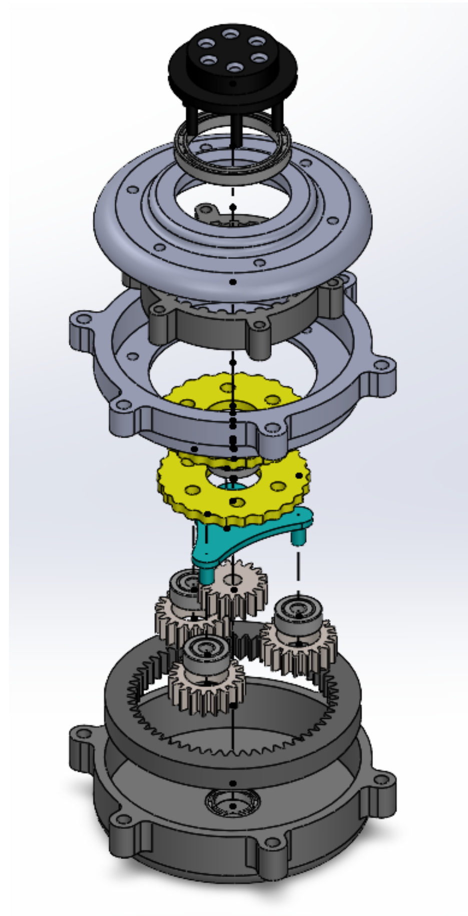

Fig. 5. Isometric view of the hybrid planetary-cycloidal actuator.

C. DC Motor (Brushed)

In simple automation tasks, a standard DC motor can be used. The high internal friction of the hybrid gearbox provides a ”quasi-self-locking” effect. While not mathematically self-locking, the back-driving torque required is significantly higher than the forward-driving torque, providing safety against gravity loads in lifting applications when power is lost.

VII. DESIGN TRADE-OFFS AND LIMITATIONS

While the hybrid architecture offers significant benefits in torque density and packaging, inherent limitations exist compared to other gear solutions.

A. System Efficiency and Heat Dissipation

The primary trade-off of the cycloidal mechanism is efficiency. Unlike involute gears which rely primarily on rolling contact, cycloidal drives involve significant sliding friction between the lobes and housing pins. While a single-stage planetary gearbox typically achieves 95-98% efficiency, a cycloidal stage operates in the range of 80-85%. Consequently, the total theoretical system efficiency is lower than a pure multi-stage planetary system. This necessitates careful thermal management at the output stage during continuous high-load operation.

B. Back-drivability

The high reduction ratio of 105:1 results in a non-backdrivable system. While advantageous for position holding (holding a robotic arm against gravity without power), it effectively removes the ”compliance” or transparency required for force-feedback applications. The actuator cannot be easily rotated by external forces, which may risk internal component damage if the output shaft is subjected to shock loads exceeding the yield strength of the housing pins.

C. Comparison with Multi-Stage Cycloidal Architectures

A common alternative to the proposed hybrid design is stacking two cycloidal stages in series to achieve similar reduction ratios (e.g., $10 : 1 \times 10 : 1$). However, the Hybrid Planetary-Cycloidal approach was selected over the Multi-Stage Cycloidal approach for three critical reasons:

1) **Input Speed and Vibration:** Cycloidal drives rely on an eccentric mass rotating at the input speed. If a cycloidal stage were used as the pre-stage (connected directly to a 3000 RPM motor), the eccentric forces would generate significant vibration and noise. Planetary gears, being rotationally symmetric, are inherently balanced and superior for handling high-speed motor inputs.
2) **Thermal Efficiency:** The sliding friction of a cycloidal drive generates heat proportional to speed. Placing a cycloidal stage at the high-speed input would result in rapid thermal buildup. By using a planetary stage for the high-speed reduction, the cycloidal stage is reserved for the low-speed, high-torque output where its efficiency penalty is minimized.
3) **Manufacturing Complexity:** A multi-stage cycloidal drive requires a complex ”floating” intermediate carrier to couple the eccentric motion of the first stage to the input of the second. The hybrid design simplifies this by using a standard planetary carrier, which provides a rigid, concentric output shaft to drive the final cycloidal stage.

VIII. Future Scope

Future work will focus on the empirical validation of the analytical models presented in this study. Key areas for development include:

- **Thermal Characterization:** Experimental testing to quantify heat generation at the cycloidal interface under continuous load cycles.
- **Profile Optimization:** Implementing genetic algorithms to optimize the cycloidal lobe shortening parameter (S) to minimize sliding friction.
- **Dynamic Control:** Developing a closed-loop control scheme that utilizes the planetary input stage’s low inertia for high-bandwidth torque control.

IX. Conclusion

The design of a 105.88:1 hybrid actuator successfully addresses the trade-off between torque density and geometric volume. By integrating a planetary pre-stage with a robust cycloidal output, the system offers a versatile solution for general-purpose high-torque applications. Theoretical analysis confirms the geometric compatibility of the stages, and the modular design allows for integration with various motor technologies to suit specific control requirements.