TECHNICAL OVERVIEW: Low-Cost, Water-Cooled QDD Actuator

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Focus: Low-Cost, High-Torque Density Robotics & Thermal Management

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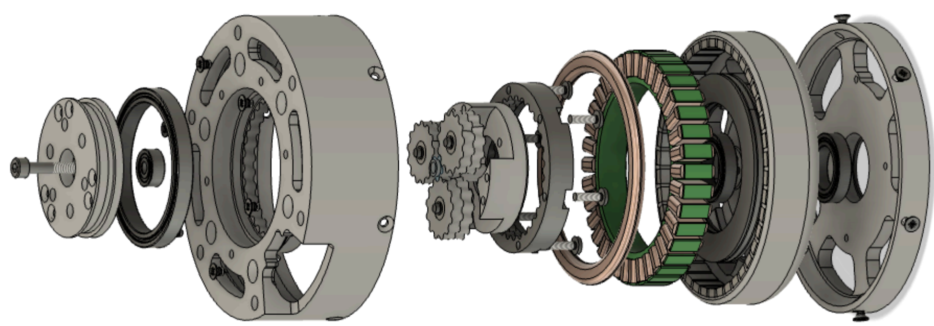
1. Executive Summary

This project addresses the "thermal ceiling" of 3D-printed robotic actuators. While plastic actuators are incredibly cost-effective, their low thermal conductivity typically limits continuous torque. By integrating a custom water-cooling loop directly against the stator windings, this design achieved a 309% increase in continuous torque, reaching **8.6 Nm**—performance comparable to commercial metal units ($200+) at a material cost of **$37.30**.



2. Key Specifications & Performance

Material Cost (USD)	$37.30
Peak torque (Nm)	16 Nm
Peak current (A)	≥ 46.5 A
Continuous torque water-cooled (Nm)	8.6 Nm
Continuous current water-cooled (A)	6.5 A
Continuous torque no cooling (Nm)	2.1 Nm
Continuous current no cooling (A)	0.85 A
Gear Reduction	7.2
Weight (g)	588 g

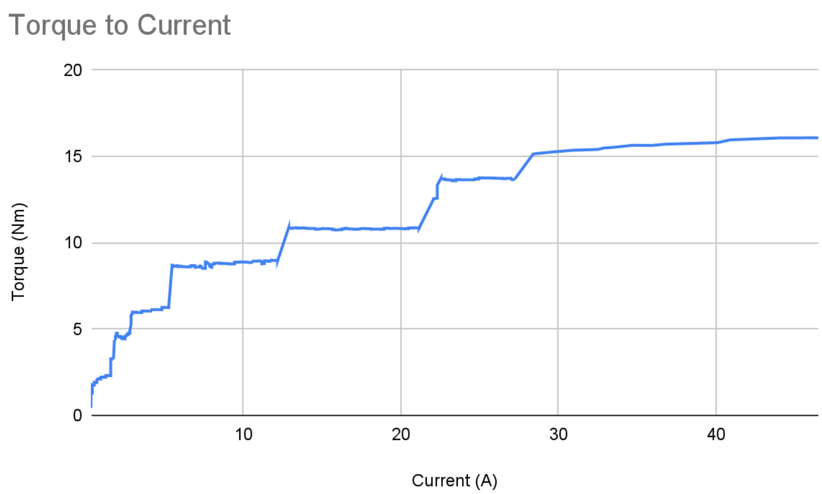


Figure 1. A torque step of the water-cooled actuator with increasing torque commands.

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3. Engineering Rigor & Methodology

A. Mechanical Design

To overcome the failure points of 3D-printed spur gears, I implemented a **7.2:1 Cycloidal Planetary Gearbox** with a herringbone profile, minimizing backlash while greatly increasing durability.

I calculated bearing moment loads using statics diagrams and dynamic load ratings, identifying failure points and iterating to achieve a final load capacity of **~25 Nm**.

B. Electromagnetic Customization

- **Stator:** 8110 36-slot stator, hand-wound with six parallel strands of AWG27 (6 turns/slot).
- **Rotor:** 3D-printed Polycarbonate backing with 42 N52 Neodymium magnets.
- **Simulation:** Used Simscale Electromagnetic Analysis to quantify the 13% flux loss from omitting a metal back-iron, justifying the trade-off for weight and cost.

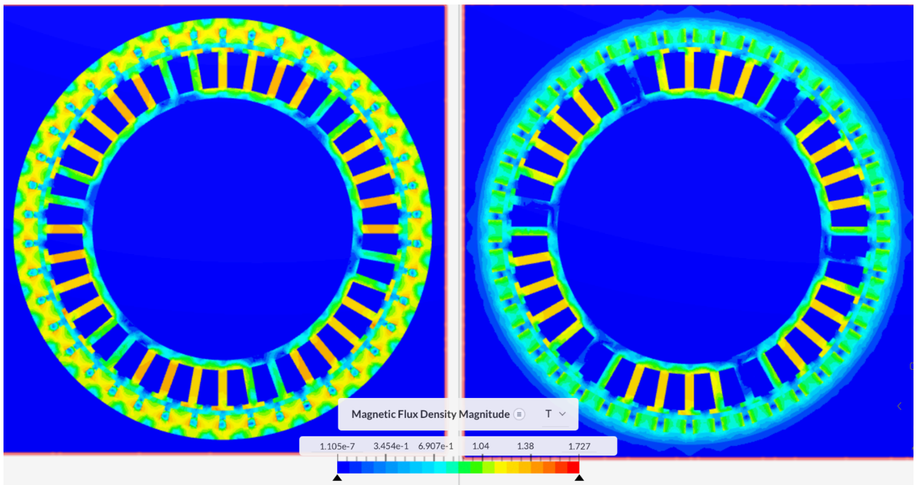

Figure 2. An electromagnetic analysis of the actuator with (left side) and without (right side) a back iron.

C. Thermal Management (The Main Innovation)

The water-cooling channel consists of flattened 1/4" copper tubing clamped directly to the windings.

- **Simulation:** Tested various channel geometries and setups using Fusion 360 Thermal Analysis at different currents, optimizing to the final design.
- **Physical Implementation:** Used thermal paste to bridge the air gaps in hand-wound coils, achieving thermal equilibrium at **6.5A continuous current** (665% increase) while maintaining winding temperatures below **70°C**.

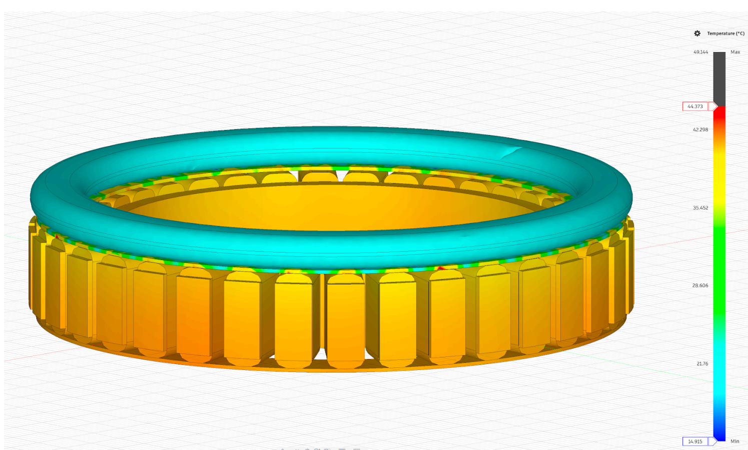

Figure 3. A Thermal analysis of the actuator with water cooling at 9A, disregarding air gaps and enamel between motor wires.

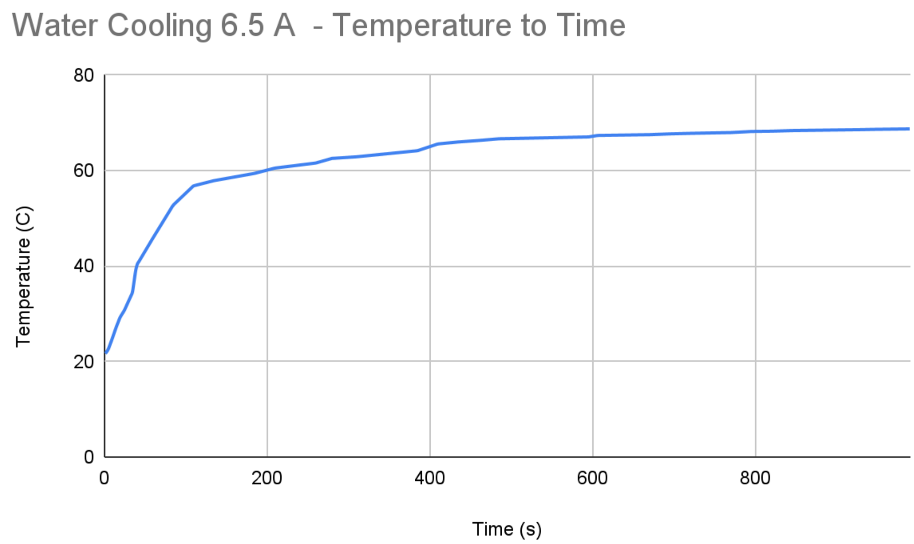

Figure 4. The maximum coil temperatures of the actuator with water cooling at 6.5A; thermal equilibrium reached at ~70°C.

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4. Experimental Validation

- **Setup:** Custom test rig utilizing a 20kg load cell, HX711 amplifier, and a 300mm lever arm.
- **Control:** Field Oriented Control (FOC) via MKS XDrive.
- **Future Research Directions:** The torque-current relationship showed early magnetic saturation at 10A alongside unusual torque jumps, providing clear goals for Version 2.