

**Mechanical Design of a Scaled Electrical Differential
Excavator Tilt Rotator for Training and Teleoperation
Research**

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Abstract— This paper presents the mechanical design and integration of a 1/12-scale tiltrotator with grapple attachment for a miniature excavator training and teleoperation platform. To avoid the cost and complexity of scaled hydraulic systems, a differential gearbox driven by stepper motors through non-backdrivable worm gears was developed. The assembly was constrained to a maximum height of 85.7 mm, a maximum platform envelope of 135 mm $\times$ 135 mm, and a mass of 2 kg. The final assembly achieved $\pm 50^\circ$ of tilt and continuous 360° rotation at 7.5 rpm. Performance testing demonstrated a peak output torque of 226.0 N-cm, exceeding the 200 N-cm design requirement, with a measured mechanical efficiency of 53.3%. These results show that an electrical differential tiltrotator can provide sufficient torque and range of motion to support scaled excavator training and future research in excavator teleoperation.

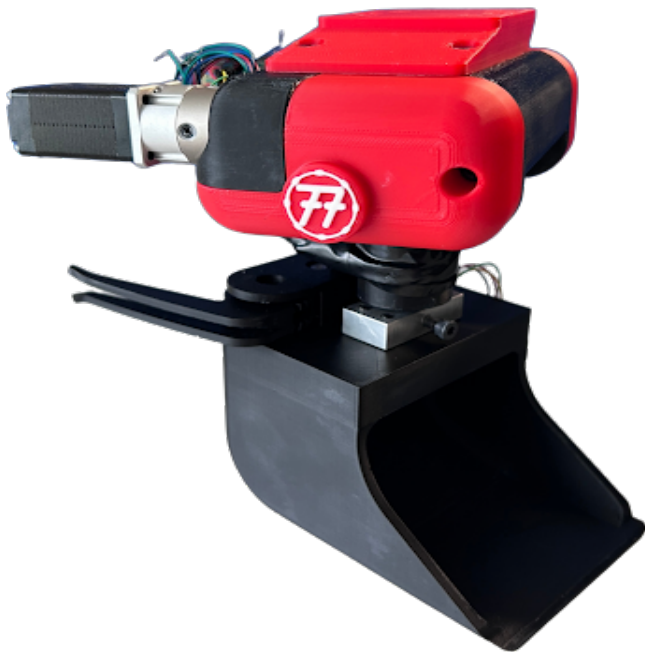


Figure 1: The final tiltrotator assembly

I. INTRODUCTION

Heavy machinery training is often laborious, expensive, and difficult to scale safely. Currently, excavator training is mostly conducted on full-size equipment, which demands significant resource allocation and limits. With 54% of con-

struction firms reporting project delays due to worker shortages [1], the industry faces a decline in skilled excavator operators as the current workforce ages out. Furthermore, specialized attachments like tiltrotators—which add continuous 360° rotation and lateral tilt to the bucket—are becoming standard in cramped urban environments and high-precision jobs [2]. This increased flexibility allows operators to perform more precise tasks and work from multiple angles without repositioning the excavator, improving both efficiency and productivity. However, the cost and liability of training inexperienced operators on full-scale tiltrotator-equipped excavators remain prohibitively high.

To address these challenges, 1/12 scale excavator simulators offer a low-liability environment for operator training. While full-scale commercial tiltrotators rely entirely on hydraulic actuation, reproducing this hydraulic architecture at a 1/12 scale introduces prohibitive costs and complexities [3].

This paper investigates the feasibility of replacing scaled-down hydraulics with a compact, electrical differential gearbox. The objective is to design, manufacture, and test a 1/12 scale tiltrotator with an integrated grapple that meets the physical packaging, torque, and non-backdrivability requirements of a miniature training excavator. For more details on the electrical and controls systems design see our companion paper [4].

The main contributions of this paper are:

1. The design of a compact differential gearbox using non-backdrivable worm gears to achieve dual-axis bucket actuation without hydraulic components.
2. The mechanical integration of a grapple mechanism using a slip-ring for full capabilities while maintaining 360° continuous rotation.
3. Experimental validation of the system's torque, efficiency, and holding capabilities during simulated gravel-digging tasks.

The rest of the paper is organized as follows. Section II defines the technical problem statement and design constraints. Section III details the mechanical design alternatives and selected methodology. Section IV presents the experimental setup, torque test results, and system evaluation. Section V concludes the paper.

II. PROBLEM STATEMENT

The objective is to design a miniature tiltrotator attachment that interfaces with an existing 1/12 scale training excavator while having the strength to dig through and move gravel, as well as pick up and place objects using the grapple attachment. The system must operate within strict spatial and weight constraints defined by the host excavator's linkage geometry [5].

Height is defined as the distance between the end of the excavator arm and the closest face of the bucket. The platform envelope defines the maximum footprint parallel to the height of the tiltrotator. In addition to spatial constraints, the mechanism must have sufficient strength to maintain position under load without a constant current applied to the motors, which necessitates a non-backdrivable system containing worm gears with a low lead angle. A baseline output torque requirement of 200 N-cm was calculated with a free-body diagram, assuming an estimated 4.5 kg load at the tip of the bucket.

III. METHODOLOGY

A. Design Alternatives

Two primary architectures were evaluated for the tiltrotator mechanism:

- **Scaled Hydraulic Architecture:** A traditional two-cylinder hydraulic layout in the style of full-scale systems. While this would need no software changes to make this operate the same as a full-scale tiltrotator, hydraulic motors and pistons of this size introduce higher costs and exceed the max forces needed for a 1/12 scale platform.
- **Electrical Differential Architecture:** A system driven by dual stepper motors connected to a central differential through worm gears. This was selected as the better solution. The primary limitation of this approach is that its internal actuation differs from full-scale commercial hydraulic tiltrotators, which introduces a software problem to match the electrical differential design to the standard hydraulic tiltrotator. The final design is shown in Fig. 1.

B. Differential Design and Kinematics

The final architecture utilizes a differential gearbox driven by stepper motors through worm gears. Starting from the motors, power is routed through a 10:1 planetary gearbox into a 20:1 worm gear stage. This setup is mirrored onto the sides of the front and the back of the excavator's arm and attached to a central differential. The inner assembly, as seen in Fig. 3, relies on three 1:1 1045 carbon steel miter gears, constrained by an 11 mm cube with three 6 mm outer-diameter bearings. The worm is made out of 1045 carbon steel, the worm gear is made out of bronze, and all shafts are machined out of aluminum stock.



Figure 2: The finalized tiltrotator on the scale excavator

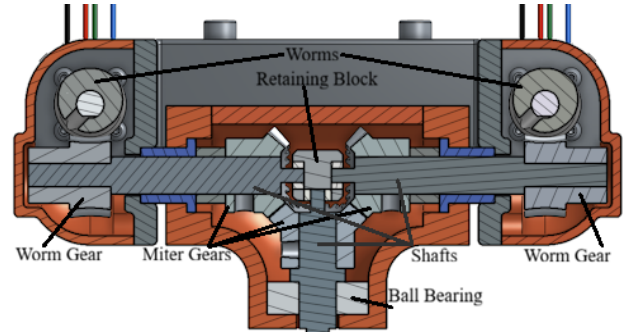


Figure 3: The internal worm gear driven differential of the tiltrotator

Because the two worm-driven inputs act on opposite sides of the differential, equal input velocities produce pure tilt, while equal and opposite input velocities produce pure rotation. Intermediate combinations allow simultaneous tilt and rotation. The worm gears were selected with a lead angle below 5° , reducing backdrivability and allowing the tiltrotator to hold position under expected loads without motor power [6].

C. Grapple Mechanism

A built-in grapple was integrated into the rear of the modified bucket to increase capability on the job site. An earlier grapple concept used a string-driven closing mechanism with elastic reopening; this approach was rejected because maintaining a closed position required the motor to have continuous high current draw.

The finalized design utilizes a NEMA 8 stepper motor driving a four-gear herringbone spur train with a 16:27 overall ratio. The inner two gears are identically sized, while the outer two are 1.28 times larger, ensuring symmetric operation. The motor is connected to one of the central gears, directly providing power to one side of the grapple and providing power

through an idler gear to the other side. Power and control signals are routed through a central slip ring, allowing continuous 360° rotation of the tiltrotator without wire binding. The grapple is required to open to a full 180° and close completely with overlapping claws in order to mimic true tiltrotator grapple attachments.

D. Gear Efficiency Estimation

Gear efficiency was estimated using standard worm gear and bevel gear efficiency relationships. The overall drivetrain efficiency was approximated as the product of the individual stage efficiencies. The assumption was made that the miter gears had 95% accuracy.

$$\text{Efficiency-worm} = \frac{\cos \alpha_n - \mu \tan \gamma}{\cos \alpha_n + \mu \cot \gamma}$$

$$\eta_{total} = \eta_{worm} \times \eta_{bevel}$$

Assuming ideal gear transmission, the estimated output torque for the system was calculated as 423.7 N·cm. Accounting for estimated friction losses in the worm and bevel gear stages, the predicted output torque was 242.2 N·cm, corresponding to a predicted mechanical efficiency of 57.2%.

IV. EXPERIMENTAL RESULTS AND DISCUSSION

A. Torque and Speed Testing Setup

To validate the system's output against the design requirements, torque and speed tests were conducted. Output torque was measured using the standard tiltrotator grapple bucket. A spring scale was applied perpendicular to the lever arm until the mechanism stalled or slipped. Three trials were performed and averaged. We used a spring scale and fixed the tiltrotator to the table, as shown in Fig. 4, to test torques.

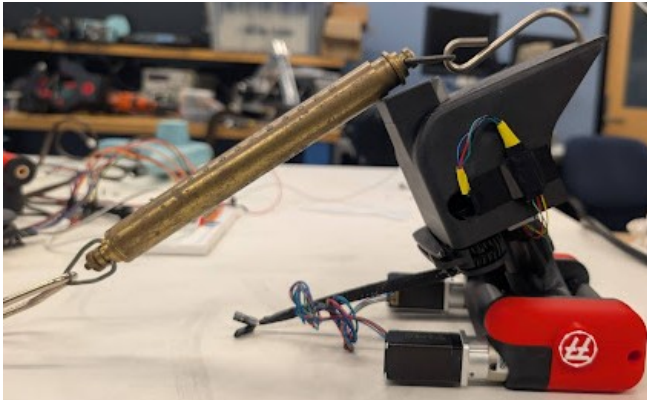


Figure 4: Torque testing setup using spring scale and tiltrotator screwed into the table

B. Performance and Power Output

The tiltrotator satisfied the requirements for tilt range, continuous rotation, torque output, and size constraints. Speed testing confirmed the assembly can tilt and rotate at 7.5 rpm. We measured rpm using a stopwatch to time how long one rotation took.

The peak output torque was measured as 226.0 N·cm using the spring-scale test fixture. To estimate the torque required for actual digging, the excavator was tested in dense gravel while operating the tiltrotator in a reduced-torque (half-stepping) motor mode. In this mode, the maximum available output torque was approximately 151.8 N·cm, and the mechanism stalled during aggressive digging. Therefore, the torque required for the most demanding observed gravel-digging condition is estimated to be near 151.8 N·cm. Since the full-power configuration produced 226.0 N·cm, the tiltrotator provides a torque margin of approximately 48.9% over the observed digging requirement.

C. System Efficiency

The measured output torque of 226.0 N·cm, compared to the idealized torque of 423.7 N·cm, yields a measured system efficiency of 53.3%. This closely aligns with the predicted efficiency of 57.2%. The high friction losses were anticipated and represent an acceptable design tradeoff to achieve the necessary non-backdrivability provided by the worm gear stages.

D. Grapple Performance

The integrated grapple successfully opened and closed through its designed range of motion. During testing, the grapple was able to grasp and hold 0.36 kg cylindrical objects, as well as move them without losing grip.

E. Constraints and Final Specifications

The final mechanism successfully met or exceeded all physical and performance constraints, as detailed in Table 1.

Table 1: Design Requirements vs. Achieved Results

Parameter	Requirement	Achieved Result
Height	Max. 85.7 mm	80.9
Platform envelope	Max. 135 mm × 135 mm	127 mm × 130 mm
Mass	Max. 2 kg	1.13 kg
Tilt Range	±50°	±50°
Rotation Range	Continuous 360°	Continuous 360°
Output Torque	Min. 200 N·cm	226 N·cm
Rotation speed	7.5 RPM	7.5 RPM

V. CONCLUSION AND FUTURE WORK

The development of a 1/12 scale tiltrotator successfully supports the use of electrical miniature excavators for advanced

operator training. By utilizing a differential gearbox, non-backdrivable worm gears, and stepper motors, the attachment met all spatial constraints, weighed 0.87 kg below the 2 kg goal, and generated 48.9% more torque than needed in the tested gravel-digging requirements.

A limitation of this approach is the inherent mechanical efficiency loss (measured at 53.3%) traded for non-backdrivability, as well as the deviation from true hydraulic control architecture. However, this mechanical framework provides a highly capable, low-cost platform that may support future research in miniature excavator-based operator training and teleoperation.

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