

Electrical and Control System Design of a Scaled Excavator Tilt Rotator for Teleoperation Research and Training

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Abstract— Teleoperated excavators have the potential to improve operator safety while enabling the development of advanced human-machine interfaces. However, developing and testing these systems on full-scale excavators is costly, resource-intensive, and potentially dangerous. This paper details the electrical and controls design of a 1/12 scale excavator tiltrotator platform (as shown in Fig. 1) intended for teleoperation research and operator training. The system combines NEMA 8 stepper motors, TMC2209 stepper drivers, and an ESP32 microcontroller to provide precise bucket tilt and continuous rotation while maintaining a compact form factor. UART communication enables adjustment of motor operating modes, while a non-backdrivable worm gear transmission eliminates the need for continuous holding current. Experimental testing demonstrated that the tiltrotator met the required torque, speed, and range-of-motion specifications. The resulting system supports future research in teleoperation, advanced excavator control, and human-machine interfacing.

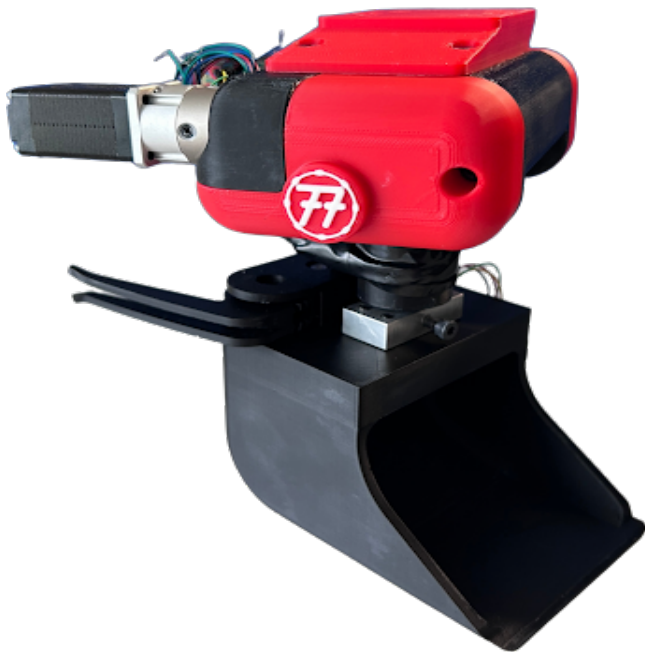


Figure 1: 1/12 scale excavator tiltrotator platform with integrated grapple.

I. INTRODUCTION

Excavator operation often requires skilled operators and work in hazardous environments [1]. Teleoperation offers the ability to remove these operators from dangerous situations while enabling advanced control methods, including future human-machine interfaces [2] such as gesture-based control and human pose estimation. Developing these technologies on full-scale excavators, however, is expensive, resource-intensive, and impractical during early-stage development. To improve these technologies, The 77 Lab is currently engaged in ongoing research on teleoperation of scaled excavators.

Scaled excavator platforms provide an affordable and repeatable environment for developing and evaluating new control systems before implementation on full-scale equipment [2]. In addition to supporting teleoperation research, these platforms can also improve operator training by reducing cost, increasing accessibility, and eliminating many of the risks associated with training on heavy machinery.

Tiltrotators are excavator attachments that provide two additional degrees of freedom by allowing the bucket to tilt left and right while continuously rotating 360° [3]. This increased flexibility allows operators to perform more precise tasks and work from multiple angles without repositioning the excavator, improving both efficiency and productivity.

Many commercial tiltrotators also include an integrated grapple mounted behind the bucket, allowing operators to grasp and manipulate objects without changing attachments [3]. Although these systems have become increasingly common on full-scale excavators, they are rarely incorporated into scaled models, as miniature hydraulic systems are complex and expensive to produce.

This work uses a modified 1/12 Scale Earth Digger 4200XL Hydraulic Excavator as the base research platform (see Fig. 2) [4]. Rather than reproducing the hydraulic tiltrotator found on full-scale machines, the attachment is electrically actuated using stepper motors and a differential gearbox. This design provides the required functionality while creating a compact, efficient platform for embedded control and teleoperation research. For more details on the mechanical design, see our companion paper [5].

II. SYSTEM REQUIREMENTS

The electrical system was designed to meet the performance requirements established for the 1/12 scale tiltrotator while remaining compatible with the size and weight constraints of



Figure 2: 1/12 Scale Earth Digger 4200XL Hydraulic Excavator used as the base research platform with installed tiltrotator.

the scaled excavator platform. The attachment was required to provide continuous 360° bucket rotation and a tilt range of $\pm 50^\circ$ while fitting within an overall footprint of 135×135 mm and a height of 85.7 mm.

Target operating speeds were selected by examining and matching the performances of commercially available full-scale tiltrotators [2]. Based on these systems, bucket tilt and rotation speeds between 7.5 and 10 RPM were selected. Free-body analysis using the desired bucket geometry and a full gravel payload established a tilting torque output requirement of 1.62 N·m.

In addition to meeting the required torque and speed specifications, the electrical system was designed for extended operation. Because the platform is intended for repeated teleoperation experiments and operator training, excessive motor heating would shorten testing time, increase power consumption, and reduce long-term reliability. Minimizing idle power consumption and motor temperature therefore became a necessary design requirement.

III. ELECTRICAL AND CONTROLS SYSTEM DESIGN

A. Motor Selection

Several compact DC motors and stepper motors were evaluated for the tiltrotator. Stepper motors were ultimately selected because they provided significantly higher torque than similarly sized DC motors while maintaining the positioning accuracy required for precise bucket control. Although DC motors offered higher maximum speeds, the relatively low operating speed requirements made the higher torque of the stepper motors the more appropriate choice.

NEMA 8 bipolar stepper motors (StepperOnline 8HS15-0304S) coupled with 10:1 planetary gearboxes (StepperOn-

line EGS8-G10) were selected because they satisfied the project's size, torque, and speed requirements.

B. Driver Selection

Each motor is controlled by a TMC2209 stepper driver operating from a 24 V supply. The TMC2209 was selected because it provides sufficient current capacity while supporting UART communication for runtime configuration [6].

UART communication allows motor operating parameters to be adjusted without hardware modifications, including microstepping resolution and motor current. These capabilities were used to tune torque, speed, and smoothness for different operating conditions while also providing diagnostic features such as stall detection.

C. Controller and Operator Interface

The control system is centered around an ESP32 Thing Plus C development board, which communicates with three TMC2209 drivers over UART. Operator input is provided through a two-axis joystick, with one axis controlling bucket tilt and the other controlling continuous bucket rotation.

The joystick's integrated push button performs several functions. Short button presses are used to define the mechanical tilt limits during system calibration, while long presses cycle between different operating modes that prioritize either speed or torque. By switching to a higher microstepping resolution, such as 1/256, the tilt rotator can produce higher torque at a much lower speed, similar to a gear reduction. Conversely, lower microstepping resolutions allow the system to operate at higher speeds when greater torque is not required. Once calibrated, the tilt limits are stored in the ESP32's nonvolatile memory and retained after power is removed.

This calibration method is possible because each differential input is driven through a worm gear transmission. Since the worm gears cannot be back-driven, the bucket maintains its position when the motors are disabled, allowing the stored limits to remain valid between operating cycles. Over extended use, however, missed motor steps or unexpected external loading may require recalibration.

When the grapple is enabled, the joystick push button instead controls the grapple mechanism. Each button press alternates between opening and closing the grapple, allowing the operator to repeatedly actuate the mechanism while maintaining simultaneous joystick control of bucket tilt and continuous rotation.

D. Grapple Integration

Commercial hydraulic tiltrotators with integrated grapples typically transmit hydraulic fluid across the rotating joint using a rotary union, allowing continuous actuation of the grapple and unrestricted bucket rotation. Reproducing this hydraulic design at 1/12 scale, however, would significantly increase system complexity and cost.

Instead, electrical power is transmitted across the rotating joint using a 7 mm inner diameter, six-channel through-hole slip ring (VXB Bearings). The slip ring provides continuous power to the rotating assembly while preserving unlimited bucket rotation. To simplify the overall design and remain consistent with the existing system, the grapple is driven by an additional NEMA 8 stepper motor identical to those used for the bucket tilt and rotation mechanism. Reusing the same motor and driver reduces the number of unique components while providing sufficient torque and speed for grapple operation.

E. Power Management

The non-backdrivable worm gear transmission also eliminates the need for continuous holding current when the tiltrotator is idle. Conventional stepper motor systems must continuously energize the motors to maintain position, resulting in unnecessary power consumption and significant heat generation.

Initial testing showed that continuously applying holding current caused the motors to become prohibitively hot to touch after approximately five minutes of operation. To address this issue, the controller automatically disables motor current after a short period of inactivity while relying on the worm gears to maintain bucket position. This reduced standby current from approximately 0.8 A to 0.02 A, significantly reducing motor heating while extending the platform's usable operating time during experimentation.

Experimental Results

F. Motor Performance

As shown in Fig. 3, the selected stepper motors were evaluated over a range of operating speeds and microstepping resolutions to identify settings capable of meeting the required torque and speed specifications.

Testing showed that half-step (1/2-step) microstepping provided the highest usable torque while maintaining smooth operation. Although higher microstepping resolutions produced smoother motion, they reduced the available output torque and were therefore less suitable for the intended application. Motor speed was then adjusted to achieve the required operating performance while maintaining sufficient torque for realistic excavation tasks.

G. System Performance

Experimental testing demonstrated that the electrical architecture met the project's required torque, speed, and range-of-motion specifications. The combination of NEMA 8 stepper motors, TMC2209 drivers, and ESP32-based control provided sufficient flexibility to tune system performance while maintaining control of both bucket tilt and continuous rotation.

The non-backdrivable worm gear transmission also allowed motor current to be disabled during idle periods with-

Torque vs. Speed by Microstepping Resolution

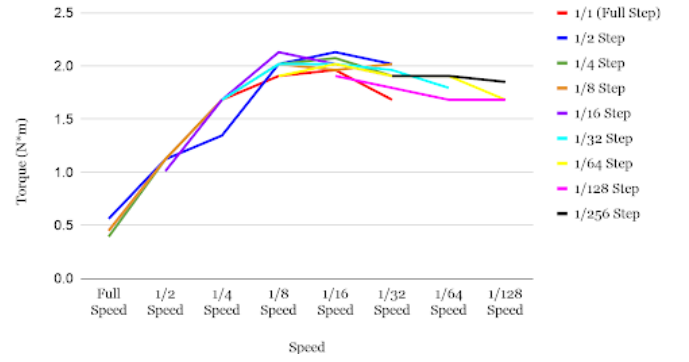


Figure 3: Torque vs. Speed relationship for the stepper motors at various microstepping resolutions.

out loss of bucket position. This reduced standing current and significantly reduced motor heating during idle operation.

IV. DISCUSSION

The motor testing demonstrated a clear tradeoff between microstepping resolution, torque, and operating speed. The 1/2-step configuration provided the highest usable torque while maintaining sufficiently smooth operation for the intended application. Higher microstepping resolutions improved motion smoothness but reduced available output torque, making them less suitable when the tiltrotator is required to produce higher loads. This behavior is consistent with the operating characteristics of stepper motor systems and supports the use of selectable microstepping rather than a single fixed resolution.

The ability to adjust the motor operating characteristics through UART communication is particularly useful for a scaled excavator platform because different operations may place different demands on the tiltrotator. Higher torque settings can be used when greater force is required, while higher-speed settings can be used when rapid movement is more important. This provides flexibility that would not be available with a fixed motor configuration.

The reduction in standing current provided by the non-backdrivable worm gear transmission also has implications for extended operation. Because the transmission can maintain the bucket position without continuous motor torque, the motors can be disabled while the system is stationary. The significantly reduced power consumption and motor heating, which is beneficial for a platform intended for extended teleoperation experiments and repeated operator training sessions.

These results support the use of the selected electrical architecture as a practical approach for controlling the scaled tiltrotator. The combination of programmable motor drivers, UART communication, and ESP32-based control provides the flexibility needed to adjust system behavior without requiring changes to the mechanical hardware.

V. CONCLUSION

This paper presented the electrical and embedded control design of a 1/12 scale excavator tiltrotator platform intended for teleoperation research and operator training. Using NEMA 8 stepper motors, TMC2209 stepper drivers, and an ESP32-based control system, the platform met the required torque, operating speed, and range-of-motion specifications while providing control of bucket tilt and continuous rotation.

The motor testing demonstrated the importance of selecting an appropriate microstepping resolution to balance torque, speed, and motion smoothness. UART communication also provided runtime flexibility for adjusting motor operating characteristics. Additionally, the non-backdrivable worm gear transmission allowed the motors to be disabled during idle periods while maintaining bucket position, reducing standing current and motor heating.

Overall, the developed system provides a functional electrical and embedded control foundation for a scaled tiltrotator platform and future teleoperation research.

VI. FUTURE WORK

Several areas remain for future development of the tiltrotator platform. The current implementation relies on manually selected stepping and speed modes. Future work could use current sensing to automatically adjust motor operating characteristics based on applied load, allowing the 1/12 scale tiltrotator to more closely replicate the variable performance of full-scale hydraulic tiltrotators.

Because position is currently determined through open-loop stepper control, missed motor steps or external disturbances may introduce small positioning errors over time. Integrating rotary encoders would provide closed-loop position feedback, improving long-term accuracy and reducing the need for periodic recalibration.

The control of the integrated grapple is another area for future development. While the current system provides reliable opening and closing functionality, it does not yet replicate the level of control available on full-scale hydraulic tiltrotators. Integrating the grapple with the excavator's existing controls will provide more realistic operation and improve the platform for teleoperation research and training.

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