



TECHNOLOGY WHITE PAPER

Transverse Flux for Direct-Drive Robotics

A path to dexterous, fast, and robust
robots without gearboxes

1. Why Gearless Actuation Matters for Robotics

For embodied AI, permanent-magnet synchronous motors (PMSMs) are widely used for actuation, and they can produce substantial power at high speed, but robot joints often need high torque at much lower speeds, including while holding a large torque load at near zero speed. A gearbox trades motor speed for output torque, allowing a compact motor to meet the joint's load requirements.

But gearboxes introduce problems in motion quality, simulation fidelity, and reliability. Friction and backlash can limit the collection of smooth, accurate demonstrations at human speed. Transmission behavior that varies with load and wear is difficult to model, contributing to a large sim-to-real gap. Mechanical failures interrupt data collection and reduce deployment uptime.

If transverse-flux motors can deliver the required torque and speed within a joint's size, weight, and cooling limits, removing the gearbox could improve all three. Eliminating gear friction and backlash could enable smoother, more precise demonstrations of dexterous tasks at human speed, producing higher-quality data. Removing these transmission effects could make physical behavior easier to model, drastically reducing the sim-to-real gap. Eliminating the possibility of gearbox failure could support longer uninterrupted data collection and higher deployment uptime.

2. How Transverse Flux Can Enable Gearless Actuation

A more detailed derivation of the math in this section can be found in Appendix A.

How's torque produced?

Consider one phase of each motor. Flux linkage sums the rotor-magnet flux linked by all winding turns. For the magnet-current torque, a small linkage change $d\lambda$ transfers work $i d\lambda$, where i is instantaneous current. Adding this work over one electrical cycle gives

$$W_{\text{cycle}} = \oint i d\lambda = \pi \hat{\lambda} \hat{I} \quad (1)$$

$\hat{\lambda}$ and $\hat{I}$ are peak flux linkage and current. With correctly timed sinusoidal current and linkage, integrating sine squared over 2π electrical radians gives π .

With p pole pairs, one mechanical revolution contains p electrical cycles and delivers work pW_{cycle} . Average torque is this work divided by the revolution's 2π radians:

$$\bar{T} = \frac{pW_{\text{cycle}}}{2\pi} = \frac{1}{2}p\hat{\lambda}\hat{I} \quad (2)$$

More electrical cycles per revolution increase torque if the winding preserves its work per electrical cycle.

Now hold the overall working-gap envelope and clearance, useful gap field, total series turns N , and current amplitude fixed. Here, N counts every series turn across all coils in the phase. Let's examine how each architecture responds to finer pole pairs or, in other words, more electrical cycles per revolution.

Transverse flux can increase torque with finer pole pairs

A transverse-flux ring winding is shared by magnetic circuits around the shaft. Group these circuits into p identical pole-pair repeats, each linking all N turns. With total working area fixed, more repeats make each repeat smaller. If useful field and coupling are maintained, its peak useful flux per turn, $\hat{\Phi}_{\text{pair}}$, scales as

$$\hat{\Phi}_{\text{pair}} \propto \frac{1}{p} \quad (3)$$

Each turn of the ring coil links the useful contributions from all p repeats. These contributions add in phase, so their sum is $p\hat{\Phi}_{\text{pair}}$ per turn. Multiplying by the winding's N turns gives

$$\hat{\lambda}_{\text{TF}} \approx Np\hat{\Phi}_{\text{pair}} \propto p \times \frac{1}{p} \quad (\text{independent of } p) \quad (4)$$

More repeats compensate for less flux per repeat, preserving total linkage and work per electrical cycle. At unchanged peak current, Equation 2 therefore gives

$$\overline{T}_{\text{TF}} = \frac{1}{2}p\hat{\lambda}_{\text{TF}}\hat{I} \propto p \quad (5)$$

Why a slotted winding scales differently

A conventional slotted turn links the local pole region its coil spans. Finer poles make that region smaller, so its effective peak flux per turn, $\hat{\Phi}_{\text{turn}}$, scales as

$$\hat{\Phi}_{\text{turn}} \propto \frac{1}{p} \quad (6)$$

Adding coils divides the same N turns among the p pole pairs, $\frac{N}{p}$ per pair. Each turn still links a local pole region, and $\hat{\Phi}_{\text{turn}}$ accounts for how those coil contributions combine. Summing over the pole pairs gives the complete winding's peak linkage:

$$\hat{\lambda}_{\text{slot}} = p \times \frac{N}{p}\hat{\Phi}_{\text{turn}} = N\hat{\Phi}_{\text{turn}} \propto \frac{1}{p} \quad (7)$$

Summing p pole pairs with $\frac{N}{p}$ turns each leaves no extra factor of p : a slotted turn does not link all p repeats as a transverse-flux ring turn does. Substituting Equation 7 into Equation 2 gives

$$\overline{T}_{\text{slot}} = \frac{1}{2}p\hat{\lambda}_{\text{slot}}\hat{I} \propto p \times \frac{1}{p} \quad (\text{independent of } p) \quad (8)$$

Work per electrical cycle falls in proportion to the mechanical angle per cycle, leaving average torque unchanged. The transverse-flux shared winding preserves that work, allowing more cycles per revolution to increase torque.

3. The Engineering Limits of Transverse-Flux Motors

Motor design challenges

At smaller pole pitches, flux leakage tends to be more difficult to control in transverse flux motors than in conventional slotted machines. In a direct drive architecture, torque ripple is transmitted directly to the robot joint, making ripple reduction a key design priority. Addressing both challenges requires careful motor design guided by electromagnetic simulation.

Iron-loss management

Three-dimensional flux complicates conventional lamination construction, requiring new ways to manage iron loss. For low-speed, high-torque robotic operation, iron loss is expected to be small relative to copper loss, which mitigates this problem.

Drive requirements

Lower power factor requires higher inverter capacity for the same real power. Gallium nitride (GaN) devices reduce switching losses and enable compact, efficient inverters, helping mitigate the resulting size and thermal penalties.

Repeatable assembly

This new design is intended for existing manufacturing processes. Its assembly needs further engineering to match established slotted-motor production, with fixtures and procedures that consistently control air gaps, magnet installation, and phase alignment.

4. What the Prototype Has Demonstrated

Result	Torque (N·m)	Peak Phase Current (A)	Speed (rpm)
Measured	2.63	50	82
Measured	2.54	43	60
Projected Continuous	3.0	16.7	120
Projected Peak	7.4	49.3	120

Measured values are 2.5-second averages, with damaged coils and mechanical friction caused by rotor misalignment. The 82 rpm result was below the 120 rpm target due to a

power source limitation. Projections are estimates assuming both coils are intact and excess mechanical friction is corrected.

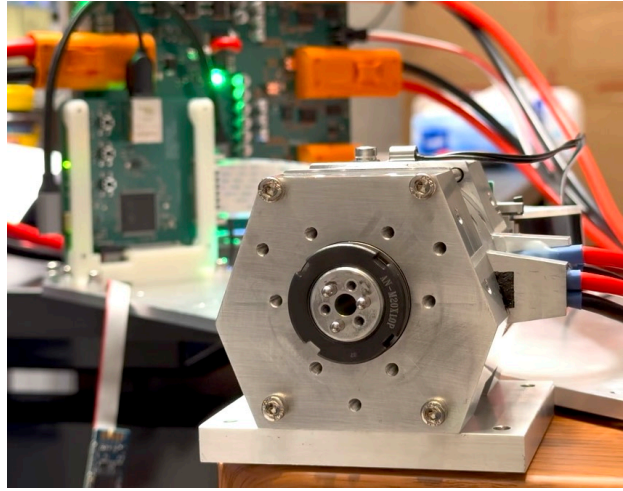


Figure 1. A two-phase transverse-flux prototype motor in the foreground, with the drive electronics in the background.

5. From Prototype to Sustained Actuator Performance

The next build must establish a sound baseline: intact windings, controlled gaps, and balanced phases. Our manufacturing partner estimates two months to complete the next build, followed by another one to three months to reach pilot production with capacity for a few hundred actuators per month.

Appendix A. Flux linkage and torque scaling

Single-phase torque and work

For one phase in a quasi-static linear magnetic model with fixed magnet state, magnetic co-energy is

$$W'_m = W'_0(\theta_m) + i\lambda(\theta_m) + \frac{1}{2}L(\theta_m)i^2 \quad (\text{A1})$$

Here, λ is magnet-produced linkage of the complete winding, L is its inductance, and θ_m is mechanical shaft angle. Differentiating at fixed instantaneous current gives

$$T_{\text{em}} = i \frac{d\lambda}{d\theta_m} + \frac{1}{2}i^2 \frac{dL}{d\theta_m} + \frac{dW'_0}{d\theta_m} \quad (\text{A2})$$

Section 2 isolates the first, magnet-current term. The others are reluctance torque and cogging.

For sinusoidal linkage and sinusoidal current, timed to maximize this torque contribution,

$$\lambda = \hat{\lambda} \cos(p\theta_m), \quad i = -\hat{I} \sin(p\theta_m) \quad (\text{A3})$$

Substituting into the first term of A2 gives

$$T = p\hat{\lambda}\hat{I} \sin^2(p\theta_m), \quad \bar{T} = \frac{1}{2}p\hat{\lambda}\hat{I} \quad (\text{A4})$$

The instantaneous torque pulsates; Section 2 uses its average over a complete electrical cycle. That cycle occupies a mechanical angle of $\frac{2\pi}{p}$. Its mechanical work is

$$W_{\text{cycle}} = \oint i \, d\lambda = \pi\hat{\lambda}\hat{I}, \quad \bar{T} = \frac{pW_{\text{cycle}}}{2\pi} \quad (\text{A5})$$

Subdividing the transverse-flux magnetic circuit

The scaling change preserves working radius, active width, gap clearance, active pole coverage, useful field waveform, total series turns, and current waveform versus electrical angle. Increasing pole-pair count p creates more, narrower repeats while preserving useful additive linkage through the shared winding.

Let A_Σ be the total working pole area, counting each independent linked-flux contribution once. Divide it among p identical pole-pair repeats. With useful effective field amplitude $\hat{B}_{\text{eff}}$,

$$\begin{aligned} A_{\text{pair}} &= \frac{A_\Sigma}{p}, \quad \hat{\Phi}_{\text{pair}} \approx \hat{B}_{\text{eff}} A_{\text{pair}} \\ \hat{\lambda}_{\text{TF}} &\approx Np\hat{\Phi}_{\text{pair}} \approx N\hat{B}_{\text{eff}} A_\Sigma \end{aligned} \quad (\text{A6})$$

Each repeat can contain more than one magnetic circuit; $\hat{\Phi}_{\text{pair}}$ includes their net useful contribution per turn. Smaller repeats carry less flux, while more repeats preserve the winding's total linkage.

Subdividing a conventional slotted winding

For a representative full-pitch turn at working radius R and active axial width L_a , integrate a sinusoidal gap field over one pole region:

$$\hat{\Phi}_{\text{turn}} = RL_a \int_{-\frac{\pi}{2p}}^{\frac{\pi}{2p}} \hat{B}_1 \cos(p\theta) \, d\theta = \frac{2RL_a \hat{B}_1}{p} \quad (\text{A7})$$

Multiplying by fixed total series turns N gives linkage proportional to $\frac{1}{p}$.

References

- [1] J. L. Kirtley Jr., *6.685 Electric Machines*, MIT, 2013.
- [2] J. L. Kirtley Jr., *6.11s Notes 8: High Torque Motors*, 2006.