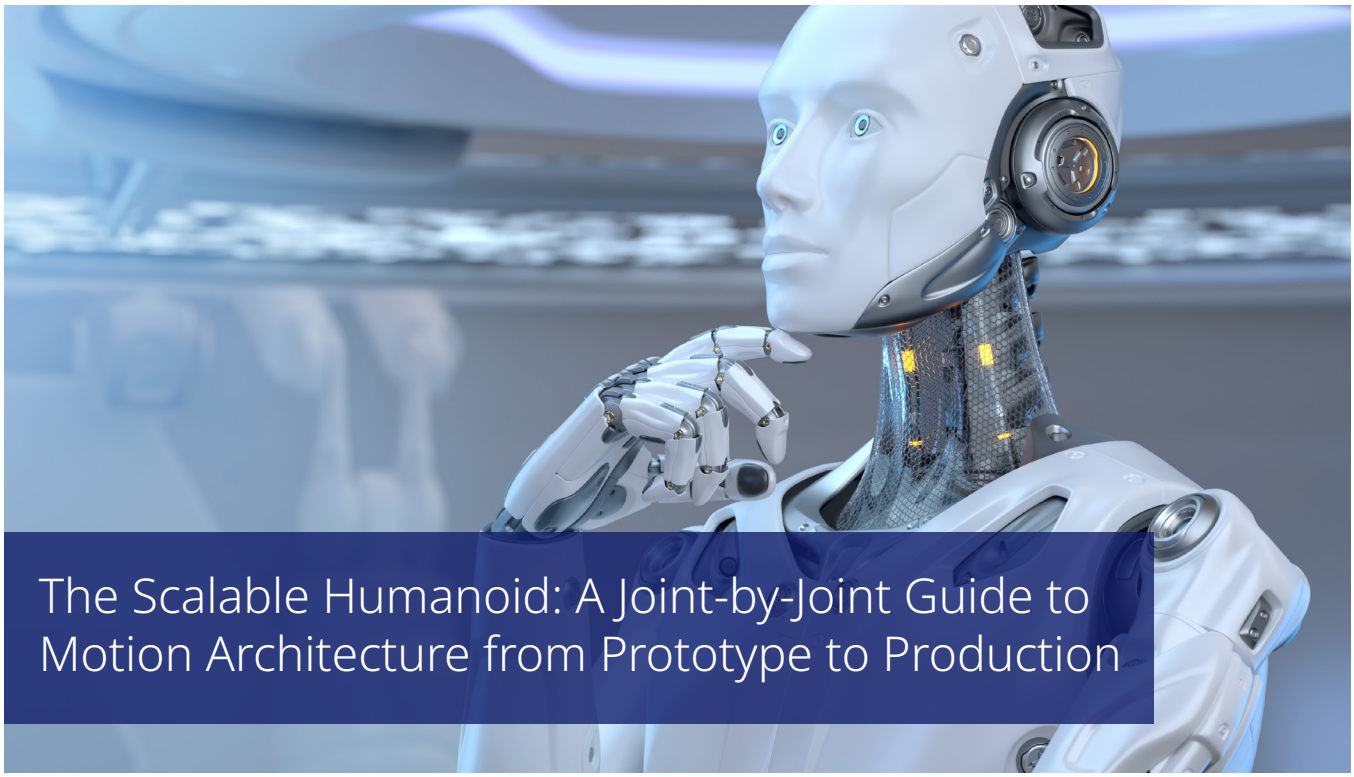
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WHITE PAPER



The Scalable Humanoid: A Joint-by-Joint Guide to Motion Architecture from Prototype to Production

A successful prototype may prove a concept, but the actuator architecture determines if it can scale. This gap is why many humanoid programs stall when transitioning from working prototype to manufacturable product.

The humanoid robotics industry is seeing billions in recent funding, strong year-over-year investment growth, and thousands of units already deployed. As companies race to innovate and scale, motion architecture becomes a critical consideration from the start. Because while software can iterate in weeks, the hardware that makes a humanoid move—actuators, gearboxes, precision joints—still takes months to reach a functional prototype and years to reach volume production.

This paper reevaluates humanoid motion development using a zone-by-zone architecture. Joint actuation is the heart of every humanoid. Each body zone carries distinct torque, speed, weight, form factor and thermal requirements. Each demands a different engineering solution. And each presents scale-readiness challenges that prototype success alone won't reveal.



The humanoid hardware bottleneck

Let's break down this gap further. Software like perception models, locomotion policies and manipulation stacks iterate at the speed of compute. The actuators, gearboxes and joints that execute those decisions don't.

In fact, joint design moves from paper to a functional prototype in months, and from a prototype to a validated, manufacturable product in years. That mismatch is the core friction in humanoid development, compounded by a supplier ecosystem for compact, high-performance actuators that is still maturing toward volume readiness.

Actuators account for 40 to 60 percent of the humanoid bill of materials. That concentration of cost and engineering difficulty demands they be central to the architectural conversation from day one.

Then, there is the layer of platform cadence. Many humanoid OEMs are overhauling their platforms on roughly annual cycles. A pace that would be extraordinary in nearly any other hardware industry. Automotive platforms typically hold their architecture for four to five years while software and interiors are refreshed. In humanoid robots, the entire mechanical system may be under review before the previous generation reaches production. This makes rapid prototyping and repeated iteration a baseline requirement.

Prototype success doesn't equal production readiness. The deciding factor is motion architecture designed for scale from the outset, including zone-specific engineering, thermal discipline, validation rigor and a motion partner engaged before the first prototype is built.

Investment Dynamic

Humanoid OEMs are active investors in their supply chain. They're open to funding tooling and non-recurring engineering (NRE) to create a clearer path to efficiencies, manufacturability and scalability. That investment accelerates innovation, with advances cascading into collaborative, surgical, agricultural and industrial robotics.



Why joint-zone thinking matters

> **A humanoid robot is a collection of mechanical zones, each with very different requirements. Treating it as one uniform system that can be solved with a universal actuator is a reliable way to force expensive rework late in a program.**

Humanoids are not industrial robots. A traditional industrial arm operates with four to six degrees of freedom, handles large payloads and works inside a cage. A collaborative robot manages six to seven degrees of freedom with force limiting for shared workspaces. An automated guided vehicle (AGV) needs two to three degrees of freedom for wheeled drive. A legged humanoid requires 40 or more actuated degrees of freedom across its full kinematic chain. Its payload is lower than an industrial arm, but its torque density requirements are far higher, because everything must fit inside a compact, lightweight joint package—operating directly alongside people, without barriers.

Requirements across the kinematic chain.

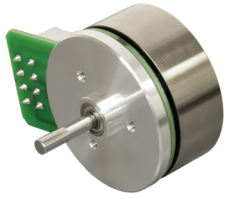
Feature	Industrial Robot	Cobot	AGV / AMR	Humanoid (Wheeled)	Humanoid (Legged)
Degrees of Freedom (DoF)	4-6	6-7	2-3	20-30+	40+
Mobility	Stationary	Stationary	Wheeled	Wheeled base	Bipedal
Payload	5-2.3K kg	3-34 kg	100-1.5K kg	5-20 kg	5-10 kg
Scope	Task-specific	Collaborative	Transport	General	General
Environment	Caged	Shared	Flat floors	Indoor mixed	Unstructured
Torque Density	Standard	Low-Medium	Drive motors	High	Ultra-high
Dexterity	Low	Medium	None	High (arms + hands)	High (arms + hands)
Safety	Caged	Force-ltd	Prox. sensors	Full-body	Full-body

Source: IDTechEx Humanoid Robots 2025–2035; IFR World Robotics Report, 2024

Full-body compliance, fenceless operation and ultra-compact actuation are why you can't just take industrial robot components off the shelf and repurpose them for humanoids. The requirements are different enough that you need purpose-built solutions from the ground up. The challenge is matching each zone to the right motor, gearing, packaging and safety strategy.

While brushless DC slotless motors remain valuable for high-speed axes and housed servo motors are sometimes used for early prototyping, neither is common in embedded humanoid joint design. The dominant embedded-joint architecture for humanoids is the frameless brushless DC slotted high-torque motor. Frameless motors integrate the rotor and stator directly into the robot's structural housing and shaft to eliminate size and weight requirements of a conventional housed motor, maximize torque density and achieve zero backlash with a direct-drive configuration.

Once the core motor technology is largely established, the remaining engineering challenge is applying it correctly across zones—and then proving the design survives the transition to volume.



Brushless DC Slotted



Frameless / Direct Drive



Brushless DC Slotless



Housed Servo Motors

A zone-by-zone design guide

This guide captures primary demands for each humanoid zone at a glance and explains what those demands mean for architecture and scale.

Hip and Knee

The hip and knee are the most challenging areas for humanoids. Torque scales with the square of the motor diameter rather than its length, which is why high-torque robotic motors trend toward a flat, pancake geometry. Extracting the required torque from a compact envelope means maximizing copper density inside that geometry.

Achieving that density repeatably at volume benefits from automated winding over manual assembly. That's because automated winding lines produce tightly organized, high-density copper arrangements that are impractical by hand and essential for consistent production-scale performance.

Higher winding density also means more heat. That heat migrates to gearing lubricants, bearings and encoders—all of which degrade well below the motor's rated ceiling. It can also reach the robot's outer surface, which is a hazard in human-proximity operation.

Architecture priorities: Frameless and direct drive paired with roller screws for high-load, high-cycle impact loads, and integrated safety brakes for standstill. Ideally, structural design manages thermal dissipation from the start.

Scale implication: Thermal margin and structural integration determine whether this design will successfully scale to production. Resolve these tradeoffs before declaring design optimization complete.

Demand	Specification
Torque	100-300 Nm
Speed	60-120 rpm
Package Weight	1.5-3.0 kg
Primary Challenge	High torque, low weight

Source: IDTechEx Humanoid Robots 2025–2035

Gearing Selection

Hip and knee joints can take different architecture paths depending on torque, efficiency, package size and load requirements. Understanding the strengths and design considerations of common gearing and screw-based approaches can help narrow the right solution for the joint.

Approach	Benefits	Watchouts	Scale Consistency
Harmonic Drive	Compact; high gear ratios	Higher cost; ~70-80% efficiency	Efficiency losses can add up in battery-powered robots
Planetary Gearing	~95%+ efficiency; mature technology	Humanoid-specific variations still developing	Mature technology provides an established starting point for scale
Cycloidal Gearing	Robust; well suited for shock loads	Larger package size	Best suited where robustness outweighs compactness
Ball Screw	~90% efficiency; low friction	Lower load and life than roller screws	Well suited for legs and torso joints requiring speed and smooth motion
Roller Screw	High load capacity; long life	Higher cost and complexity	Well suited for knees and hips with high-cycle, high-impact loads
Lead Screw	Self-locking; low cost	Better suited to lower-load applications	Well suited for wrists and grippers that need to hold position without consuming power

Source: IDTechEx Humanoid Robots 2025–2035

Shoulder and Elbow

When the arm meets resistance like a person or an obstacle, the joint must yield rather than resist. This requires engineering compliance into a high-torque joint without sacrificing controllability.

The shoulder and elbow occupy a productive middle ground. Their torque and weight requirements are less extreme than the hip and knee, and their requirements overlap with collaborative robot design. Experience with compliant actuators, torque sensing, braking and safe human interaction provides a validated starting point for humanoid arm architecture. These proven approaches can help engineers achieve the required torque density and controllability without developing every element of the joint from the ground up.

Architecture priorities: Frameless and direct drive for compliant arms, and safety brake integration for safe standstill and reduced current draw during extended hold positions.

Scale implication: Compliance that depends on hand-tuning in a prototype won't transfer to volume production without redesign.

Demand	Specification
Torque	40-120 Nm
Speed	90-180 rpm
Package Weight	0.8-1.5 kg
Primary Challenge	Backdrivability + compliance, functional safety level

Source: IDTechEx Humanoid Robots 2025–2035

Wrist

The wrist's dominant challenge is compact three-degree-of-freedom packaging in a confined envelope. Three independent axes (pitch, yaw, roll) must fit into a structure small enough to connect arm to hand without compromising form factor or weight budget.

Multi-axis packaging creates both assembly complexity and thermal burden. Several actuators in close proximity share a thermal environment, and a motor accumulates heat even while holding a static position. This makes validating performance in a tightly integrated multi-axis layout significantly harder than validating a single-motor joint.

Architecture priorities: Compact motor-gearbox combinations sized for the three-axis envelope and lead screws where self-locking position hold without continuous power is needed.

Scale implication: Miniaturization raises assembly complexity and validation burden. Prototype-feasible designs often require significant design for manufacturability.

Demand	Specification
Torque	5-20 Nm
Speed	120-300 rpm
Package Weight	0.2-0.5 kg
Primary Challenge	Compact 3-DOF packaging

Source: IDTechEx Humanoid Robots 2025–2035



Hand and Fingers

Demand	Specification
Torque	0.1-2 Nm
Speed	200-500 rpm
Total Hand Weight	<500 g
Degrees of Freedom	15-20
Finger Actuator Diameter	<8 mm

Source: IDTechEx Humanoid Robots 2025–2035

This zone is where miniaturization reaches its practical limit. Motors must deliver sufficient torque within extremely small outer diameters (OD), making torque density and packaging critical design constraints. And unlike other humanoid zones, there is no single validated hardware precedent to follow. Designs that solve the packaging challenge may still face unknown failure modes under sustained use, making the choice of actuation architecture especially critical.

There are three primary approaches to evaluate:



Knuckle Actuation

Typically, three motors per finger located at the knuckle with direct drive.

Benefit: Simplest actuation approach with the fewest mechanical parts.

Design Considerations: Limited space for torque-dense motors can result in larger, heavier hands. Motor OD must remain below 20 mm.



Palm Actuation

Two to three motors per finger packaged within the palm.

Benefit: Enables smaller, lighter hands and leverages more existing motor technology.

Design Considerations: Palm space can limit dexterity. Motor OD drops to 8–12 mm, with screw actuation likely required.



Forearm Actuation

Motors in the forearm drive the fingers through tendons using ball screws or flexible cables.

Benefit: Provides maximum dexterity and room for larger, more powerful actuators.

Design Considerations: Tendon routing adds friction and development complexity. Typical motion requirements include 16–19 mm OD high-torque frameless motors and linear ball screws.

Scale implication: Every custom element in a 20-degree-of-freedom hand multiplies validation burden and supply chain exposure. The custom vs. off-the-shelf decision is more critical here than anywhere else on the robot.



Ankles

The ankle is frequently underestimated in legged humanoids. It absorbs footfall shock and generates push-off force in a high-cycle, high-impact environment with thousands of ground contact events per hour in deployment.

Architecture priorities: Motor-gearbox combinations sized for shock loads, and ball or roller screws for push-off and ground reaction. Account for impact loading from the first structural iteration.

Scale implication: Ten-thousand-cycle reliability testing is a minimum before design freeze, and field conditions may be more demanding.

Wheeled Mobility as a Deployment Strategy

Many OEMs are deploying upper-body humanoids on wheeled platforms today while legged locomotion matures. Wheeled platforms allow OEMs to generate revenue and gather deployment data now, while the legged locomotion stack develops. For example, purpose-built AGV solutions provide a production-ready foundation for this staged strategy.

Demand	Specification
Torque	50-150 Nm
Speed	30-90 rpm
Package Weight	0.5-1.2 kg
Primary Challenge	Impact resistance + precision

Source: IDTechEx Humanoid Robots 2025–2035

	Wheels	Legged
Time to Deploy	Weeks	Months-Years
Payload	50-200 kg	10-50 kg
Stability Risk	Low	High
Terrain Flexibility	Flat Surfaces	All Surfaces
Safety Certification	Established	Emerging

Source: IDTechEx Humanoid Robots 2025–2035

Designing for scale

A prototype that works doesn't always equal a product that ships. These are disciplines that can help close the gap.

Modular Joint-module Architecture

The industry is converging on integrated joint modules. Frameless motor, precision reducer, torque sensor, absolute encoder, safety power-off brake and motor drive electronics are all in a single package. This eliminates integration variability, simplifies assembly, optimizes length & weight and creates a repeatable building block that scales predictably.

Those who design around modular principles from the start compress pre-production validation. Those who defer modularity face significant rework.

Km Over Nameplate Ratings

Humanoid joints don't run at constant speed. They need rapid bidirectional torque bursts. Which is why nameplate ratings can understate what the joint actually demands. It's better to look at the motor constant ($Km = Kt(dc) / \sqrt{Rm,l-l}$). Higher Km per unit mass means more torque per unit of heat—or a better actuator fit.

You'll also want to factor in thermal margin. As winding temperature rises, effective Km falls. By prioritizing Km and thermal margin, you ensure no performance loss from lab to field.

Thermal Margin: Design to System Limits

Class F insulation may be rated to 155°C, but the motor insulation rating isn't the limiting factor in an integrated humanoid joint. Lubricants, bearings, encoders and electronics can have much lower thermal limits. Heat can also migrate to the robot's outer surface, creating additional concerns in human-proximity operation.

The design rule is to target a maximum winding temperature of 85°C under full continuous load, with design solutions reaching as low as 70°C for specific applications. This preserves the motor constant (Km), protects every component in the joint package, and keeps external surface temperatures within safe operating limits.

Integrated Braking & Functional Safety

A built-on, safety-rated brake can be co-designed and embedded with motion components to support higher levels of functional safety and compliance with ISO 13849, while minimizing the weight, size and heating impact.

Spring-applied brake technology also eliminates unnecessary thermal buildup during extended standstill and hold periods, creating an opportunity to lower overall joint temperature.

As humanoid designs advance, functional safety requirements will continue to increase, particularly on the highest payload axes with high-torque joints at hip, knee, shoulder and elbow.



Safety From the First Iteration

Fenceless operation near people is a baseline requirement that must be built into every motion component from day one.

Proactive Safeguards:

- Torque limiting (current control + clutch)
- Collision response: <50 ms
- Dynamic speed monitoring zones
- Real-time force feedback

Fail- Safe Architecture:

- Power-off brakes: <100 ms engagement
- Redundant dual absolute encoders
- SIL-2/SIL-3 readiness
- No single-point failure modes

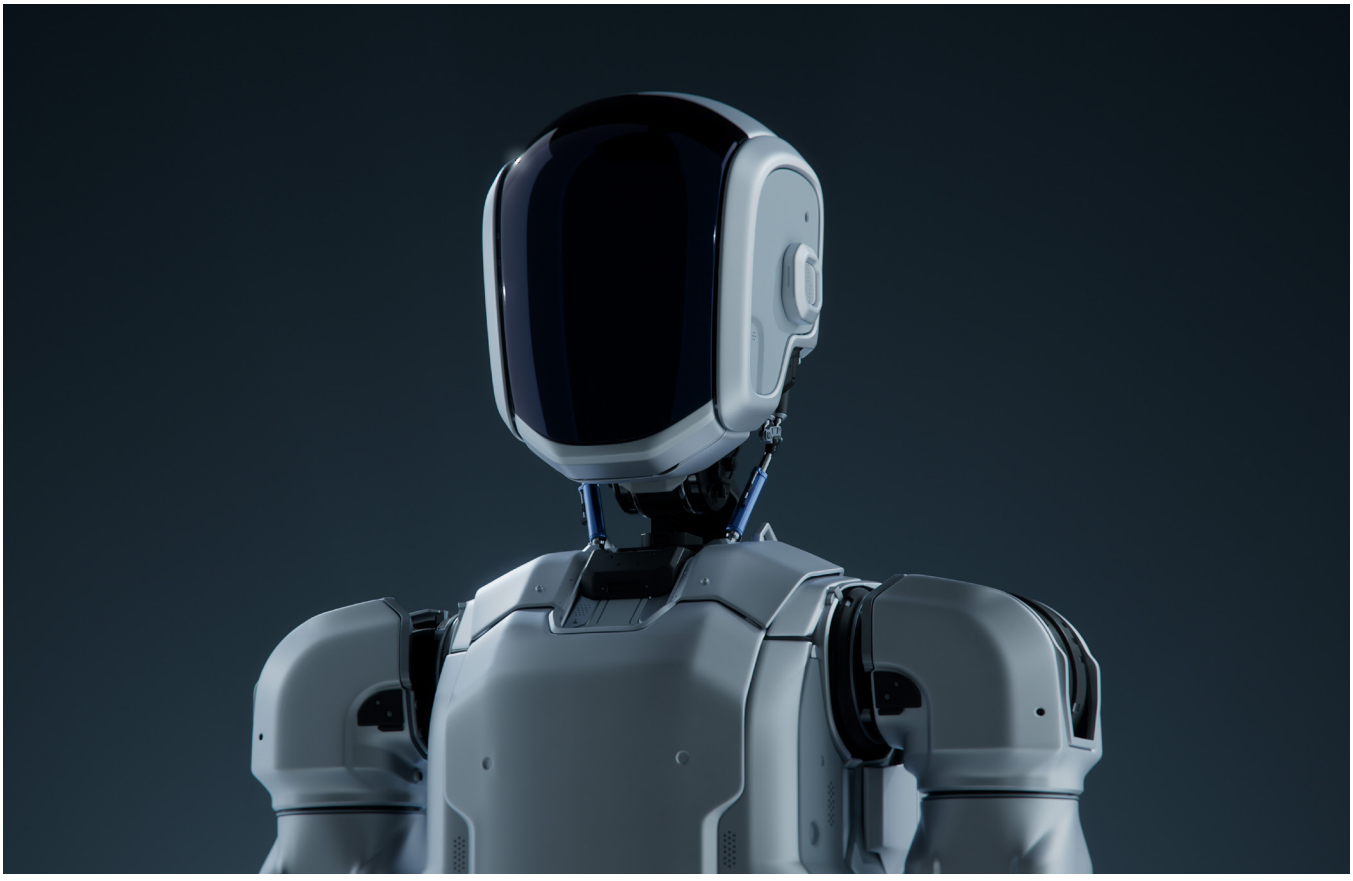
The governing standards are ISO 10218-1, ISO/TS 15066 and ISO 13849. ISO 25785-1 (dynamically stable mobile robots including legged humanoids) is in committee draft under ISO/TC 299, with full publication expected in 2028. Designing to that standard now is far less disruptive than retrofitting compliance after design freeze.

Test and Validation Rigor

Getting a prototype to work once and getting a design to work across thousands of units under production conditions are different skills. Volume production requires:

- Repeatable assembly methods that do not depend on individual technician judgment
- Reliability testing to 10,000+ cycles before design freeze
- Failure mode analysis accounting for manufacturing variation
- Cost modeling based on production-scale sourcing

Most programs stall between design optimization and pre-production validation because the validation burden exceeds internal capacity. A motion partner with production-scale experience can carry that burden and identify failure modes before they reach the production line.



What to look for in a motion partner

> **Navigating the transition from prototype to production requires a specific kind of motion partner. While startups struggle to scale beyond hundreds of actuators, contract manufacturers typically require volumes of 100,000 units. Many humanoid programs operate between these production scales.**

If you're evaluating motion partners, consider those who can close every single gap between what you need and a production-ready solution. Here are some of the key differentiators to look for:

- **Rapid prototyping and iteration.** With annual platform refresh cycles, turnaround must be measured in weeks. A partner must absorb repeated design changes without treating each one as a new program.
- **Zone coverage.** Solutions must span every body zone without requiring a different supplier for each. Fragmented sourcing multiplies risk and slows iteration.
- **Component breadth.** Frameless motors for primary joints. Miniature motors for wrist and finger actuation. Precision gearing, ball and roller screws, lead screws, and integrated electromagnetic brakes. All from one source.
- **Collaborative support.** Fast sample turns, responsiveness to design changes, domain knowledge across the full kinematic chain, and the ability to translate ambitious concepts into manufacturable assemblies.
- **Full-arc support.** From custom samples through pre-production validation to volume production, without a supplier transition at any stage.

The Regal Rexnord advantage. Our family of brands works together as a single motion partner to deliver a full-spectrum motion portfolio and integrated solutions for humanoid development. From co-engineering and a proven process to ISO-certified manufacturing worldwide, we know how to bridge the gap between robotics research and production engineering. And we have done so for hundreds of thousands of robot joints across humanoid, surgical, collaborative, and industrial applications.

Engage early and scale with confidence

Humanoid robotics is advancing what motion components can do, and that progress is cascading into every adjacent robotics category. The programs that reach production are the ones that work with the right motion partner to treat architecture as a first-order design decision. As you look to scale, remember these three takeaways.

1. **Evaluate requirements by zone.** Map torque, speed, weight and safety for each zone before selecting components.
2. **Make smarter architecture tradeoffs.** No single technology wins everywhere.
3. **Design for scale from day one.** Modular sub-assemblies, thermal discipline, and validation rigor bridge the gap between lab and line.

Ready to take the next step?

Contact Kollmorgen to discuss your needs and goals with a motion expert for humanoid and robotic applications.

About Kollmorgen

Kollmorgen, a Regal Rexnord Brand, has more than 100 years of motion experience, proven in the industry's highest-performing, most reliable motors, drives, AGV control solutions and automation platforms. We deliver breakthrough solutions that are unmatched in performance, reliability and ease of use, giving machine builders an irrefutable marketplace advantage.

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