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WHITE PAPER

Building Humanoid Robots: From Design to Delivery

The human body is a marvel, from its ability to traverse practically any terrain, to the acuity and depth of its binocular vision, to its touch and dexterity in handling objects and using tools. Environments built by and for humans are designed to make the most of these capabilities.

Such environments are common in even the most advanced manufacturing, warehousing and other industrial settings. Despite the high degree of automation, a human workforce is still required to fill the gaps between multiple fixed automation systems, each designed to accomplish a specific purpose. Human-centric tasks, which often vary from day to day, require flexible and autonomous motion to bridge automated processes and ensure the continuity and performance of the total operation.

The problem is that human strength and endurance are limited. Workers in these roles can be injured. Turnover in arduous and sometimes dangerous jobs is high. As a result, gaps can open up in the workforce, severely disrupting supply and production.

The requisite human-centric tasks can't be performed by adding more single-purpose machines without great expense and extensive modifications to the factory or warehouse. But these tasks are ideal applications for humanoid robots — eliminating concerns over labor shortages while freeing actual humans from drudgery and potential danger, so they can fill more creative roles.

That's why humanoid robots — formerly associated with science fiction fantasies and theme-park animatronics — have become a vital field of research and development. In just the past 10 years, humanoid technology has advanced to the point where many academic teams, startup companies and established firms are developing humanoids that promise to transform workplaces while taking people out of harm's way.

The ongoing revolution in humanoid capabilities is being driven by advancements in vision systems, tactile and proprioceptive sensors, battery power density, artificial intelligence algorithms, processing speed and other technologies. The bottom line, however, is always motion. If a robot's limbs can't respond to the system's sensory inputs and motion commands with speed, power, precision and even grace, then it can't perform its job satisfactorily. Advancements in motors and motor-driven actuators are core to the ongoing revolution in human-centric robotic designs.

Humanoid motion challenges are both technical and commercial

In the rapidly expanding field of humanoid robots, engineers are under pressure to quickly develop designs that can deliver new capabilities — while maintaining affordability — in advance of potential competitors. In this development environment, everything depends on quick design and iteration to arrive at a successful prototype. But it is at this prototyping stage that the true scope of the motion challenges involved becomes evident.

Designing a robot with optimal motion performance is demanding enough. Designing it in a way that is highly manufacturable adds another dimension to the challenge. The project is at risk when design teams fail to reconcile performance with marketability. A successful prototype must address both technical and commercial considerations from the start.

From a technical viewpoint, motion products that aren't designed specifically for robotic motion may be too large, too heavy and poorly suited to the kinematic requirements of performing human-like tasks at a human scale. For example, designers may be tempted to specify widely available motors that were originally designed for use in drones. But these motors are designed to operate at comparatively high rpm and can't deliver the consistent torque across the full speed range required for humanoid arm and leg joints.

From a commercial point of view, designing for manufacturability and marketability is critical from the outset. A motor that provides an approximate fit at a low price can help design engineers meet tight timelines and budgets. However, if the robot performs suboptimally, and if an affordable off-the-shelf motor isn't manufactured with consistent quality and backed by effective technical support, then a bargain in the design phase becomes a liability at market.

On the other hand, a high-quality custom solution increases risk because it substantially increases costs and may not be scalable to volume production.

These performance and market risks aren't inevitable, however. Technical and commercial challenges may seem to be in opposition, but they can both be solved by means of an optimized development strategy that specifies motion products based on both performance and manufacturability requirements.

Start with a system-level motion strategy

Motion decisions should take the overall system into account. At the performance levels required for humanoid motion, a motor is not just a motor. It must be optimized for form, weight and highly specific performance characteristics, including the ability to respond to the dynamic acceleration bursts required of a humanoid robot joint while operating with greatest efficiency. And, as we've discussed, it must meet those criteria while maintaining the affordability and manufacturability of a commercial off-the-shelf solution.

To achieve the ideal motor specification, begin by understanding and documenting the application requirements of each robotic joint, including the full dynamic torque and speed range, the breadth of inertial loads likely to be encountered in operation, and any targets for weight and installation footprint.

Once you understand the dynamic requirements of each joint, begin the joint design not by specifying the motor, but by specifying the mechanical system — whether a rotary or linear actuating joint — and the gear box architecture. These specifications will determine how you pair the right motor with your gear system.

For example, think about the potential effects of compliance and backlash in the gearing. The slight imprecision that might be acceptable in an industrial automation application might be problematic in a humanoid robot that is expected to keep its balance while performing extremely delicate and powerful tasks. Or consider that even the most capable humanoid can be expected to bump into things or fall down in a dynamic world, just like a live human does. Your selected gearing needs to be able to withstand these unpredictable forces and loads.

A thorough discussion of gearing types is beyond the scope of this paper. However, we will note that rotary joints are the most common type in humanoid robots, combined in ways that replicate the motion of ankles, knees, hips, shoulders, elbows, wrists and so on. Harmonic gearing, also known as strain wave gearing, serves the requirements of these rotary joints exceptionally well.

Harmonic gearing offers:

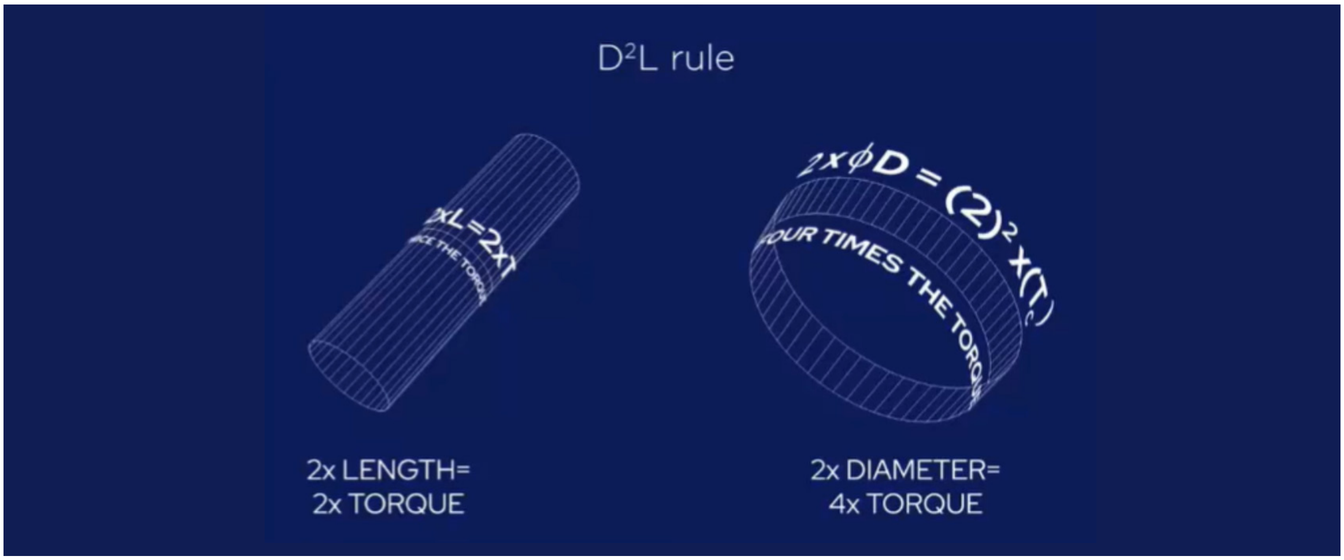
- High reduction ratios in a single stage for high power density and smooth acceleration/deceleration.
- Zero backlash for accurate positioning and reliable holding.
- The most axially compact form factor, enabling a compact and agile robot design.
- Reliability and resilience when encountering impact loads.
- Availability in commercial off-the-shelf products appropriate for use in robotic joints.

Gear Type	Torque/Force	Backlash	Weight	Efficiency	Cost
Planetary	Neutral	Negative	Neutral	Positive	Positive
Harmonic	Positive	Positive	Positive	Negative	Negative
Cycloidal	Positive	Neutral	Negative	Neutral	Negative
Ball Screw	Positive	Neutral	Positive	Neutral	Positive

Gear reducer types and their relative attributes

When selecting harmonic gearing, consider whether a relatively larger outer-diameter gear set could meet your design requirements. Increasing the diameter allows you to use a larger-diameter motor, enabling you to take advantage of the D^2L rule. This rule states that torque increases in direct proportion to an increase in motor lamination stack length — or, alternatively, as the square of an increase in moment arm diameter.

In other words, doubling the diameter of the moment arm produces a fourfold increase in torque — or, alternatively, allows the stack length to be reduced by three-fourths with no loss of torque. The D^2L rule offers a simple way to maximize the torque of each joint. Also, in many designs, reducing the axial length of a robotic joint allows for a more agile robot with more clearance to work in tight spaces and in close proximity to objects in the world around it.



Design for manufacturability and marketability at scale

Once you have designed a joint architecture that makes sense, the next step is to evaluate whether the components of that architecture can scale up to full production of a robot that your intended market will embrace. Ask yourself whether your design is solid enough to scale and whether the components you have selected will be easily available, functionally optimal and mechanically reliable when you transition from prototype to full-scale production.

At Kollmorgen, we have seen many instances of prototypes that were created under time or budgetary constraints, with design expedience or product pricing as leading selection criteria. When the results are a joint design that is too large, too heavy and subpar in performance, the result is even more time and money spent on redoing the design to get it right — or even abandoning the project altogether. The worst result is to forge ahead with productizing the design at great expense, only to face rejection in the marketplace.

We strongly believe in the short- and long-term value of getting the design right from the beginning, so you can go to market faster with a better, more profitable product. For many companies, this requires changing a mindset that segregates R&D from production. In reality, success requires placing R&D and production on a continuum of shared goals, resources and processes.

Operational excellence — in addition to functional design — should be built into the prototyping process. From the inception of your project, consider how the design will evolve and scale up from prototype to field testing, to low-rate initial production, and then to full-rate production. That way, you can avoid delays, setbacks or even the need for a total redesign.

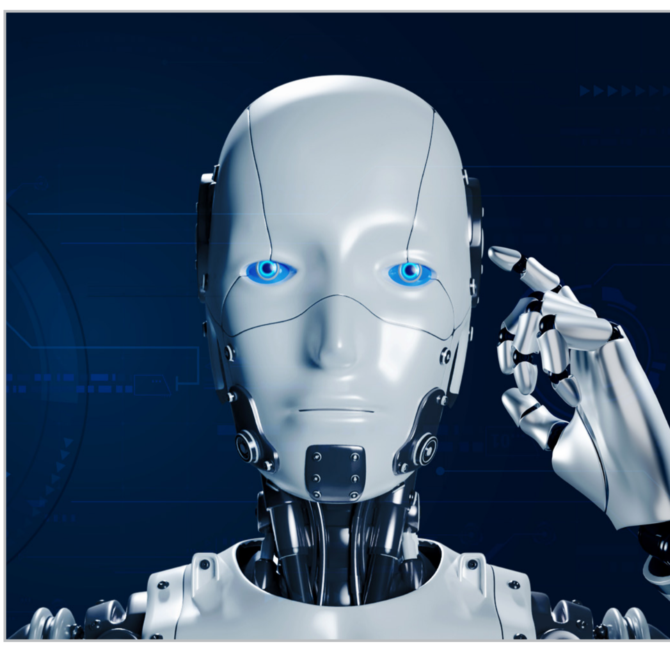
With regard to selecting, sizing and configuring motors, this means taking into account several factors in addition to speed, torque and power characteristics, for example:

- The loading characteristics of the gearing system in the highly variable environments that humanoid robots operate in, and the performance requirements placed on the motor.
- The distance between the motor, gearbox and other components of the joint.
- Ambient operating temperatures, the motor's thermal rise and any provisions for heat dissipation.
- How excess heat might affect motor performance or nearby components such as gearing lubricants and feedback electronics.
- The manufacturing sequence in terms of where cables run, how feedback devices are installed, how adhesives are distributed and so on.

These and many other factors are critically important when engineering a prototype that incorporates the principles of design for manufacturability (DFM). Kollmorgen has always worked with DFM in mind, both in our own motion system design and manufacturing as well as in engineering collaborations with our customers to help optimize their projects for DFM.

We have hundreds of years of collective experience and have worked with thousands of customer applications, helping optimize motors for the application's performance requirements as well as manufacturability. Our proven processes include collaboration from initial design, through prototyping and iterative design, to final design reviews and full production scaling, giving customers confidence in a project that stays on track from beginning to end.

Plus, we deliver motion products of identical specification and quality year after year — even as we continually innovate to meet the needs of an ever-evolving market. Our goal is always to provide optimally performing products for new development initiatives while also ensuring consistent access to the products needed for full production and aftermarket service requirements.



Multiple industry leaders in humanoid robotics have proven our processes, capabilities and products for themselves by visiting our production plants in order to conduct their own audits. With each visit, Kollmorgen has exceeded expectations.

Incorporate kollmorgen frameless technology

Mechanical systems are infinitely varied, and motion products are not created equally. Kollmorgen is dedicated to delivering the largest selection of robot-ready motors, in a wide range of sizes, with cost-effective standard and custom modifications that meet the precise performance requirements of each application without sacrificing manufacturability.

Kollmorgen's commitment and specialty is to deliver reliable performance in the highest-quality motors plus reliable manufacturability at any scale.

For example, two of the most important requirements are to minimize power consumption, since humanoid robots typically operate autonomously on battery power, and to optimize torque, since they must carry their own weight while performing tasks applying human or even superhuman strength with extreme accuracy.

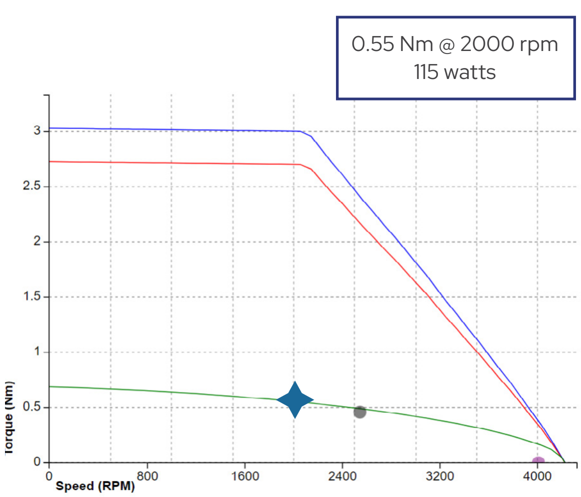
Kollmorgen offers frameless motors specifically designed for the requirements of robotic joints. They are compact, lightweight and energy-efficient — including the option to fine-tune winding characteristics for maximum efficiency in each application's specific torque and speed ranges.

These characteristics help robotics engineers minimize size, weight and energy consumption by delivering optimum torque in smaller, lighter motors. Lightweight joints allow for better weight distribution that improves robot balance and stability. Axially smaller joints enable greater robotic arm dexterity while reducing the risk of impact with structures and objects. Energy efficiency allows for longer operating times between battery charges.

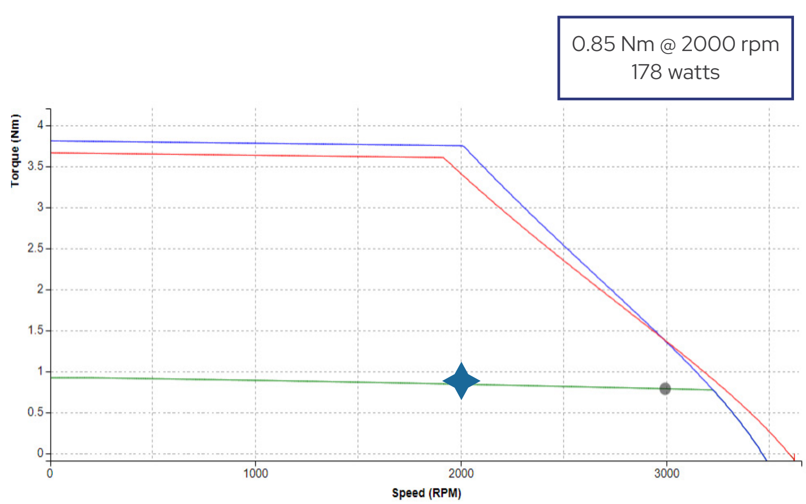
Consider, for example, Kollmorgen's TMB2G series of frameless servo motors, engineered specifically to meet the form-factor, energy consumption and performance requirements of robotic joints. They are designed to fit the dimensional, torque and speed requirements of standard harmonic gearing to enable the most compact and precise robotic joints without the expense of specifying custom gearing.

TBM2G motors take advantage of the D^2L rule to deliver full performance in the most lightweight, axially compact joints. This design also allows for a large thru-bore to accommodate wiring and other components that pass through the joints of the robot arm. These motors work with a wide range of encoders and can even be supplied with integrated Hall sensors that don't increase motor length.

With an exceptionally low thermal rise, TBM2G motors can operate in close proximity to temperature-sensitive components with no performance compromise. For example, the 155°C maximum winding temperature of a motor with Class F insulation equates to a nominal 140°C in close proximity to encoder and gearing components. But TBM2G motors can deliver exceptional performance without exceeding 85°C, greatly improving the reliability and lifetime of robotic joints.



Typical motor performance at 25°C ambient and a maximum winding temp of 85°C



TBM2G Motor performance at 25°C ambient and a maximum winding temp of 85°C

Kollmorgen's powerful Performance Curve Generator, one of several self-service online design tools available on the Kollmorgen website, was used to create the motor analyses shown in the charts. As you can see, the TBM2G motor provides exceptional performance while running at a winding temperature of 85°C. In order to achieve comparable performance, virtually every other available frameless servo motor must run much hotter, typically at a maximum winding temperature of 155°C.

This is a major problem for tightly integrated robotic joints. As the winding temperature climbs above 85°C, gearing lubricant quickly degrades and electronic feedback devices can become unreliable. Conversely, if a motor designed for optimum performance at 155°C is operated at a maximum winding temperature of 85°C, its performance suffers substantially. TBM2G is the only frameless servo motor on the market designed to deliver superior performance within the real-world temperature limitations of a robotic joint.

TBM2G servo motors also offer robot designers the ability to right-size each motor for each joint. Unlike the two or three frame sizes usually offered with typical servo motors, TBM2G motors are available in seven frame sizes, each with three stack lengths, and a range of standard options for an ideal application fit. A choice of winding variations optimizes motor performance at various bus voltages, including windings that are ideal for battery-operated humanoid robots.

The TBM2G series is built to the highest standards of quality, with the manufacturability, delivery and support you need to take your humanoid robot from prototype to full-scale production at any volume, anywhere in the world.

Your motion partner matters

The TBM2G frameless servo motor series is just one example of Kollmorgen's commitment to superior robotics. Our TBM and RBE frameless motors, along with several other products, fill a wide range of motion requirements for the diverse and rapidly growing field of humanoid as well as other robotic designs.

Just as important, our engineering team has vast robotics experience. We can help collaboratively engineer the optimum motion solution to bring your robot's unique capabilities to life. With our lean manufacturing, repeatable processes and quality controls, we'll help you quickly transition from prototype to full-rate production, with motion systems delivered on time, every time. And we'll provide long-term support, in-region/for-region, to sustain product delivery throughout the lifecycle of your robot, managing costs while scaling production as needed.

Contact us to discuss your needs and goals with a Kollmorgen robotics expert.

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.