Beyond Motors: Gearboxes as the Unsung Heroes in Robotics and Heavy-Duty Machines

Pablo López García

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As the trend towards electrification and the establishment of modern robotics technology continue to advance at an unprecedented pace, a new paradigm is emerging in the world of machinery. Modern robots and machines are no longer just tools; they are becoming intelligent, efficient, and adaptive systems that redefine how we interact with machines in our daily lives. This shift is not only changing industries from manufacturing to construction but is also paving the way for smarter, more sustainable, and useful mechanical solutions.

Movement is pivotal to any machine, as it is the primary means by which a machine interacts with and influences the physical world, enabling it to perform useful work. This movement is driven by actuators, which convert energy into mechanical motion, serving as the critical components that determine the machine's overall performance. Whether it's precision, speed, or power, the ability to control and optimize movement is what defines a machine's effectiveness and its ability to accomplish complex tasks.

Central to this paradigm shift in modern machinery is the actuator—a critical component that powers these machines, ensuring their reliability, torque, and precision. In this era of electrified machinery and autonomous robotics, the actuator choice plays a pivotal role in reshaping the future of how machines operate.

Modern Robotics: Machine Versus Human Movement

In recent years, the development of advanced, human-centric robotic systems—such as collaborative robotic manipulators, bionic prostheses that restore limb functionality, injury-preventing exoskeletons, and humanoid robots used in industrial and service sectors—has substantially accelerated. These innovations hold great potential to revolutionize multiple industries by augmenting human abilities and taking over monotonous, hazardous, or physically demanding tasks. Yet, despite these advancements, robotics still faces significant hurdles in realizing its full potential for societal impact.

While progress in cognitive systems and AI is a critical bottleneck, the field also grapples with a fundamental hardware challenge, as highlighted by Tesla's development of its first humanoid robot, Optimus. The issue is straightforward: as engineers incorporate all the necessary components for a robot's functionality, the resulting system becomes excessively heavy. This high mass limits speed and reduces productivity, and it increases the energy required for movement. A key contributor to this weight problem is the actuators—typically around 30 in a humanoid robot—comprising an electric motor, gearbox, and control circuit with sensors.

As an engineer with a background in the automotive industry, I was intrigued by this issue when I transitioned into robotics a decade ago. My previous experience had shown me the sophistication of actuation technologies in other fields, which made this challenge in robotics surprising. However, working with the highly experienced Brubotics team of the Vrije Universiteit Brussel, I quickly realized the unique demands of robotic actuation and became passionate about finding innovative solutions to overcome these limitations.

Robotic devices—such as cobots, exoskeletons, prostheses, and humanoids—are designed to operate in environments that are shared with humans. These settings are often unpredictable, making human-centric movement a crucial requirement. At Brubotics, our research during over three decades has shown that robots safely interacting with humans must move in a compliant and predictable manner that should be quite close to human motion. This distinguishes modern robots from traditional machines, which generally follow more rigid movement patterns, conditioned by the extreme position accuracy requirements of these devices.

However, replicating human movement in a machine is a complex engineering challenge. While humans may initially not be considered top performers in movement compared to some animals or to modern machinery like helicopters or CNC machines, engineering human-like movement is incredibly difficult. One major challenge is replicating the high specific torque that the human body produces. For instance, when jumping, each ankle generates torques over 400 Nm (Ref. 1)—comparable to a Formula 1 engine at each foot! Our joints, such as hips, shoulders, and elbows, deliver impressive torque relative to their size.

Beyond torque, speed is also a factor. Human joints typically move at under 100 rpm, whereas electric motors and engines can easily exceed 15,000 rpm. This contrast highlights that the challenge in replicating human movement isn't about moving fast—it's about creating lightweight systems capable of high torque.

This concept, known as torque density (or more precisely, torque-over-weight), is central to what is currently known as the hardware problem of modern robotics. Even with cutting-edge technology, electric motors are still about ten times heavier than human joints with comparable torque output. This weight problem makes building robots that move like humans extremely challenging. Interestingly, most videos showing collaborative robots at work are sped up by 5 to 10 times; otherwise, their slow movements would be tedious to watch for more than a couple of seconds.

Heavy-Duty Machines

A machine that moves surprisingly close to humans, albeit at a different scale, are excavators and other off-road, heavy-duty machinery. These machines can achieve extremely high torque densities while moving at moderate speeds. At a certain point, I began using this example to visually explain the hardware problem in modern robotics: humans move more like excavators than electric motors.

To build these off-road machines capable of delivering very high torque densities at moderate speeds, a combustion engine is often combined with a hydraulic actuation system. In the past, cable and pulley systems were used to actuate these machines, but due to reliability and cost issues, they were largely replaced by hydraulics over 70 years ago.

It should thus come as no surprise that hydraulics and cable-pulley systems have been intensively explored as well in modern robotics over the last few decades to achieve the high torque densities required. The amazing (former) ATLAS robot from Boston Dynamics, a pinnacle of human-like movement performance in modern robotics, uses hydraulic actuators. The use of cable-pulley actuation systems, often termed 'remote actuation' in modern robotics (Ref. 2), involves locating the actual prime mover remotely from the actuated joint and using a cable or flexible shaft to transfer the movement. Many exoskeletons, robotic hands, and lightweight robotic manipulators developed in recent decades have employed these solutions (Refs. 3,4,5).

Interestingly, Boston Dynamics' largest commercial success is not ATLAS but SPOT, a highly versatile, four-legged robot that can also incorporate a robotic arm on its back. SPOT's joints use electric motors and gearboxes instead of hydraulic actuators. Additionally, the new ATLAS generation recently presented by Boston Dynamics has transitioned from hydraulic actuation to using electric motors and gearboxes, like other prominent humanoid robots such as Tesla's OPTIMUS, Figure's 01, or Apptronik's APOLLO. These

Human-centric robots vs. excavators.

robots achieve acceptable torque density using electric motors by means of employing an actuation strategy fine-tuned by collaborative robots (cobots) over the past decade: the use of high-ratio gearboxes.

On a larger scale, in off-road machinery, there is a noticeable and increasing parallel trend towards electrification. The shift in this case is primarily driven by efficiency gains and maintenance advantages of electric actuation compared to the combination of combustion engines and hydraulics traditionally used in this industry. The off-road industry is heavily investing in finding solutions to replace engines and hydraulics with electric motors and gearboxes. However, the high torque-densities required in this sector make the transition to electrification extremely challenging. Currently, although some battery-driven electric systems can be found already in the market, powering smaller off-road machines (Ref. 6), combustion engines and hydraulics remain the predominant choice for larger machines (Ref. 7). As a result, the electrification of off-road machines significantly lags behind other sectors such as passenger cars.

Gearboxes in Robotics

As noted by the famous MIT's Robotics Professor Sangbae Kim, the father of a Cheetah robot that can run faster than its animal equivalent, *"gearboxes are where the problem starts..."* in modern robotics.

High-ratio gearboxes add complexity, weight, losses, non-linearities, backlash, and other challenges to robotic systems. Nevertheless, they are essential for compensating for the low torque densities of electric motors. High-ratio gearboxes (typically over 100:1) allow small, lightweight motors to deliver high torques by trading speed for torque. The strain-wave gearbox, known for low backlash and high-ratio capabilities, has a clear advantage from the control perspective that makes it today the dominant gearbox technology in modern robotics.

Despite their advantages, strain-wave gearboxes have their own problems. This explains on the one side Prof. Sangbae's view of gearboxes at the core of the hardware problem of modern robotics, and on the other side the extensive and active research on high-ratio gearboxes during the few last years, that contrasts with decades of relative calm in this domain. Innovative gearbox technologies are continually being developed at the present, to try to address the challenges in modern robotics.

Cycloidal gearboxes, another promising technology, offer high torque density and robustness. They are particularly suitable for industrial robots and heavy-duty machinery. Cycloidal gearboxes can handle high shock loads, making them ideal for applications in rough conditions where minimizing machine downtime is vital.

Planetary gearboxes, commonly used in automotive and industrial applications, are also being adapted for robotics. These gearboxes provide high efficiency, compactness, and the ability to handle high torques. Advanced manufacturing techniques and materials have further enhanced their performance, making them a viable option for robotic applications where positioning accuracy is not pivotal.

Other disruptive gearbox technologies have also been recently developed and are discussed in more detail in our publication (Ref. 8).

Gearboxes in Off-Road Machinery Electrification

Comparing the challenges of off-road machinery electrification and modern robotics reveals striking similarities. Excavators and collaborative robotic manipulators provide a representative example: both are basically self-carrying manipulators that

- have an own weight that is an order of magnitude larger than their payload
- need to operate in highly unstructured environments
- require actuators with extremely large torque densities
- are often subject to unexpected impacts
- have duty cycles involving large uptimes and variable operating conditions that make particularly challenging achieve energy efficiencies compatible with battery power
- have non-linear torque-angle movement characteristics
- require moderate position accuracies
- require moderate power densities
- are (or will be, in the case of robotic manipulators) highly mobile
- show a high value potential related to the exploitation of energy regeneration

From this analysis, it becomes apparent that gearboxes are predetermined to play a pivotal role in the electrification of heavy-duty machinery, just like for human-centric, modern actuation. Suitable gearboxes for off-road vehicles need large gear ratios, compact designs, good efficiency, and the ability to handle higher power densities. Cooling and lubrication solutions are essential here, due to the higher powers involved.

Conclusion

Our analysis suggests a promising role for high-ratio gearboxes along the path towards electric actuation in off-road machinery and modern robotics. In heavy-duty machines, high-voltage, high-speed electric motors achieving power densities beyond 2.5 kW/kg can be combined with high-ratio planetary and cycloidal gearboxes. These gearboxes incorporate two degrees of freedom that can be used to combine the input from two different electric motors (Dual-Motor actuation) [9] that is like the split principle used by some hybrid vehicles.

This provides a versatile solution that can cope with operating conditions both in robotics and heavy-duty machines, involving frequent, maintained operation at substantially different torque and speed ranges. Gearbox backdrivability will also play a crucial role in enabling energy recuperation, reducing battery size requirements, while the optimization of cooling and lubrication systems will be fundamental in making these solutions viable alternatives to hydraulic-based actuation for achieving large torque densities.

The future of heavy-duty machinery and modern robotics lies in the successful integration of advanced gearbox technologies and electric motors. By addressing the challenges of torque density, efficiency, and power management, these innovations will drive the transition to more efficient and sustainable machines.

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Pablo López García was born in Asturias, Spain, in 1972. He obtained a master´s degree in industrial engineering with the Escuela Técnica Superior de Ingeniería Industrial de Gijón, Spain, in 1998. He completed a doctorate with the Brubotics research institute of the Vrije Universiteit Brussel (Belgium) on the potential of planetary gear transmissions in human-robot interaction, in 2022.

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