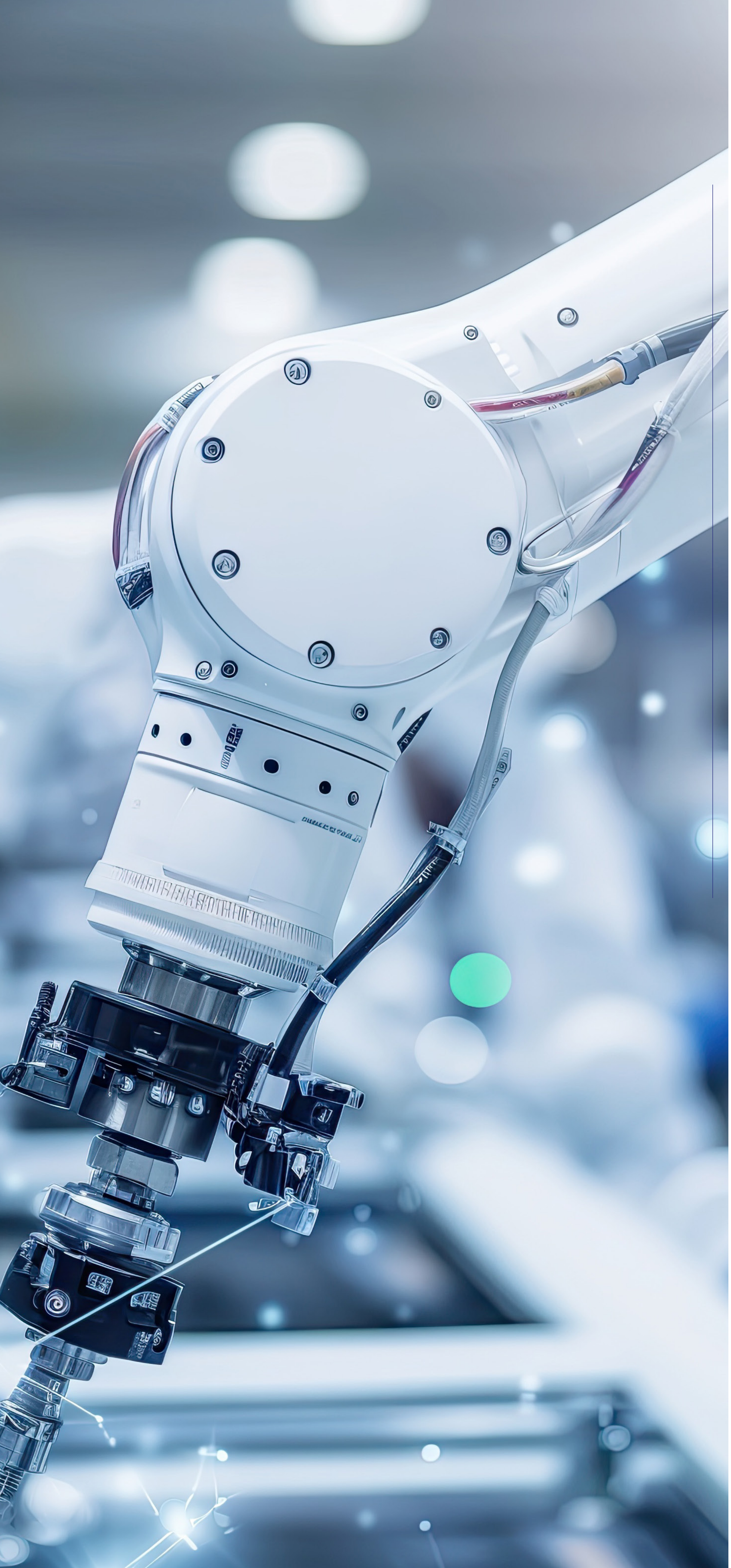


American Gear Manufacturers Association®

AGMA Robotics Committee

WHITE PAPER:

Gear Backlash in Robotics Applications

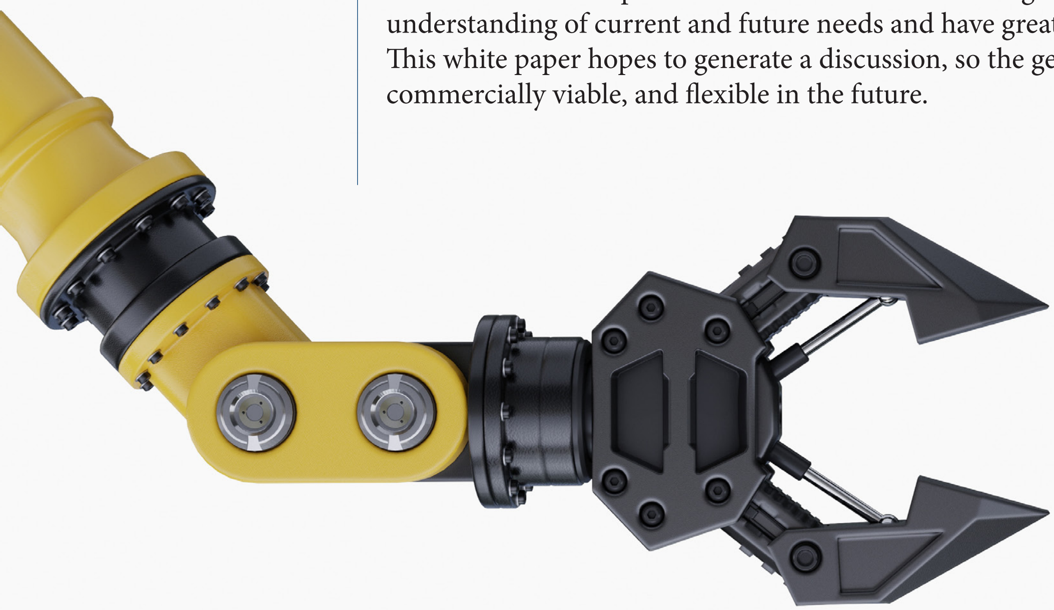
The search for flexibility, performance, and economical systems

Introduction

Recent headlines at technology conferences confirm that quantum computing with Artificial Intelligence (AI), biotechnology, nanotechnology, and robotics have the potential to reshape the world for the second quarter of the 21st century. This is certainly good news for gear manufacturers and allows them to be at the forefront of the technological history trajectory, as robots' joints and handling apparatus are made of motors, actuators, controllers, sensors, and gear drives. According to the International Federation of Robotics (ref. 1), in 2023, the industrial robot market is expected to grow by 7% to more than 590,000 units worldwide. During the recent RoboBusiness Conference (ref. 8) industry experts agreed that over the next 10-15 years, personal and collaborative robots (cobots) will exceed the industrial robot market and become common in homes, aiding with tasks such as cleaning, cooking, and caring for children or the elderly. These robots will be equipped with advanced artificial intelligence, allowing them to perform a wide range of tasks and provide personalized assistance to individuals. The annual production rate of 10 to 30 million robots per year is in the realm of possibility, and ramping up capacity to meet this exponential demand is a priority for US gear manufacturer leaders. Robert Kufner, President/CEO at Designatronics, mentioned that, "At Designatronics, investing in automated high performance machining centers and industry 4.0 with the integration of intelligent digital technologies into manufacturing and industrial processes would be key to meet the future gear demand for robotics." We also reached out to Denis Rancourt, Professor in Bio-Mechanical Engineering at Sherbrooke University in Quebec to learn more about future humanoid robots and exoskeletons and seek ideas for areas of potential improvement for gear drives. Dr. Rancourt revealed that, "We elected to go direct drive on the majority of our bio-engineering mechatronics projects because gearbox backlash, lost motion, and impedance introduce uncertainties and are difficult to model for accurate and safe motion control."

Industry experts agree that over the next 10-15 years, personal and collaborative robots will exceed the industrial robot market and become common in homes.

Is the future of gear drives in robotics to grow exponentially or is it doomed because of the intrinsic problems with backlash, wear, unpredictability, size, and high cost? Over the past few months, we conducted research and interviews with leaders in the robotics and gear drive industry to understand the challenges and opportunities with robotics applications. We tried to understand how gear backlash problems could be overcome with better motion control, sensors, AI, and new drive technologies for robotics applications. This white paper does not provide a roadmap for overcoming backlash errors in motion control. Instead, it does examine gear drive backlash and the specific requirements of the robotics industry. It looks at current technology transformation and provides recommendations to the gear industry so they can gain a better understanding of current and future needs and have greater participation in the robotics market. This white paper hopes to generate a discussion, so the gear industry remains technically and commercially viable, and flexible in the future.



BACKGROUND

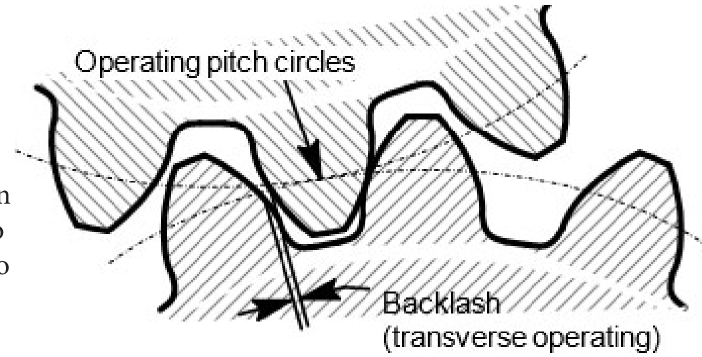


Figure 1 - Gear Backlash

Gear backlash refers to the clearance, or play, between the teeth of gears in a mechanical transmission system, as shown in Figure 1. Gear designers have strived to minimize gearing systems' backlash due to the impact on precision, efficiency, noise, vibrations, wear, motion control, system complexity, and safety. Their significance varies depending on the applications, but designers need to carefully consider these factors when developing robotics systems to ensure they meet the desired performance and safety standards.

Precision and accuracy

In high-precision applications such as industrial robots or CNC machines, minimizing gear backlash is crucial. Excessive backlash can lead to inaccuracies in positioning and reduced repeatability. This can result in poor performance in tasks that demand tight tolerances. Higher gearing ratio reduces the output position uncertainties, to the detriment of desired lower output mechanical impedance in certain applications.

Gear Backlash
refers to the clearance or play between the teeth of gears in a mechanical transmission system.

Efficiency and hysteresis

Torsional stiffness and backlash determine the surface contact area between the loading and unloading gears and correspond to the gearbox's efficiency. The phenomenon is called hysteresis. As a general term, hysteresis means a lag between input and output in a system upon a change in direction. Whenever these hysteresis curves are not available from the manufacturer, lost motion and stiffness variation can be used as alternative parameters to assess the hysteresis of the gearbox. Proper characterization of the hysteresis curves is critical for accuracy and results from the interaction of concentricity and other assembly errors with indexing errors, tooth corrections, stiffness variations during meshing, and other geometrical deviations. (ref. 7)

Oscillations and vibrations

Backlash can contribute to oscillations and vibrations in the robotic system, especially when the robot changes direction or stops and starts suddenly. These vibrations can affect the overall stability of the system and its ability to handle delicate tasks, as demonstrated in 2022 by Giovannitti (ref. 2) in the Journal of Intelligent Manufacturing 2022 and shown in Figure 2, below.

Wear and tear

Over time, gear backlash can lead to increased wear and tear on the gear components, reducing the lifespan of the system and potentially leading to maintenance issues.

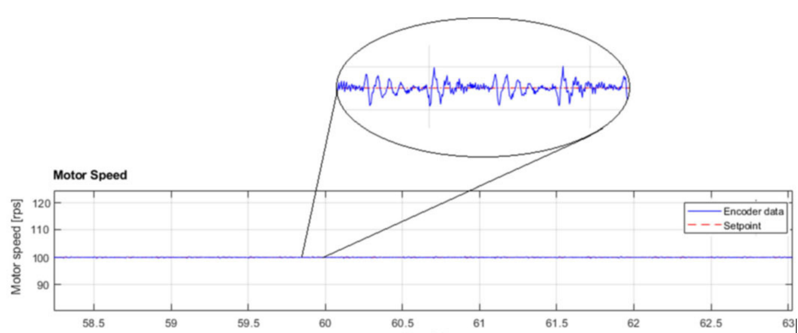


Figure 2 - Noise and vibration due to gear backlash

Control and manufacturing complexity

Compensation for backlash in control algorithms can be complex and may require additional sensors and software to account for the mechanical play. This adds to the complexity of the control system. In addition, the search for near-zero backlash increases design complexity and gearbox cost.

Position control

Position control is a fundamental aspect of robotics, and it involves accurately and reliably controlling the position of robot joints or end-effectors. Backlash causes a discrepancy between where the load should be and where the load is actually located.

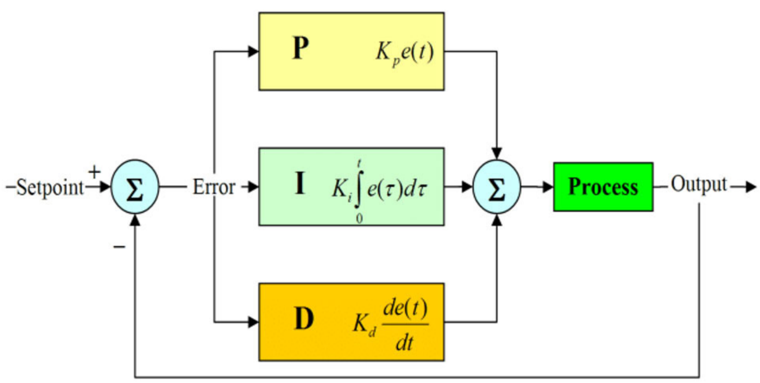


Figure 3 - Basic PID control block diagram

Position control is also crucial for various reasons. In many robotic applications, precise positioning is essential for the successful execution of tasks. This includes tasks such as pick-and-place operations, welding, assembly, and more. Poor position control can lead to errors in task execution. Typically, the control is done on the moving loads with a fixed mechanical and electrical characteristics system that uses an encoder on the motor shaft to provide the position and velocity information for control, as shown for closed-loop Proportional, Integral, and Derivative (PID) position control systems in Figure 3, where the errors come from the gearbox and associated backlash.

Depending on the direction of movement, the gear backlash may result in a different load position on the output side, causing delays and oscillations at the start or stop of the movement. The first solution that comes to mind is to mount a second encoder on the gear output shaft, and base the control on a double feedback loop, increasing the complexity and errors compensation. The controller first closes the inner loop, which is the velocity control loop, and then a second load position loop. See Figure 4 (ref 3). The velocity control loop receives feedback from the motor encoder, and this feedback determines the appropriate velocity feedback gain, which imparts a damping effect on the system to reduce oscillations.

Position errors can also be reduced with a higher gear ratio by increasing resolution and therefore minimizing the effect of gear backlash. The increased resolution is due to finer control of the system's output for a given input. With more teeth on the gears, the system can make smaller and more precise movements, resulting in improved resolution. This finer control helps minimize position errors. Lastly in a PID control system, higher gear ratios can enhance the overall rigidity of the mechanical system and improve the

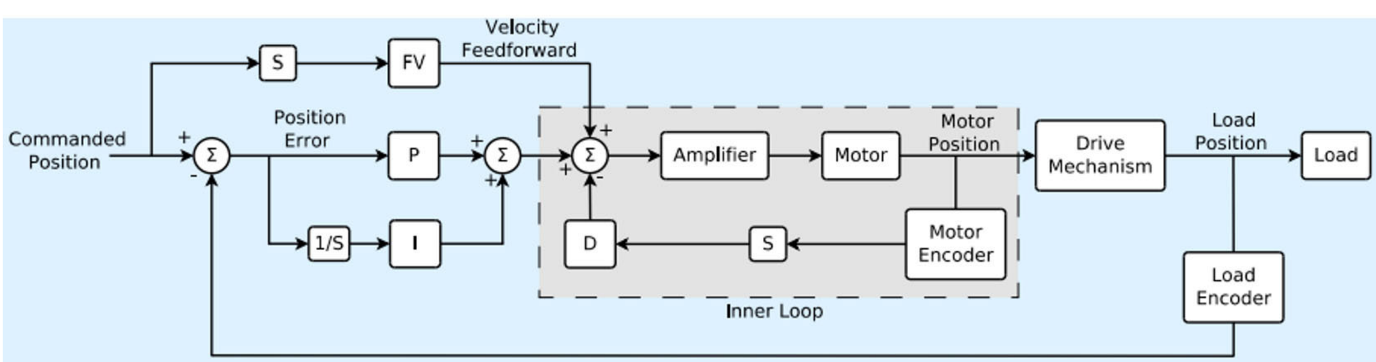


Figure 4 - Standard dual Loop PID control block diagram

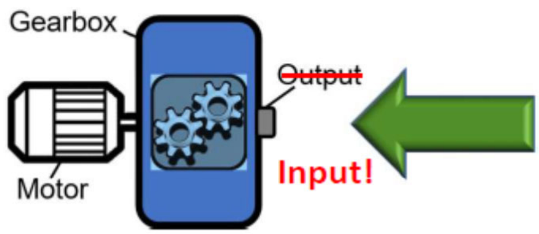


Figure 5 - Backdrivability - Mechanical compliance from the input side

stability during position control, minimizing the impact of vibrations or external disturbances that could introduce errors.

The challenge for gear manufacturers in the industrial robot market remains the predictability, limitation of material to minimize weight, size, inertia, and longevity of gear components.

Backdrivability for safety and human interaction

Safety is a primary concern in robotics. Accurate position control ensures that the robot operates within its defined workspace and avoids collisions or accidents. Robots that work alongside humans require agile position control to ensure that they do not pose a safety risk to human operators. As such, backdrivability (i.e. low impedance system) is essential for mechanical compliance to be driven from the load side, managing contact with humans and undefined objects (Figure 5, ref 4). The backdrivability is characterized by its mechanical impedance consisting of the gearbox inertia, stiffness, and losses due to backlash and friction.

DISCUSSION

For most industrial robot applications, gearing backlash is an issue robot manufacturers have been able to work around by using strain wave gearing (also known as harmonic gearing), introduced in 1957, and later, cycloidal drive or cycloidal. Strain wave gearing uses a flexible spline with external teeth, which is deformed by a rotating elliptical plug to engage with the internal gear teeth of an outer spline, as shown in Figure 6. These drive systems provide compactness, relative light weight, high gear ratios, and high torque capacity.

John Tuohy (Manager, Business Development at FANUC America) mentioned that FANUC, with their gear partner Nabtesco, have been able to produce robots with less than half of an arc-minute backlash under load and positioning precision of 0.02 mm at high velocity using large gear ratios ranging from 100:1 to 300:1. The challenge for gear manufacturers in the industrial robot market remains the predictability, limitation of material to minimize weight, size, inertia, and longevity of gear components.

The advent and the significant growth in the next 8-10 years of human-centered robots (humanoid and collaborative robots) has a significant impact on how the mechanical drive should be integrated. In conventional industrial robots, robustness and performance

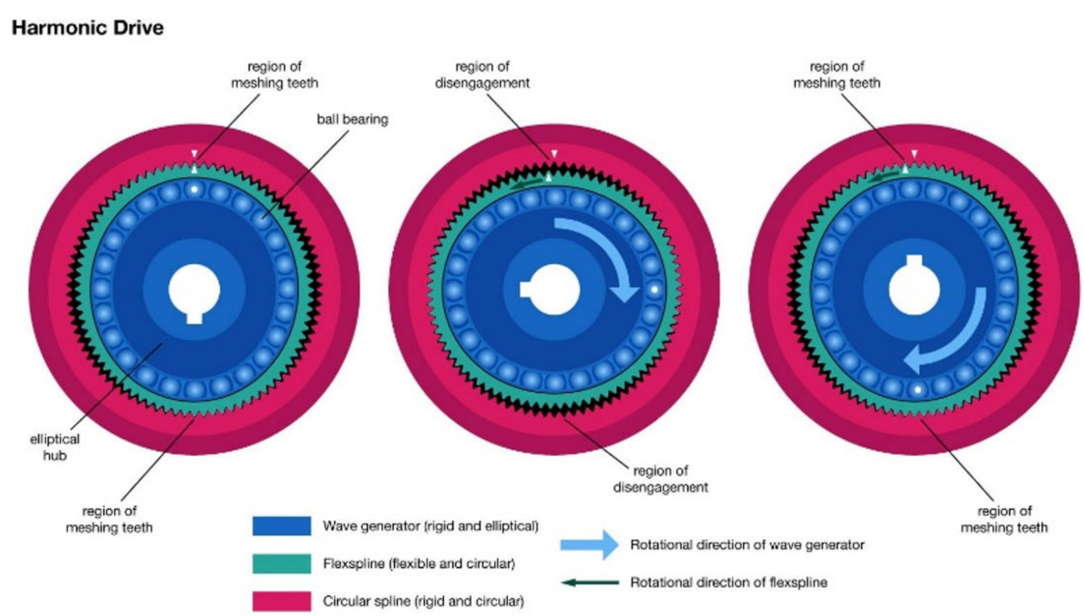


Figure 6 –Strain Wave Gearing (Harmonic Drive)

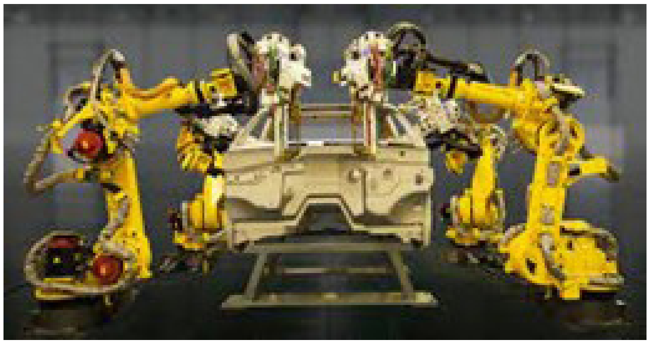


Figure 7 - FANUC Industrial Robots

are linked to the robot's ability to maintain its position trajectory under an external disturbance force. In contrast, in human-centered robotics, the close interaction between robots and humans requires low forces when there is a deviation from the position trajectory. Therefore, they require low mechanical impedance or backdrivability for safety reasons, as discussed in the background section (paragraph g), above. In addition, human-centered robots are required to operate in an unpredictable environment with an undefined sequence of operations/tasks. The table below summarizes the differences in gear drive requirements and challenges for gear manufacturers for industrial and human-centered robots.

We can see that gear backlash is one of the most important elements in robotics systems, but near-zero backlash may not be sufficient to meet the future need in human-centered robotics. New technologies, such as the Archimedes Drive from Innovative Mechatronics Systems with a Wolfrom drive and traction rollers (see Figure 9), is at the forefront of zero-backlash innovation. Thibaud Verschoor, founder at IM Systems, recognizes that true zero backlash is difficult. Engineers working on servo applications generally consider "zero backlash" to be between 0.5-5 arc min. (ref. 6). Verschoor offers the following classification for backlash accuracy:

- Micro accuracy: < 1 arc-minute
- Increased accuracy: < 3 arc-minutes
- Standard accuracy: < 6 arc-minutes

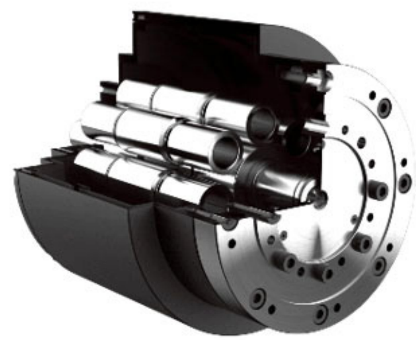


Figure 9 - Compound planetary traction system inside the Archimedes Drive

	Industrial robots	Human-centered robots
Gear General Requirements	- High torque density - High gear ratio - Controlled industrial environment - High speed and accuracy - High volume production - Deterministic system - Predictability, reliability, and maintainability - Position controlled - Minimal interaction with humans	- Low torque density and gear ratio - Backdrivability / low mechanical impedance - Position and force control - Flexibility in tasks performed in less deterministic AI-controlled space - Interaction with humans and multiple decision points - Unpredictable environment - Low noise and vibration - Multiple configuration and fragmented market - Position and force controller in proximity of humans
Gear Challenges	- Lower manufacturing cost - Material development for longevity and maintainability - Predictive reliability - Production capacity	- Lower weight and size - Backdrivability - Predictable backlash and hysteresis over product life and variable environment - Availability of data to accommodate environmental errors

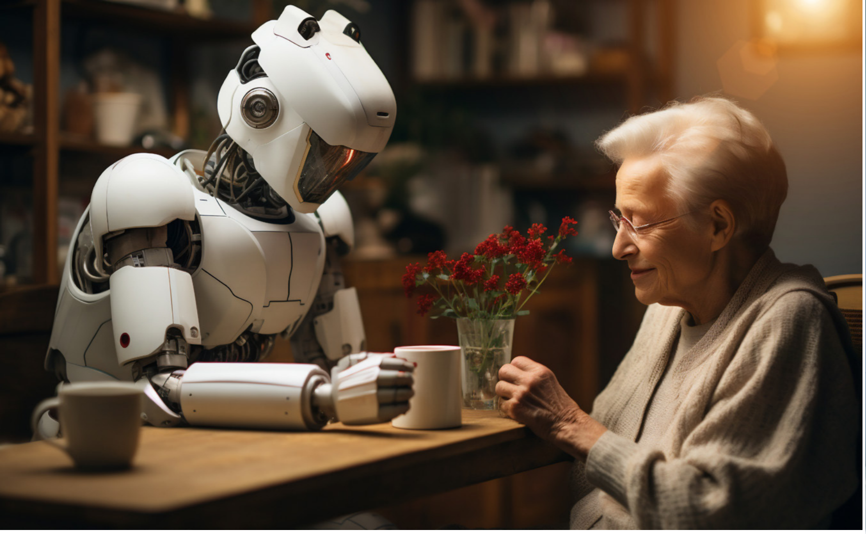
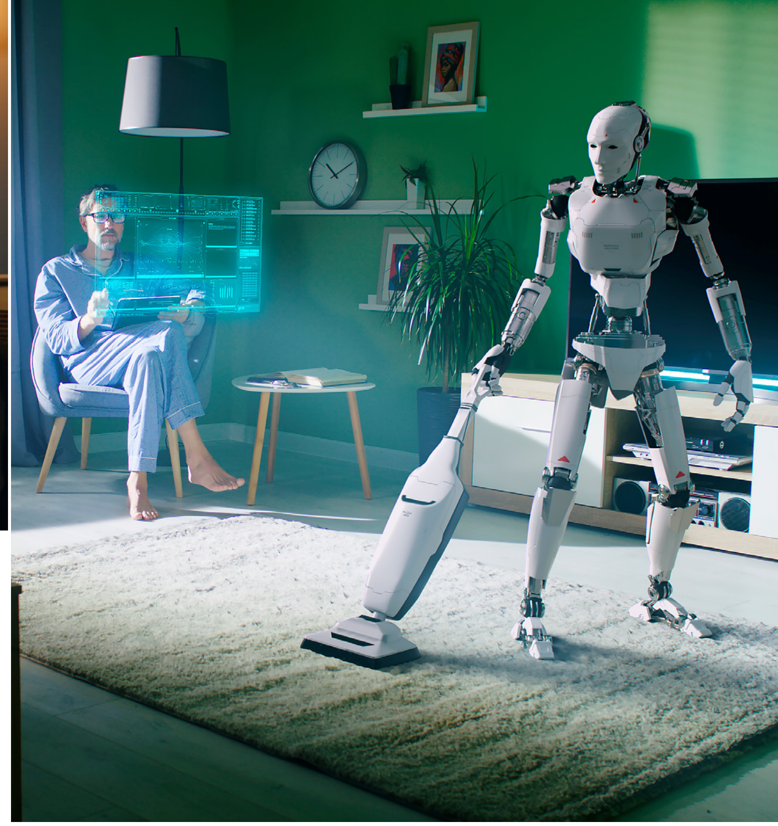


Figure 8 - Human-centered Robots



The unpredictability of human-centered robots will require sophisticated integration of the electromechanical hardware with artificial general intelligence to achieve the connection between a human's physical and cognitive behavior. Within the human environment AI database, the human-centered robot will evolve and learn from the information collected from the environment. These parameters, such as backlash, are needed to modify the motion control models from the initial build throughout its life, as components wear out and patterns and rules of operations change. As Robert James, Vice President Product Technology at Motus Labs mentioned, "The software will be driving the gear drive robotics joint. With AI, we will have to be able to predict drive degradation, feedback errors, and maintenance issues. The essence of the gear drive will be to understand the DNA of the gear profiles, its backlash, and performance over time. We are the widget of the software industry." The drive backlash can no longer be considered an error in the system that will be compensated for, but instead it should be integrated into the future human-centered robot blueprint.

As human-centered robots become a motion-control computing problem, calculating errors from backlash range becomes the Achilles heel of drive systems. With computing power increasing drastically and the ability to collect large databases of data during gear manufacturing, the next generation of gears will have to go beyond backlash range to cognitive gear modeling. In this approach, the gear manufacturer and robot designer recognize that each gear is part of a more complex AI control system model, and each can be characterized with its own DNA, from the embryonic material science to the final manufacturing process and assembly. The proposed future cognitive gear model recognizes the backlash and mechanical impedance in the design and fabrication, but also serves as an evolving function within the human robot software model.

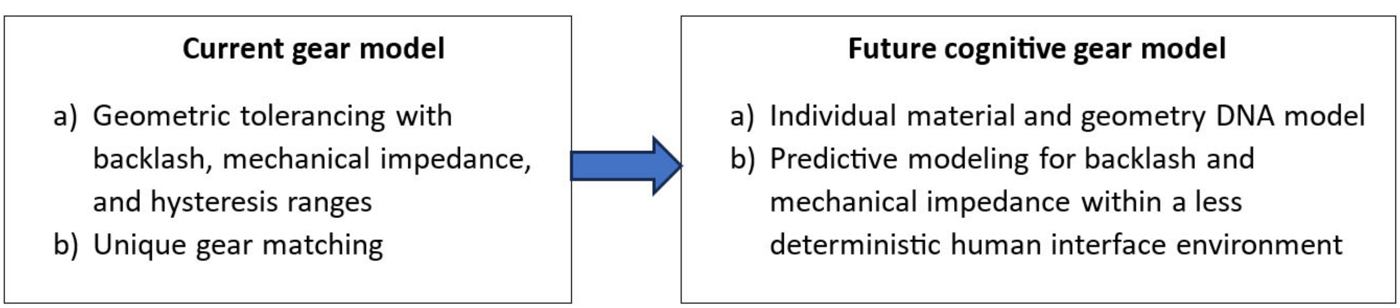


Figure 10 - Proposed Future Cognitive Gear Model

CONCLUSION

Despite recent progress in the range and accuracy of robot sensors and more powerful computing controllers, drive backlash remains one of the most significant problems in robotics. This is especially true for human-centered robots where gear ratios are generally lower than the industrial robots and backdrivability is required for safety. Gear backlash causes errors in the position and force control loop that affect the robot's mechanical impedance, generate noise, lose efficiency, and induce vibrations. From micro to standard accuracy gearboxes, the backlash value is sold with a zero to max range where the lower and upper limit might provide significant difference in the motor/gear PID model. To further compound the issue, the backlash range changes over time due to wear in materials, lubricants, and environmental conditions. The environmental conditions and usage of human-centered robots are much more highly unpredictable than industrial robots. Backlash remains an unknown factor that the present robotics software can't insert into its motion-control model.

Today, robotics is a computer problem but "transmissions are where the problem starts" (ref. 9) as Sangbae Kim, director of the Biomimetic Robotics Laboratory and a professor of Mechanical Engineering at MIT said. To play a major part in the next 10 years of human-centered robotics, the mechanical drive industry needs to develop a means to leverage next-generation computing power with a large AI database and capture gear digital mechanical DNA to allow computer modeling to account for errors in backlash and cognitive AI gears. These new gear drive digital models should be augmented by the research and development of new lighter anisotropic materials, a smaller drive envelop, and performance modeling in unpredictable environments.

The global robot market is expected to grow 50-fold in the near future. Increasing production capacity with the integration of intelligent digital technologies into manufacturing and industrial processes, such as IoT networks, AI, robotics, and automation will maximize operational returns and lower the cost of industrial robot's drives.

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Figure 1	AGMA
Figure 2	*Journal of Intelligent Manufacturing* (2022) 33:1921-1937 Eliana Giovannitti1, Sayyidshahab Nabavi2, Giovanni Squillero3, Alberto Tonda4
Figure 3	Scientific Figure on ResearchGate. Available from: https://www.researchgate.net/figure/PID-Block-Diagram-PID-stands-for-Proportional-Integral-Derivative-control-A-PID_fig1_316709017
Figure 4	Galil Motion Control, Kaushal Shah, kaushals@galil.com
Figure 5	Pablo Lopez Garcia 2022 AGMA Fall Technical Meeting Presentation
Figure 6	*Encyclopædia Britannica*, https://www.britannica.com/technology/Harmonic-Drive
Figure 7	FANUC America via John Tuohy, Business Development Manager
Figure 8	AdobeStock
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Figure 10	AGMA Emerging Technology Robotic Committee, December 2023, Jacques Lemire, P. Eng.

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