

HarmonicDrive®

Designing High-Reliability Servo Gear Trains and Actuators for Medical Systems

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Overview

Medical systems present unique mechanical and control challenges that influence gear train, actuator, and system level design decisions. Gear train and actuator selection should be treated as a system-level architectural decision rather than a component-level optimization, as its impact propagates through precision, reliability, validation effort, and long-term clinical performance. Integrated servo actuators with well-characterized behavior reduce interface risks that can lead to latent reliability issues, enabling medical devices to maintain precision and reliability throughout long clinical service lives.

As a global leader in high-precision motion control, [Harmonic Drive, LLC](#) engineers and manufactures standard and custom servo actuators, gearheads, zero-backlash gear components, and planetary gears. Harmonic Drive's specialized "strain wave gears" are known for their compactness, zero backlash, and high torque capacity, making them a foundational technology for applications such as robotics, spaceflight, semiconductor manufacturing, surgical robots, and medical equipment.

Context

The presenters discussed medical device requirements and explained how key mechanical components can ensure long-term performance and reliability.

Key Takeaways

Strict medical device requirements often cannot be met using traditional gears and actuators.

Medical electromechanical systems operate under a set of constraints that are significantly more demanding than those in general industrial automation.

- Applications such as surgical robots, radiation therapy positioning, and diagnostic imaging demand **extremely high motion precision**—typically with micron or even sub-micron accuracy. Small errors that would be acceptable in industrial settings are often unacceptable in a medical context, as they may lower diagnostic quality or compromise patient safety.
- Medical systems also require **quiet and smooth operation**. Acoustic noise, vibration, and torque ripple can affect patient comfort, interfere with imaging modalities, such as MRI or CT, and degrade force-feedback performance in robotic surgery.

- Medical systems often operate in sealed or **sterile environments where maintenance access is limited or impossible**. These strict environmental containment restrictions place severe constraints on lubrication choices, material selection, and heat dissipation.
- Devices must achieve stable **long-term performance with minimal maintenance**. Reliability expectations are unusually high, as failures can interrupt critical procedures or take expensive equipment offline. And because medical systems must pass strict, expensive, and time-consuming regulatory approval, making post-deployment design changes is extremely—often prohibitively—expensive.

In high-reliability medical systems, mechanical errors such as backlash, compliance, friction variation, and wear directly affect output performance and cannot be fully eliminated in software. Gear train and actuator architecture can limit achievable performance and reliability, regardless of how sophisticated the downstream control algorithms may be.

Early design decisions also determine how easily a system can be analyzed, tested, and certified, impacting whether a medical system can meet clinical, regulatory, and economic goals over its lifecycle.

“Poor actuator choices often lead to extended development timelines, repeated design iterations, and unexpected failures during verification testing. In contrast, selecting a gear and actuator technology that inherently minimizes backlash, distributes load efficiently, and offers predictable life characteristics simplifies both mechanical and control design.”

- Richard Kawko, Harmonic Drive

Figure 1: Medical devices demand extremely high precision and repeatability



Strain wave gears enable critical performance and reliability in medical devices.

When designing gear trains for medical applications, engineers must decide between several competing requirements. One of the most critical tradeoffs is between **backlash and torsional stiffness**. Traditional gear technologies, such as spur and planetary gears, achieve high stiffness but typically introduce measurable backlash that impacts positioning accuracy and force control. Reducing backlash using preloading techniques often increases friction, wear, and sensitivity to manufacturing tolerances.

Long-term **wear and lubrication** are also difficult to address in sealed or sterile environments, as medical devices may operate for years without service access—lubricant breakdown or contamination can directly limit system life. These systems must be designed with low-wear gear architecture and stable lubrication.

Material selection can also introduce challenges, as gears must resist corrosion and cleaning agents, and must meet biocompatibility standards while maintaining high fatigue strength. Certain materials and surface treatments common in industrial gearboxes may not be acceptable in medical contexts.

These design challenges make it difficult for traditional gear trains to deliver stable, high-precision performance over long lifetimes. Strain wave gears, on the other hand, are

ideal for medical systems, as they offer near-zero backlash, distributed load sharing, and reduced wear mechanisms for more stable performance over long operating lives.

Integrated actuators enable critical performance and reliability in medical devices.

In addition to gear train design considerations, engineers must consider tradeoffs at the actuator level, including torque density, thermal limits, and duty cycle.

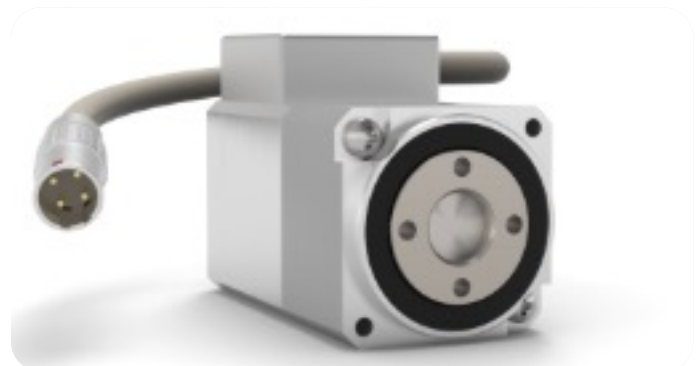
Medical robotics applications often require **compact actuator designs with high torque density** to operate in constrained spaces. However, increasing torque density typically raises **thermal stress** on motors and surrounding components, making heat dissipation in sealed medical environments an especially critical challenge to overcome.

Different applications also require **different duty cycles**. Imaging systems often require static holding torque with minimal motion, which can cause motor windings and magnets to accrue thermal stress of time. Surgical robots experience intermittent high torque bursts combined with rapid reversals, which can cause motor fatigue and demagnetization.

To ensure precision and safety, **integrating high-resolution encoders and force sensors** directly into actuator assemblies is vital. Note that sensors must be integrated in a way that maintains signal integrity and reliability on the thermal and mechanical loads.

Integrated servo actuators that combine motors, strain wave gears, and encoders into a unified assembly address this challenge. Bringing the components together into a single unit allows designers to optimize thermal design, reduce interface losses, and ensure that torque, speed, and sensing capabilities are calibrated to match the application's duty cycle.

Figure 2: Actuator choice impacts medical device performance and reliability



Failure modes inform medical system design choices.

Understanding common failure modes in medical servo systems inform design decisions. On the mechanical side, gear wear and fatigue are dominant concerns. Conventional gears experience localized tooth contact and sliding that cause gear wear, which progressively increases backlash and reduces stiffness over time. Lubrication breakdown increases friction, further degrading gears, especially in sealed systems where maintenance is limited or impossible.

On the electromechanical side, motor overheating accelerates insulation aging, reduces bearing life, and can even cause demagnetization of permanent magnets, reducing torque capability.

Interactions between mechanical and electrical subsystems can create coupled failure mechanisms. For example, increased mechanical friction leads to higher current draw and additional heating in the system.

Because failures are often due to progressive wear or complex failure interactions, they can be difficult to detect during short-duration testing. Understanding what the failures are and why they happen informs design choices for better performance and longevity.

“Designing with a clear understanding of these failure modes allows engineers to incorporate appropriate margins, monitoring strategies, and architectural choices like strain wave gears that inherently reduce the likelihood and impact of wear-related degradation.”

- Kyle O’Connell, Harmonic Drive

Figure 3: Harmonic Drive’s strain wave gear technology



Life testing and validation are essential components of medical actuator development.

Robust validation builds confidence not only in the initial performance of a system, but in its long-term clinical reliability and viability.

Accelerated life testing exposes components to elevated loads, temperatures, and duty cycles to reveal failure mechanisms practice time frames. However, it is crucial that these tests accurately reflect real-world operating conditions—unrealistic acceleration can produce failure modes that would never occur in practice.

Thermal margin validation, which ensures motor and gear temperatures remain safe during operation, is especially relevant to integrated actuators with closely connected motor and gear temperatures. **End-of-life performance measurements**, including backlash, stiffness, and efficiency, provide valuable insight into performance degradation over time.

Tracking measurements of motor current, temperature, and vibration data can help engineers identify wear progression, enabling **predictive maintenance**. For systems designed for use in sealed environments, these measurements help engineers assess long-term performance and reliability of a design.

Harmonic Drive's Recommended Best Practices

When designing servo gear trains and actuators for high-reliability medical systems, Harmonic Drive recommends engineers follow practical, proven guidance:

- Design reliability into the system from the beginning, rather than adding later during validation.
- Mechanical and control co-design is essential, as high-quality mechanics simplify control and reduce validation burden.
- Identify and remediate long-term thermal and mechanical margins that can lead to significant degradation over time.
- Value predictable behavior over absolute peak performance to ensure a strong foundation for meeting clinical and regulatory requirements.

“By applying these principles proactively, teams can reduce development risk, shorten validation timelines, and deliver more reliable medical systems.”

- Jim Leonard, Harmonic Drive

Additional Information

To learn more visit: [HarmonicDrive.net](https://www.harmonicdrive.net)

Biographies



Jim Leonard

VP of Sales,
Harmonic Drive

A graduate of Alfred University with a B.S. in Ceramic Engineering (1987), Jim has a 36 year career in the field of servo gear mechanisms and servo actuators. Jim has been with Harmonic Drive LLC for 10+ years and currently serves in the role of Vice President of Sales.



Richard Kawko

Regional Sales Manager - East,
Harmonic Drive

Rich Kawko is a Regional Sales Engineer for the Eastern Region for Harmonic Drive LLC supporting New York, Pennsylvania, and all of Canada. Rich works closely with OEMs, sales representatives and integrators to align advanced actuator and strain wave/planetary gearing solutions with demanding application requirements across industrial, medical, aerospace, and emerging robotics markets. Rich graduated from Polytechnic University (formerly Polytechnic Institute of New York) in Farmingdale, New York in 1985 with a Bachelor of Science in Aerospace Engineering and a Minor in Mechanical Engineering. He has worked in the motion control field for over 30 years.



Kyle O'Connell

Mechanical Design Engineer,
Harmonic Drive

Kyle O'Connell is a Mechanical Design Engineer at Harmonic Drive specializing in servo gear train design for high-precision motion systems. His experience supports applications including surgical robotics and medical equipment, where reliability, process control, and system level integration are essential.