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WHITE PAPER

Engineering Motion Systems for Space: A Guide to Reliability, Scalability and Mission Success

The space economy is undergoing a profound transformation. From the rapid commercialization of Low Earth Orbit (LEO) to ambitious extraterrestrial missions targeting the Moon, Mars and beyond, the pace of innovation has never been faster.

Engineering teams are now expected to prototype quickly, iterate rapidly and scale production efficiently while still designing systems capable of surviving years of operation in some of the harshest environments imaginable.

Even when you know the kinematics and have modeled the torque and speed requirements, the challenge isn't just building for space. It's knowing which decisions made on the ground will create problems 240 miles up and farther, or on the surface of a planet. There's no convective cooling in space. Standard insulation systems degrade under radiation. Materials that perform flawlessly in a lab can contaminate sensitive optics in a vacuum.

This paper addresses the specific decisions that separate a terrestrial prototype from a space-capable system—and how to make them early enough to matter.

Key domains of space applications

Space is not a monolithic environment. Different missions expose motion systems to dramatically different combinations of vacuum, radiation, thermal cycling, contamination risk and operational lifespan. Designing a universal "space motor" is often both technically inefficient and economically impractical.

Kollmorgen segments space applications into six distinct domains based on key stressors. This taxonomy helps align motion design with mission reality, preventing both catastrophic under-design and costly over-engineering.

Exhibit 1: The Six Domains of Space Motion

Domain	Key stressors	Design implications	Space recipe intensity
Ground Stations	Standard atmosphere, weather, 24/7 duty cycles	Commercial-off-the-shelf (COTS) industrial-grade components suffice. Focus remains on extreme uptime, precise tracking, and environmental sealing.	Low – standard or lightly modified commercial product
Terrestrial Prototyping	Gravity loading; no environmental extremes	Validate torque/speed profiles and mechanical footprint using standard frameless servo motors. Maintain scalable architecture path to space.	None – but architecture choices here determine upgrade ease
Low Earth Orbit (LEO)	Hard vacuum, rapid thermal cycling (−150°C to +120°C), atomic oxygen erosion, moderate radiation	Full vacuum outgassing compliance required. Atomic oxygen coatings. Recipe intensity varies with mission life.	Low to Medium – mission life (3–15 yr) drives how much space recipe is needed
Deep Space	Extreme cryogenic cold, intense cosmic rays, multi-year missions (30+ years)	Full vacuum compliance, cryogenic lubrication (MoS_2), proprietary radiation-resistant encapsulation. Motor sized for thermal performance.	High – maximum space recipe
Space Habitation	Breathable atmosphere, moderate temp, human proximity, 30+ year life	Outgassing critical for atmospheric integrity. Often achievable with modified commercial-grade motors (full space recipe may not be required).	Medium – application-specific modifications
Extraterrestrial Surfaces	Abrasive regolith, variable gravity, massive diurnal swings, extreme radiation	Mechanical sealing, dust mitigation, extreme thermal resilience. Highest bar: designed for absolute reliability with zero maintenance.	Highest – fully custom space recipeper mission

The table (Exhibit 1) also defines cost exposure. For example, a commercial motor for terrestrial prototyping might cost a fraction of a fully customized space-ready cryogenic design. Right-sizing the recipe to the mission is one of the most impactful decisions an engineering team can make early in the design process.

Space-rated vs. space-ready

Space-rated motors exist. They're certified, documented and built to survive a defined set of environmental conditions. But while "space-rated" indicates a motor can survive in space, it doesn't mean it's optimized for a specific space application.

A motor rated for a 4-year LEO satellite has fundamentally different requirements than one built for a lunar surface vehicle operating on the dark side of the Moon. Even within NASA's Artemis program, operating conditions can vary significantly depending on mission location (light or dark side) and thermal exposure. Applying a LEO-rated motor to an extraterrestrial surface mission could lead to premature failure, while over-engineering a short-duration LEO mission with deep-space specifications can inflate non-recurring engineering (NRE) and other costs.

Kollmorgen's approach starts with a space-capable architecture, backed by a proven mechanical and electromagnetic foundation with 60+ years of heritage across Gemini, five generations of Mars rovers, and programs in between. From that foundation, we co-engineer a space recipe tailored to a specific domain, mission life, radiation environment and thermal cycling range. The result is a motion system designed for the mission with a clear, validated path from terrestrial prototype to in- or on-orbit deployment.

Critical design considerations

Once the domain is established, engineers must navigate the physics and material science of the space environment. Terrestrial motor designs rely on convective cooling, standard neodymium magnets, and polymer-based insulations. All three assumptions break in space.

Outgassing and vacuum environments

In the high vacuum of space (e.g., 10^-7 Torr), many standard manufacturing materials sublimate or outgas. This outgassing can condense on sensitive optical lenses, solar panels and sensors, severely degrading mission capabilities.

- **Outgassing standard:** NASA-STD-6016A dictates the acceptable limits for outgassing. Engineers must look at two primary metrics: Total Mass Loss (TML) must be under 1.0% (often pushed strictly to <0.5% for sensitive optics), and Collected Volatile Condensable Materials (CVCM) must be <0.1%.
- **Material risk:** Standard polyester-based materials, Mylar films, vinyls, nylon, silicone rubbers and standard motor winding varnishes perform poorly in a vacuum. The cross-linked polymers in these materials degrade, causing the physical integrity of the insulation to disintegrate.

The solution is proprietary encapsulation processes and radiation-resistant materials, applied as part of a tailored space recipe. In many cases, analytical testing based on the actual Bill of Materials (BOM) can predict TML and CVCM without requiring months of physical vacuum testing, which directly accelerates development timelines.

One often-overlooked outgassing risk is that even if a motor meets the standard, other components in the system may not. Kollmorgen works with customers to evaluate system-level outgassing exposure, including secondary encapsulation and thermal bake-out procedures for components we don't supply.

Radiation resistance

Gamma and neutron radiation continuously bombard spacecraft. Over time, this ionizing radiation destroys standard electrical insulation and adhesives.

- Motor encapsulation must utilize proprietary, radiation-resistant e-cap materials.
- While standard neodymium (Neo) magnets may be suitable for some missions, others may require alternative materials optimized for long-term environmental stability and performance retention.
- Material decisions can introduce additional sourcing and lead-time considerations, but engaging a motion partner early in the design process can help evaluate tradeoffs before the form factor is locked.

Thermal dynamics and cryogenics

Thermal management is the most underestimated challenge in space motion design. With zero convective cooling, all heat generated by the motor (copper losses, iron losses) plus external solar radiation must be managed through pure conduction and radiation.

- **Heat extraction:** Spacecraft typically utilize liquid cooling loops to carry conducted heat from the motor to deep space radiator arrays. Motors must be meticulously sized for their actual thermal performance to prevent insulation failure.
- **Cryogenic shift:** Historically, subsystems were artificially heated to remain above -145°C because material science could not guarantee survival below that threshold. However, next-generation extraterrestrial missions (such as those exploring the dark side of the Moon) are targeting ambient temperatures of -185°C to -220°C.
- **Thermal fatigue:** The dynamic range of temperature is just as destructive as the absolute cold. Passing from cryogenic cold to solar-radiated hot repeatedly causes extreme thermal fatigue on aluminum housings, steel laminations and copper windings. Insulation systems must be highly specialized to survive these violent contraction and expansion cycles without fracturing.

Shock, vibration and size/weight optimization

Space motion systems must survive intense launch forces and long-duration operation while minimizing overall payload mass. To achieve this, engineers must strategically balance structural durability, performance and manufacturability.

- **Launch survivability:** Shock and vibration loads during launch can affect winding integrity, magnet retention and mechanical alignment before the spacecraft ever reaches orbit.
- **Weight reduction:** Every gram added to a payload increases launch costs and fuel requirements, making compact and lightweight actuator designs critical.
- **Torque density tradeoffs:** Reducing size and weight can't come at the expense of performance or reliability. Motion systems must still deliver the required torque, stiffness and thermal performance for the mission.

Why choose frameless motors

In space, every component that can be eliminated should be. Frameless motors help simplify motion architectures by eliminating unnecessary housings, shafts and couplings while allowing engineers to integrate the motor directly into the actuator design.

Unlike housed servo motors, frameless motors consist only of the stator and rotor. This gives engineers greater flexibility to optimize the surrounding structure for the specific thermal, mechanical and environmental demands of the mission.

Here are several important advantages of frameless direct drive architectures:

- Reduced size and weight by eliminating redundant mechanical components and enabling compact actuator integration
- Improved thermal management by allowing the actuator housing itself to become part of the conductive heat path
- Greater environmental adaptability through application-specific sealing, material selection and contamination mitigation strategies
- Higher precision and stiffness by reducing backlash and compliance within the motion system
- Scalable development paths that support continuity from terrestrial prototyping to mission-capable designs

Kollmorgen offers multiple frameless motor models that support different space application priorities. TBM and KBM motors are commonly used in compact robotic joints, gimbals and precision positioning systems, while TBM2G motors are optimized for improved thermal performance in thermally constrained designs. RBE motors offer the size range and proven heritage for high-torque, low-speed applications requiring long-term reliability.

Accelerating time-to-space

The most important insight for engineering teams entering the space market is that the mechanical envelope you validate on the ground should be the same one that goes into space. That requires the right motor architecture from day one.

1. Start terrestrially, think architecturally

The most efficient approach is to begin with standard commercial-grade frameless motors (such as the Kollmorgen TBM or KBM series) to build physical prototypes, map out torque and speed profiles, and finalize the structural footprint in a matter of weeks—at a fraction of the cost of customized space hardware. The key is selecting a motor family with an established upgrade path.

2. Co-engineer the "space recipe"

Once the form factor and electromagnetic performance are validated on the ground, motion control experts collaborate with OEM engineering teams to apply the correct "space recipe." This may involve transitioning to specific magnet types, radiation-resistant insulation systems and low-outgassing encapsulations while preserving the core motor architecture and mechanical footprint. By maintaining actuator geometry and integration points, engineering teams can reduce redesign effort and accelerate the transition from terrestrial prototyping to mission-capable systems.

3. System-level mitigation

While they may not be building the platform, expert motion partners can provide system-level mitigation strategies. For example, at Kollmorgen, we advise on secondary encapsulation techniques within the actuator housing or on establishing specific thermal "bake-out" procedures to force outgassing on Earth before the system is ever loaded onto a launch vehicle. This is where an engineer-to-engineer model earns its value. The goal is to help teams de-risk design decisions before they become mission-critical problems.

Typical prototype lead times are 2–3 weeks for standard frameless motors (50mm–115mm), or 12–20 weeks for larger, customized ground-based systems.

A co-engineering model built for today's space market

Two distinct engineering philosophies are emerging in the space market. Traditional OEM engineers with years of experience who move deliberately and understand the cost of a mission failure. And then, commercial and startup teams that move fast, prototype aggressively and embrace a fail-forward mindset. Kollmorgen offers a rapid prototype-to-space-recipe path, along with 60+ years of co-engineering heritage and documented material validation to serve either approach.

Design realities and tradeoffs

Every decision impacts the next when navigating motion design for space. Here are some of the common challenges teams face, and recommended approaches to plan early and deploy faster.

Challenge	Recommended strategy
Searching for an off-the-shelf 'space-rated' motor	Seek space-capable architectures that can be upgraded with a tailored space recipe. Every mission's thermal, radiation and vacuum requirements are unique, and the motion system should meet those specific application demands.
Underestimating cryogenic cold	Don't assume standard materials survive dynamic thermal cycling to −200°C without validation. Deep cryogenic cold is the most frequently underestimated failure mode in space motion design.
Over-specifying for LEO	Applying full deep-space radiation and outgassing standards to a 4-year LEO satellite inflates cost and NRE dramatically. Match the recipe to the mission duration and domain.
Ignoring thermal management until late in design	With zero convective cooling in space, heat removal should be a first-principles design input. Size the motor for thermal performance from the start and plan the liquid cooling loop early.
Choosing a terrestrial prototype motor with no upgrade path	Pick a motor family with an established scalable path. The mechanical envelope you validate on the ground should be the same one that goes into space.

Built for the mission

The space economy is growing faster than the workforce supporting it. Programs are moving from decade-long development cycles to rapid iteration. Cost pressure is real. The window between prototype and production is compressing. Making the right motion system decisions made early benefits the entire program—eliminating rework, reducing NRE and accelerating time-to-space.

Kollmorgen brings over 60 years of domain expertise and proven frameless motor architectures, along with a full portfolio of sustainable solutions that power, transmit and control motion. We operate as an extension of your engineering team, helping you navigate the complexities of rapid innovation, precise thermal management and highly scalable manufacturing. We know there is no margin for error, and we're here to help ensure the right space recipe for mission success.

Ready to launch?

Contact Kollmorgen to discuss your needs and goals with a Kollmorgen frameless motor specialist.

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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