WHITE PAPER

Miniature Linear Bearings Help Prolong Curiosity's Mars Mission

Highly reliable bearings keep camera up and running in extreme space environment.

The launch, landing and overall mission of NASA's Mars Science Laboratory (MSL) is arguably one of the most daring—and successful—space exploration endeavors ever undertaken. After a successful landing at Gale Crater on August 6, 2012, MSL's Curiosity rover has already surpassed its 23-month mission target, and it continues to transmit informative images of the Martian surface on a daily basis.

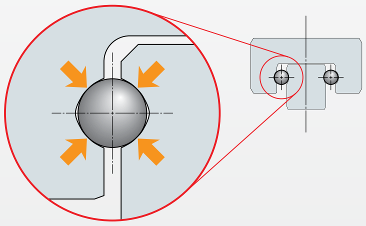
The longevity of the Curiosity rover in such a harsh, remote operating environment pays testament to NASA's superb reliability engineering capabilities. Every aspect of this mission was put through the utmost scrutiny before launch in November 2011. Among the most important and thoroughly vetted systems are the cameras used to guide Curiosity and send images back to earth.

The Curiosity Mars rover has 17 total "eyes" including six engineering cameras that help with navigation duties and four to performance science investigations. Images are often stitched together to create panoramic views of surrounding landscape as it travels the planet.

experts in MOTION

BEARING BASICS: LWL MINIATURE LINEAR MOTION GUIDE

IKO's Linear Way L (LWL) is a miniature type of linear motion rolling guide, which incorporates two rows of steel balls arranged in four-point contact with the raceways.



Although small in size, it provides stable accuracy and rigidity due to its simple design, even in operations under fluctuating loads with changing direction and magnitude or complex loads. Standard products are made of stainless steel and a wide range of variations in shapes and sizes are available.

LWL bearings used on Curiosity's MastCam were modified to operate smoothly in temperatures as low as -130°C. The bearings also incorporate special corrosion-resistant materials and packaging suitable for vacuum and cleanroom environments. In addition, ball recirculating and ball retaining features were optimized to ensure smooth motion, even under fluctuating temperatures.

More than three years after Curiosity's landing date, these camera systems have survived the rigors of space. Among the robust components used in the rover is a set of precision linear bearings from IKO, the LWL Miniature Linear Motion Guides (see sidebar). These bearings include specialized reliability features that allow them to operate for years without human intervention in environments as challenging as the Mars surface. Further, NASA's Jet Propulsion Laboratory (JPL) team chose the LWL bearings for their extraordinarily smooth operation. In fact, another IKO customer familiar with the tiny bearings from a commercial camera lens application recommended them to the JPL team. Reliability and long life are additional attributes offered by the LWL bearings, achieved by IKO's tightly controlled manufacturing and stringent quality assurance processes.

Beyond quality and reliability, LWL bearings were specified based on IKO's engineering expertise and intensive customer support capabilities. IKO engineers helped customize the bearings to meet the exact needs of the space application with regard to finding the optimal clearance, selecting the best materials, choosing the right packaging and lubricant, and modifying the ball return and ball retaining features. More specifically, clearance was determined based on achieving continuously smooth motion even in extreme temperatures reaching -130°C, which was confirmed through rigorous low temperature bench tests prior to launch. Special materials focus on surviving the extreme space atmosphere and include features such as end plates made of corrosion-resistant stainless steel. Regarding packaging, a specialized vacuum and cleanroom style was used, which is free of dust, lint, oil and rust. Further modifications were also made to the LWL bearings, including optimizing the ball recirculation and ball retaining features to ensure smooth motion under fluctuating temperatures.

Most linear motion systems don't need to withstand the temperature extremes, contamination and mechanical stresses that Curiosity endures. But the rover's design does offer some lessons for engineers wanting to improve the precision and reliability or earthbound applications. Here's a more detailed look at what Curiosity can teach us about linear motion.

Curiosity's cameras. In total, Curiosity has 17 "eyes" including six engineering cameras that help with navigation duties and four to perform science investigations. Within the science set is the pair used for the mast cameras, MastCam. Two camera systems are mounted on a mast extending upward from the MSL rover deck. These cameras function like human eyes, producing 3D stereo images by combining two side-by-side images taken from slightly different positions. Since landing, these cameras continue to fulfill their duty of taking color images and video footage. Images are often stitched together to create panoramic views of the landscape surrounding Curiosity as it travels the planet.

MastCam is being used to study the Martian landscape, view weather conditions and support the rover's driving and sampling operations. Although the cameras feature two different focal lengths (34 and 100 mm), both include auto-focus and auto-exposure control as well as commanded-focus and commanded-exposure capabilities. Central to MastCam's focusing mechanism are tiny linear bearings built and specified to meet the demanding conditions of space travel and exploration.

When designing systems for use in space, every component must undergo rigorous scrutiny in terms of meeting the most challenging engineering requirements. These include the ability to handle extreme temperatures, withstand contamination and guarantee high precision and reliability—all in the most lightweight and space-constrained package possible to keep payload to a minimum.

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NASA's Jet Propulsion Laboratory team chose IKO's LWL Miniature Linear Motion Guides for its Curiosity Mars rover. These bearings include specialized reliability features that allow them to operator for years without human intervention in environments as challenging as the Mars surface.

The reliability aspect cannot be overestimated: Systems and their individual components must be able to operate on their own via remote control for the entire mission. After more than three years on Mars, the MastCam's linear bearings continue to play a flawless role in capturing dramatic images of the Mars landscape.

MastCam design details. The mechanical design of the MastCam system is based on another primary science camera aboard Curiosity called the Mars Hand Lens Imager (MAHLI), with each lens design facing the same constraints: Operating temperature range of -120 to +40°C; lifetime of one Martian year (=1.88 Earth year) (x3 margin); acceleration loading of 150G; and mass <250 grams. In addition, due to particulate concerns, all moving parts and optics had to be housed internally. The camera lens assembly holds a highly complex mechanism in a cylindrical volume approximately 7x7 cm tall.

Within this assembly, the drive system enables actuation of the focus lens group. As part of this actuation system, cam barrel rotation imparts linear motion to the focus lens group via the cam and follower bearing mounted on the focus lens cell. The focus lens group moves in a linear orientation using a linear bearing mounted on the primary optical housing with flexures. As the cam barrel rotates, the cam repositions the follower bearing and moves the lens group along the linear bearing. Other miniature components such as worm shafts and gears help complete the drive system to enable camera operation. The mission-critical IKO linear bearing was specified due to its extreme precision, smoothness and—above all—reliability. Test-beds were used to validate the bearing and several other vital components within the lens assembly. Based on testing results, minor tweaks were made to various components such as slightly modifying the geometric profiles of the cam surfaces and linear bearing end-caps.

Specifying linear bearings for extreme environments. Designing a system that can stand up to the rigors of a space mission is at the extreme end of what most engineers will ever face. That said, the overall lessons learned from such a design endeavor can be applied to any challenging environment. Many manufacturing applications involve extreme temperatures, moisture, particulates, and difficult space and mass constraints, meaning that every component must be specified with survival in mind. When linear bearings must be used in harsh environments, consider these tried and true tips:

- **Know your design constraints.** When specifying linear bearings, be sure to communicate application details to your supplier. For example, consider the required rigidity, loads and moment loads involved, necessary precision and accuracy, maintenance schedules, vibration and noise levels, and space/weight constraints. These basic parameters will help guide your linear bearing selection. Think as quantitatively as possible rather than relying on more general qualitative ideas during this stage. Realistic assumptions about actual numbers regarding loads and stresses are much more useful than vague concepts.

- **Consider test and lifecycle data.** While building a dedicated test-bed to validate components is unrealistic for most noncritical applications, designers can at least ask suppliers for testing and lifecycle data. Be sure to mention any extreme operating conditions the linear bearing will need to endure. Further, ask your supplier if the particular linear bearing you are considering has been used in similarly demanding applications.

- **Know that even small loads can cause big problems.** Just because a load is small, it must not be ignored. Overall stress depends on component size as well as load size, meaning everything is relative. This is especially true with small parts such as miniature linear bearings. Use engineering numbers to guide your decision-making.

- **Small parts can easily malfunction due to debris.** One of the lessons learned in designing the lens systems for Curiosity's cameras is that small mechanisms tend to jam easily. Microscopic particles can easily prevent correct operation of tiny mechanisms such as bearings, gears and cams. Keep protective accessories in mind such as wipers, bellows and dust covers.

- **Don't be afraid to rely on outside expertise.** Bearing suppliers are often your best source of reliable advice, based on a multitude of experiences with wide-ranging applications and challenging environments. For example, IKO bearings have an excellent track record of bringing precision and reliability to the most challenging environments, including their flawless performance aboard the Curiosity rover still operating on Mars. Be sure to ask for expert help and advice when you need it.

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