Let the Great World Spin*

Fiber Optic Rotary Joints Add a Spin to Sensing, Mobile, and Robotic Fiber Systems

Abstract

To the passing optical signals, fiberoptic rotary joints (FORJs) are nothing more than fiber connectors, which provide connection between one or multiple fibers. Their unrestricted ability to rotate, however, gives them a critical role in many sensing, mobile, and robotic fiber systems such as ROVs (remotely operated vehicles), aerostat radars, submarines, satellite antennae, OCT (optical coherence tomography), mining vehicles, cranes, wind turbines, robotic vehicles, broadcasting (mobile cameras), etc. This article discusses some of the applications where optical rotary joints are indispensable.

Introduction

Over the past three decades, optical fibers have revolutionized the telecommunications industry. They offer a huge advantage over traditional copper wires in bandwidth, throughput, security, life span, weight, and cost. However, applications outside of the telecommunications field have been limited until recent years. One of the unexpected boosts came as a result of the last recession around the turn of the century, when an army of fiber optic engineering talent migrated from telecom to other engineering fields. Consequently, we are experiencing a surge of new innovations involving optical fibers in a growing number of fields.

Applications

The wind energy sector, as an example, epitomizes the depth of penetration of fiber technology into non-telemetry applications. With the insatiable desire for clean wind energy, wind turbine blades grow larger and larger. To ensure the safety of the machines, the crew, and people or livestock that might be around them, it is important to have embedded sensors that transmit the heartbeat of the blade to the control unit. Smart fiber sensors, such as fiber Bragg gratings, are ideal for this application. To pass the signals from the fast-moving blades to the stationary control unit, a fiber optic rotary joint comes into play. The device needs to be able to withstand the weather, sometimes extreme conditions, last essentially forever, and have a small footprint. Since the FORJ takes up the center of the complex rotary joint that consists of a FORJ, electrical slipring, and hydraulic fluid rotary union, a larger FORJ would drive up the size of everything else.

The same concept has seen application in aeronautics such as helicopter design. The rotor blades are the lifelines of the crew and the machine. So constant monitoring on the blade's condition is essential for the well-being of the flying machine. Optical fiber provides clean, low-noise, and low-interference passage of the sensor signal. Fiber rotary joints are also more suitable for high speed rotation compared to electrical sliprings because the optical coupling is contact-free.

On the other end of the energy spectrum is oil, offshore oil to be exact. ROVs are the intricate part of the massive offshore arsenal. They perform underwater surveys, inspect offshore oil rigs, and repair underwater pipelines and infrastructure. They go where humans are not capable or are unwilling. The average depth of the ocean floor (~4,000 m) makes copper wire unsuitable for carrying telemetry due to signal degradation, low bandwidth, and heavy weight. Signal loss through optical fiber per kilometer is less than 0.5 dB. So a typical optical budget of 15 dB in a media converter can permit up to 20 km of cable length while allowing greater than a 5-dB margin for connector and other component losses. That is far longer than any copper cable's capable range.

Continuous fiber connectivity is ensured by one or sometimes two fiber optic rotary joints. The second FORJ is often used in an underwater cage where the ROV rests during off hours in applications where the vehicle needs to be on location for extended periods. The second FORJ needs to be pressure-compensated for pressures that can be as high as 690 bar (10,000 psi). Electrical sliprings are almost always used in tandem with the FORJ to provide power, except on rare occasions where a battery is the power source.

Fiber rotary joints play a similar role in terrestrial robotic vehicles where a fiber umbilical cord is part of the design. Cameras, especially HD video cameras, and controls are the main signal streams the fibers carry. There are also smart designs that track the vehicle's distance to the cable reel, which control the cable length to avoid unnecessary cable tangling.

FORJs even find their role in autonomous vehicles where no umbilical cord is employed. Cameras in this case are the eyes of the vehicles. Their need for free rotation requires a fiber rotary joint to pass the optical signal to the vehicle's brain. The two-camera design, one in the front and one in the rear of the vehicle, is very common.

Another interesting application involves neither cameras nor controls. The fiber cables themselves are the sensors in submarine towed arrays. Fiber sensor arrays detect enemy vehicles. With sensor lengths over thousands of meters, their accuracy far exceeds sonar. Unlike sonar though, the optical sensor does not give away its location. The towed array's frequent pay in and pay out requires a fiber optic rotary joint in its cable reel.

Compared to fiber towed arrays, OCT comes on a tiny scale. However, their optical structures are similar. Unlike the towed array, OCT requires a single strand of singlemode fiber as the probe that gets inserted into a patient's blood vessel through a catheter. A micro turning prism is often placed at the tip of the fiber probe. The fast-spinning fiber probe, which carries a coherent laser beam, scans the inner wall of the vain while moving along it. A computer interprets the reflected signal and constructs a 3-D image of the blood vessel's inner wall. OCT is an exciting new technology in the field of cardiology.

The next example has a lot or everything to do with telemetry. It involves lighter-than-air airborne vehicles or aerostats. The slow-moving or stationary aerostat is used as a mobile platform for radar, cell phone transmitter, TV, radio, or WIFI transmitter, camera (especially HD camera), or military communication station. At a flying height of a few kilometers, their coverage range can be as large as 50 kilometers in diameter, far greater than most ground-level, permanent transmission towers. Fiber optic rotary joints allow these vehicles to fly at different altitudes without losing connection to the ground vehicle. The importance of these systems is being realized in applications such as border patrol, communication for disaster relief, and even on battle fields. Like the ROV application, electrical slip rings are also important parts of the system.

Before fiber came on the scene of telecommunications, the communication backbone consisted of electrical cables and microwave antennae, which still play an important role in communication. Some antennae spin constantly and some spin slowly to track satellites. Radio frequency (RF) rotary joints sit at the throat of those systems to pass the RF signal down. Compared to fiber optic rotary joints, RF rotary joints have limited bandwidth, are more costly to produce and maintain, and are much larger, especially when more than one channel is involved. Therefore, it is desirable in some cases to convert the signal from RF to optical and pass it through a FORJ and fiber. With WDM (wavelength division multiplexing) technologies, multiple channels of RF signal can be multiplexed into one fiber to greatly reduce system size and cost. The interconnection between RF waveguide and optical fiber is much more widespread than most people realize.

The increasing acceptance and deployment of high-definition video broadcasting systems and cameras has created a new market for optical fiber and media converters that can extend the camera to distances that copper cables are not capable of. Although there is no defined maximum cable length, a good quality HDMI cable does not extend beyond 15 meters. An optical cable with media converters, however, can extend beyond 10 to 20 kilometers with no signal degradation. If the cameras are mobile, then fiber optical rotary joints will be called for in the cable reels. As cost goes down, high-end security and surveillance cameras are spitting HD images instead of those ubiquitous snowy scenes in bank robbery recordings. Rotating cameras need fiber optic rotary joints to ensure continuous connection.

Cranes and mining machinery are probably among the most unlikely places one would expect to find fiber optic rotary joints. The truth is that they are becoming increasingly important as mines get deeper and cranes grow taller. For the same reason we've discussed before, HD video images, sensor signals, and control signals, the nerves of the giant machines, require fiber cables and rotary joints since the scale of these machines are much larger than 10 to 15 meters.

Flight simulators, rotational concert stages, strain gauges, scientific research, etc., are among the minor applications for fiber rotary technology today. However, their importance in those fields is growing.

Fiber optic rotary technology

Fiber optic rotary joints are sometimes referred to by the following names: fiber sliprings; fiber rotary couplers; fiber rotary junctions; optical slip rings, etc. They can typically accommodate one to twelve singlemode or multimode fibers. Channel counts as high as a few dozen are also possible. However, it is more of a design preference than necessity in most cases. A single singlemode fiber has bandwidth exceeding terahertz, much larger than what is required by most known mobile systems.

Redundancy is often cited as the reason for large channel counts. In reality, one is most likely better served with spare units than redundant channels as a larger channel count usually implies a more complex structure on the FORJ level. Life span or reliability is likely the price to pay.

In certain military applications, classified channels have to be physically separated from non-classified channels for security reasons. That might have been a valid argument 20 years ago when crosstalk performance of most optical components such as WDMs was relatively high (20-30 dB). Today the same components offer 40 to 55 dB crosstalk performance, which is really not that different from physical separation. In other words, whether the channels are physically separated or multiplexed together makes very little difference from a crosstalk point of view.

The most compelling reason to use more than one fiber in a system is the limited choice of media converters, especially those that employ CWDM (course wavelength division multiplexing) technology. In other words, one often finds himself maxed out on a given fiber with what he can pass. This situation will change as more CWDM-capable media converters become available.

Unlike single-channel fiber rotary joints, two or multiple channel FORJs often require both rotational optics and a de-rotational gear box. As the fiber spins on the rotor side, the gear box slows the speed (de-rotation) of the rotational optics to half the speed of the fiber, resulting in the cancellation of image rotation. Without the de-rotation the image would spin at exactly twice the speed of the fiber. Rotational optics can be prisms, a mirror set, or even a pair of cylindrical lenses. Dove prisms are by far the most common choice. Designs without de-rotation do exist. However, they tend to be bulky and blind spots around the turns can be a concern.

The ultimate challenge in FORJ technology is to produce one or multiple channel FORJs with a center bore. What are available on the market now are not truly passive FORJs. The receiving end is fitted with photo detectors instead of fibers. Therefore, transmission is limited to unidirectional and multimode.

As discussed earlier, in order to use single-channel fiber for bidirectional single- or even multiple-channel signals, one needs to consider fiber optical circulators, multiplexers, or a combination of the two. Both circulators and multiplexers are passive devices, which are frequently available off the shelf at reasonable costs.

Fiber optic rotary joints are more than often used with electrical sliprings, fluid rotary unions, RF rotary joints, or some combination thereof. The most common marriage is between electrical and optical rotary joints since there is no efficient way to transmit power through optical fiber over extended distances.

As one can see by our discussion so far, the most cost-effective solutions are often achieved through collaboration between customers, FORJ vendors, media converter vendors, passive component vendors, and electrical slipring vendors. A well-designed system should be cost effective, easy to maintain, and upgradeable.

Conclusion

There is no doubt that more and more people will realize the benefit of optical fiber technology. Fiber optic rotary joints will find their way into ever more exciting applications. In most of the applications discussed in this article, optical rotary technology is much more than “nice to have.” Instead, it is often the enabling technology. Without it the application wouldn’t exist or would be extremely difficult to achieve.

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