White Paper

Fiber Optic Rotary Joints (FORJ) - Performance and Application Highlights

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Key Messages

- A FORJ is the optical equivalent to an electrical slip ring and are often used in conjunction with slip rings
- FORJs come in single and multi-channel versions and have practically unlimited bandwidth
- FORJs are limited in number of physical channel, but time division and wave division multiplexin g significantly expands the number of channels

Introduction

A Fiber Optic Rotary Joint (FORJ) is a device that allows an optical signal to be transmitted across the interface between a continuously rotating platform and its stationary support structure. Also known as optical rotary connectors or optical slip rings, FORJ applications have proliferated with the increasing adoption of fiber optic communication transmission lines. Such diverse applications as radar pedestals, wind turbines, armored vehicle turrets, and electro-optic sensors have incorporated fiber optic rotary joints to handle optical signals in parallel with slip rings to handle electrical power and signals. The vast majority of these applications use optical signals to carry high speed digital data, but there are a few that depend on the FORJ to carry analog data with frequency or amplitude sensitive (i.e., analog) information.

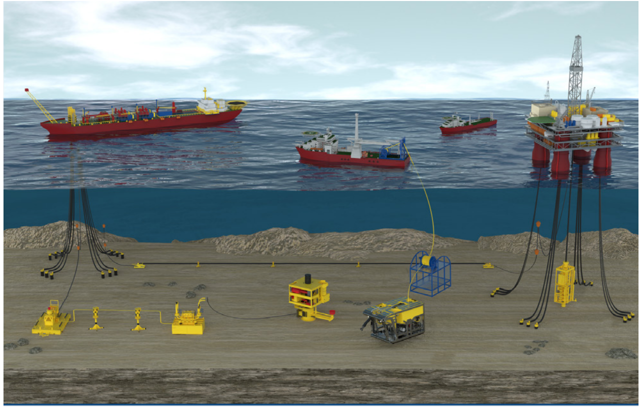

Figure 1: Cable reels that lay out control cables for Remotely Operated (underwater) Vehicles (ROVs) require FORJs to allow the fiber optic cable to spool off the reel.

It is important for the FORJ user to understand the device performance characteristics when incorporating it into a design. There are some decisions that should be made early in the design process to ensure a cost effective and successful implementation. The primary decision is how multiple channels will be implemented: by individual fibers or by multiplexing. The summary section will return to this decision after discussions of multi-pass FORJs and multiplexing. *[In this paper we will use the term "pass" to refer to the number of physical fibers of the FORJ and "channel" to refer to the number of communication paths. Therefore, a single, bidirectional (full duplex) Gigabit Ethernet channel can be multiplexed on a single pass FORJ, or can be carried on two fibers on a two pass FORJ].* Additionally, the user should carefully consider design decisions such as insertion loss and loss variation during the FORJ selection process.

FORJs can be divided into classes based on number of passes and mode of operation: single or multi-pass and passive or active. Passive FORJs transmit an optical signal from the rotating to stationary structure without any electronic processing although components such as filters and lenses can be used to "process" the optical signal. Active FORJs incorporate electronics to process the signal to improve rotor to stator transmission properties and can involve electrical/optical conversion, amplification, signal conditioning and re-clocking. Active devices are used primarily with applications requiring a through-bore. The medical CT scanner, for example, has been one application where an active FORJ has been implemented to carry high speed image data from the rotating X-ray detectors of the sensor array to the stationary data processors.

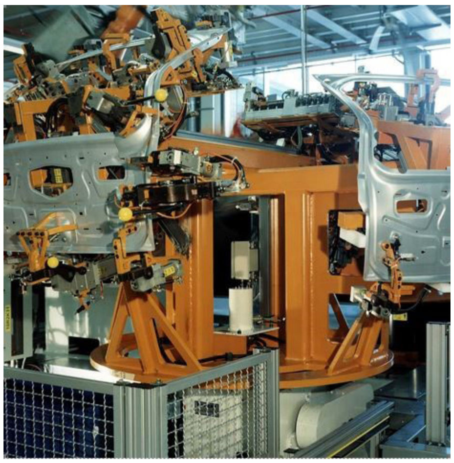

Figure 2: Complex automotive assembly turntable/robot has a fiber optic rotary joint in the center to transfer communication data. EMI isolation of fiber channel is critical in this application. Rotary joint provides power and signal slip rings as well as hydraulic power.

One of the authors of this paper reviewed fiber optic rotary joints in 1982 [2] when the technology and applications were relatively new. The primary emphasis of this earlier paper was on single pass FORJ designs. This present paper is intended to update the single pass discussion but also includes information on multi-pass devices as well as multiplexing strategies. The focus of this paper will be on single and multi-pass passive FORJs since active FORJ devices tend to be customized for specific applications. Passive FORJs have become standard catalog devices and have found uses in widespread applications. The two popular channel multiplexing strategies, wave division and time division, will also be briefly reviewed.

Analog vs. Digital

The vast majority of FORJs are used in digital data transmission lines. The wide bandwidth capability and EMI isolation of fiber has been gradually pushing fiber into increased numbers of applications. The light pulses representing the 1's and 0's of the digital data stream are launched into one end of a fiber and received at the other end. Whereas phasing problems are the most common reason for eye pattern degradation and bit errors in high speed electrical transmission lines, fiber optic transmission lines are most susceptible to signal level or amplitude problems caused by losses in the transmission line. Typically the system margin of a fiber optic transmission line, the difference between the source output level and the detectors input sensitivity, is on the order of 10 dB, allowing for some margin. System designers typically put together a loss budget (Figure 3) and components are selected that allow the system to work within this budget. The FORJ figure of merit that must be understood is the device's maximum insertion loss. The optical insertion loss IL of a fiber optic component is determined from the transmittance T of the component as $IL = -10 \times log_{10}(T)$.

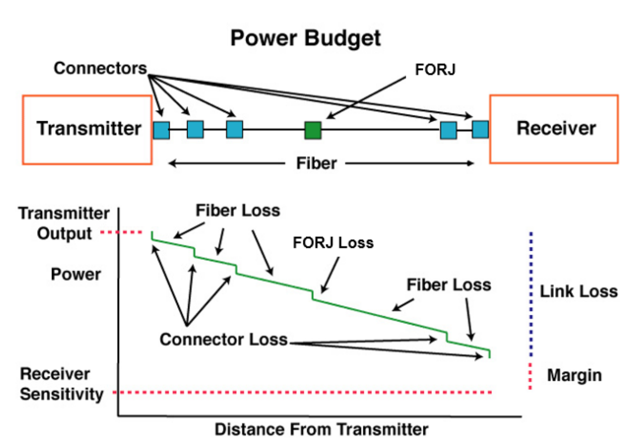

Figure 3: Loss budget must take into account all elements of a fiber optic transmission line including the FORJ.

On the other hand, there are some transmission lines where information is being carried in an analog fashion. For example, some radar systems convert RF electrical signals to optical and then transmit "RF over fiber." And fiber optic distributed sensing applications use analog shifts in signals (amplitude, frequency, or wavelength) to indicated conditions such as temperature or stress. Although insertion loss continues to be a major consideration in these systems, other factors such as loss variation with rotation, return loss, and wavelength and/or polarization dependent losses or variations could also play an important role in system performance.

Single Pass FORJ

Single pass FORJs are rotary joints where a single fiber enters the FORJ on either side of the rotating interface and optical signals are coupled between them as one fiber rotates relative to the other. In general principle, single pass FORJs work by enlarging the diameter of the coupled light by the use of lenses, fiber bundles, or large diameter fiber (Figure 4). By far the most common approach is the use of lenses to expand the optical beam thereby minimizing the effects of mechanical misalignment.

One of the first patented approach of a single pass FORJ used a quarter-pitch gradient-index (GRIN) rod lens on either side of the rotary interface each with length equal to one-quarter pitch[2]. The lens collimated the light signals, which would otherwise propagate from the fiber end face in an ever-increasing diameter cone, into a cylindrical laser-like beam which maintained its shape over a relatively long distance. Light collimated by one lens on one side of rotating interface was directed to the lens on the other side of the rotating interface which focused the light into the output fiber. Lenses and fibers were all oriented to be coincident to the rotation axis of the FORJ.

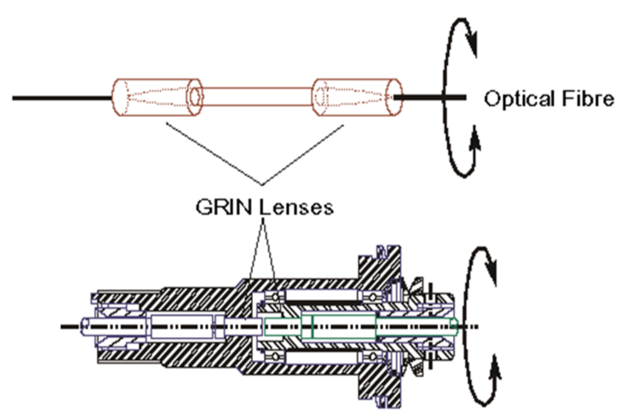

Figure 4: Single pass FORJ using 1/4 pitch GRIN lenses.

The advantages of this type of FORJ design included a lower insertion loss and relaxed mechanical tolerances compared to single fiber without lenses and fiber bundle designs. Over the subsequent years, single pass FORJs used primarily for digital data transmission have been widely commercialized using this general design philosophy using both multimode fiber (62.5 um diameter core and 50 um diameter core) and single mode fiber (8-9 um core). Optical insertion loss values of single pass FORJs are typically 1 dB (equivalent to a transmittance of 0.79 or 79% of the signal).

There has been some success with plastic optical fiber (POF) in FORJs by directly coupling light across the gap without lenses. This is made possible by the significantly greater core size of the POF (typically about 1.0 mm) which makes tolerances at all coupling sites, including connectors, less critical. The success of POF FORJ technology with depend on the adoption of POF networks in industrial applications, with the primary limitation being the shorter distance over which plastic fiber can operate

Anti-reflective coatings are used on the other ends of the GRIN lenses to reduce reflections and significantly improve the return loss of the FORJ while also improving the insertion loss to a lesser degree. Without anti-reflective coatings, the reflectance at a glass (refractive index, n_gl =1.5) to air (refractive index, n_air =1) interface normal to the beam path is

$$R = ((n_{gl} - n_{air})/(n_{gl} + n_{air}))^2 = 0.04$$

If all of this reflected light is coupled back into the input fiber the return loss (RL) is approximately 14 dB where

$$RL = -10 \times \log_{10} (R)$$

By applying an anti-reflective coating with 0.005 reflectance the return loss is improved to 23 dB. In the uncoated case only 96% of the light is transmitted through the interface; if all of this light is coupled into the output fiber the insertion loss due to the interface is 0.18 dB and the latter case the insertion loss is 0.02 dB. There are also some lens alignment adjustments that can be made to also improve the back reflection of the FORJ.

Other lens types can be used in place of the 1/4 wave grin lenses. In particular, spherical ball lenses perform the same collimating function, but often require additional structures inside the FORJ to provide the required alignment precision between the fiber and the lens. The alignment of the fiber to the lenses and the subsequent fixation is critical to successful performance of FORJ. In the case of a single mode FORJ, which has a mode field diameter of approximately 10 um, a 2 um lateral offset between the beam and the receive fiber results in a coupling loss of 0.7 dB [3].

The only wearing components in the single pass FORJ are the bearings required to align the stationary to rotating structure; the FORJ is otherwise essentially non-contacting. These bearings support a shaft holding one fiber-lens collimating assembly with the lens optical axis coincident with the rotation axis relative to a housing holding the other fiber-lens collimating assembly, also coincident with the rotation axis. In many cases a rotary seal is also required to prevent contaminants from entering the bearing and/or the optical gap between the lenses. A single pass FORJ can be expected to remain mechanically stable with minimal shift in optical properties after 100 million rotations at speeds limited by the speed rating of the bearings.

In order to allow the shaft of the FORJ to be rotated relative to the housing (or vice versa), a mounting flange is provided on the housing side of the FORJ and a torque arm or arrestor is provided on the shaft. In order to rotate the shaft relative to the housing, a rotating, loose coupling applies a torque to the arm. In order to rotate the housing relative to the shaft, a stationary loose coupling prevents the shaft from rotating as well. The coupling must be loose in order to avoid applying a load to the side of the shaft due to eccentricities in the rotational coupling. This side load can overcome the bearing preload and cause insertion loss to increase while the FORJ is rotated.

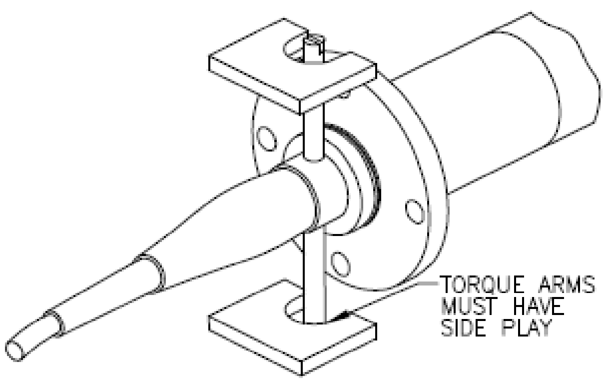

Figure 5: Mounting of the FORJ to avoid bearing damage from misalignment.

Multi-Pass FORJ

In a case of a multi-pass FORJ, multiple fibers enter the FORJ on either side of the rotating interface. Optical signals are coupled only between specific pairs of fibers across the rotating interface and because of this, a multi-pass FORJ can transmit multiple independent data streams across the rotating interface even when optical multiplexing is not used. From a mechanical perspective, multi-pass FORJs are generally more complex than single-pass FORJs because of the mechanisms required to provide rotary alignment of multiple fibers. Multi pass FORJs are available in a number of differing configurations. These FORJs tend to be physically larger than single-pass FORJs due to both the increased number of fiber pairs and the added mechanical complexity. Typically, optical insertion loss for each pass in a multi-pass FORJ is 3 dB (50% transmittance).

Lens-based A lens-based two-pass FORJ can be considered a special case of a multi-pass FORJ and is similar to a single-pass FORJ in its use of lenses to transfer the optical signals on the center line. Two internal collimating lenses facing each other across the rotating interface are oriented coincident to the FORJ rotation axis in a fashion identical to a single-pass FORJ with single-pass insertion loss performance. Located coincident to the FORJ rotation axis but further away from the rotating interface are two additional collimating lenses which face each other across the rotating interface. Light collimated by these external lenses is partially blocked by the fibers attached to the internal lenses resulting in the insertion loss of the second pass of the FORJ being higher than that of the first.

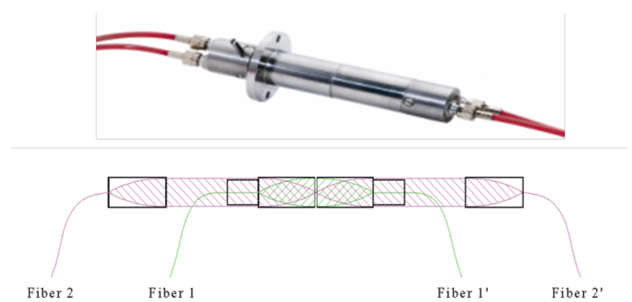

Figure 6: Lens-based two pass FORJ.

Intermediate Optical De-rotation

In 1969, an optical spin compensation device was patented by a NASA engineer [4] that involved de-rotating and optical image by utilizing an intermediate optical device (a Dove prism) that was rotated at one half of the image rotational speed thereby producing a stationary image. For those interested in a more detailed description of the "velocity compensation" technique, Shapar provides more detail [5]. In 1978, Iverson utilized this concept in an early patent for multi-pass Optical Slip Rings [1]. Figure 7 shows the illustration of the approach, again using a Dove prism, which is found in this 1978 patent. Iverson illustrated several other concepts for non-prism intermediate optical media, such as fiber bundles, that have been attempted in multi-pass FORJs but in fact the prism approach has been the only concept that has proven commercially viable to this point.

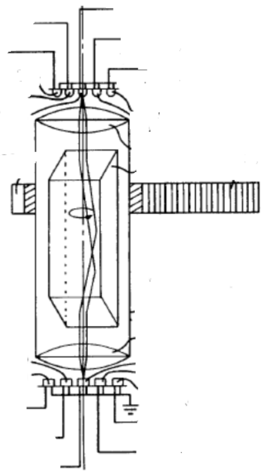

Figure 7: Prism-based multi-pass FORJ concept. The prism rotating at 1/2 of the angular rotation speed in the opposite direction of the optical signals allows the signals to be aligned with the stationary fiber ends.

In a de-rotating prism-based configuration, an array of a number of optical fibers enters the FORJ each side of the rotary interface. Oriented between them along the rotation axis of the FORJ is a particular type of prism known as a de-rotating prism; there are a number of prism designs including the roofless Schmidt-Pechan, the roofless Abbe-Koenig, and the Dove prism. The Dove prism, being the simplest design, is customarily used. As a de-rotating prism is rotated about a particular axis through the prism, the image of a stationary object will rotate in the same direction but at twice the speed. This property is used in a FORJ by using an internal gear train to cause the prism to rotate in the same direction but at one-half of the speed of the rotating array of fibers entering the FORJ. The gear train may be a single pinion shaft coupled to the rotating array of fibers and the rotating prism with gear teeth and pitches selected to provide the 1:0.5 gear speed ratio, or may consist of multiple pinion shafts coupled to the rotating and non-rotating arrays of fibers passing through the prism rotor in a spur differential configuration. Beams from each fiber pass through the single de-rotating prism, however the distance between the two collimating lenses associated with each pass is shorter in this design compared to that of the cell-based design and FORJs with fiber counts of fifty or more are commercially available.

Mirror-based Cell Approach

The mirror-based cell design as shown in Figure 8, is another approach which has found some popularity in multi-pass FORJ applications. This design is especially useful in the marine environment where it is often required to fluid fill the FORJ for pressure compensated sealing. In a cell-based configuration, an array of a number of optical fibers enter the FORJ on one side of the rotary interface and within each of the same number of mechanical cells within the FORJ, light from one fiber is reflected to the rotation axis and then along the rotation axis for a short distance using mirrors attached to a rotor which rotates at the same speed in the same direction as the array of fibers entering the FORJ. Within each cell a third mirror held stationary to the cell housing reflects the beam of light located on the rotational axis of the FORJ to a fiber oriented at 90 degrees to the rotation axis. Light from a fiber which is coupled across the rotary interface in a cell further away from the array of optical fibers entering the FORJ must pass through the rotors of all of the cells which are closer to the array and as a result the rotors within each cell must also rotate at the same speed in the same direction as each other. This is achieved by coupling the rotors to each other and to the array of optical fibers using a gear train with a single pinion shaft extending through the FORJ. The mirrors attached to each of the FORJ cell housings may be held in place by a number of techniques which allows light from fibers which are coupled across the rotary interface in cells further from the array of fibers to pass unimpeded. The distance between the two collimating lenses associated with each pass increases as the cell associated with the pass is located further from the array of fibers; the insertion loss of the fiber pass increases as a result of the increase in lens to lens distance and this generally limits the number of fiber passes to ten or less.

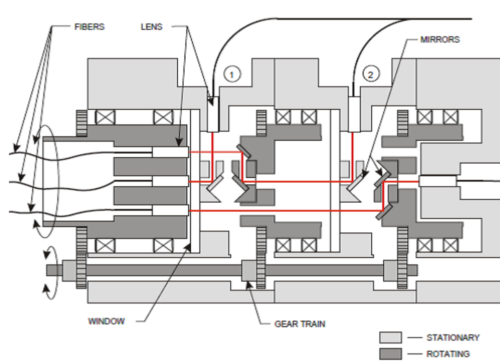

Figure 8: A 2 cell (pass) mirror based approach is shown for a multipass FORJ Cells can be added to achieve any number of desired passes up to about 10.

Active FORJ

An active FORJ aligns the either the light source or the light detector (or both) across the rotating gap. Figure 9 shows a common approach that simply aligns a transmitting element to a receiving element across a rotating interface.

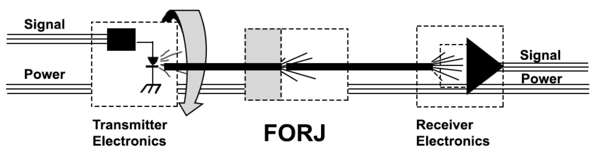

Figure 9: Active fiber optic rotary joint.

Lenses and filters may be used to improve the coupling efficiency. It should be noted in this case that the input/output of the FORJ is electrical, and the electrical to optical (E/O) conversion occurs simply for transfer of the signal across the gap. One of the most common applications for the use of this approach is to transfer optical signals when a hollow bore is required. For example, medical CT scanning imaging machines typically must allow a patient to pass through the machine typically requiring a machine bore diameter of 1-2 meters. Image data from the rotating x-ray detectors to the stationary image processor typically is transmitted at 1.25 to 10 Gbps and one technique that is used is an active optical data ring as shown in Figure 10. Although the signal is transmitted to this active FORJ optically, the active FORJ converts this signal to an electrical signal, drives the FORJ light sources, and then converts the electrical output from the light detectors back to an optical signal for transfer to the image processors. This "free space" optical transfer is typically quite lossy, so some degree of signal processing is required to clean it up. Active FORJ devices are useful when the input or output needs to be electrical, when the geometry requires a large hollow bore, or when the bandwidth requirements exceeds the capability of an electrical signal.

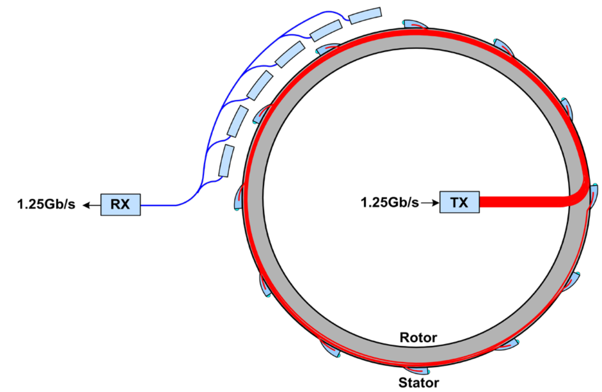

Figure 10: A large bore active fiber optic rotary joint. An optical signal (in this case 1.25 Gbps FPGA output) generated by the rotating electronics is transmitted to the rotating lenses and is transmitted across the gap to the pick-up lenses and then off the stationary electronics.

Multiplexing

The use of a FORJ in a fiber optic system plays an important role in multiplexing decisions. As earlier discussions have shown the complexity of fiber optic joints increase significantly when the number of optical passes are greater than 1. The graphic of Figure 11 shows that size and cost of a FORJ do not have a smooth functional relationship with number of passes. In the electrical equivalent of a FORJ, a slip ring, it is a simple matter to incorporate more wires as the number of passes are increased and the incremental cost is fairly insignificant. However, physical passes in a FORJ are quite dear and should be added after careful consideration. Often a more cost effective approach to adding optical passes is to use multiplexing which adds effective channels of information without adding physical passes. Multiplexing takes advantage of the almost unlimited bandwidth of a single fiber by placing multiple signals on a single (or reduced number of) physical optical pass.

Figure 12 illustrates one of the most common multiplexing schemes that allows a bidirectional communication signal to be transmitted on a single fiber using two wavelengths of light simultaneously on a single fiber. This is commonly implemented on a full duplex Ethernet connection. This scheme illustrates wavelength division multiplexing (WDM) which uses multiple light wavelengths to carry multiple signals on a single optical fiber. In the case of this Ethernet transceiver the wavelengths are separated by over 200 nm, however this separation be decreased to 20 nm, the typical separation of course wavelength division

(CWDM), or as little as 1-2 nm as in dense wavelength division multiplexing (DWDM). WDM takes advantage of the fact that multiple wavelengths of light can be transmitted on a single fiber without interference, at the expense of additional insertion loss in the system due to the inclusion of the WDM couplers.

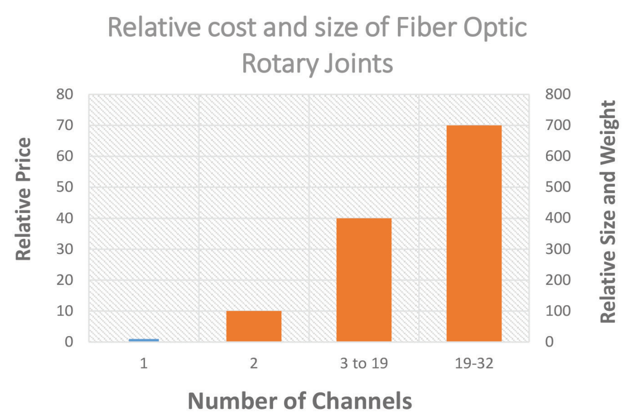

Figure 11: Approximate relationship of number of passes to size, weight, and cost of a FORJ.

An alternative to WDM is time division multiplexing (TDM) where serial data streams are sampled and these samples combined into a single data stream which carries multiple channels of information. Since sampling must be done at a faster speed than the original data (in accordance with Nyquist principle) and the data rate of multiple signals on the same channel can be quite high, TDR takes advantage of the almost limitless bandwidth of optical fiber. The increased use and flexibility of FPGA's to multiplex data, has sharply increased the use of TDR in electronic applications. The use of these multiplexing schemes in rotating systems has the effect of simplifying the FORJ. The net effect of decreasing the number of physical passes is to reduce the size, cost, and weight of the FORJ without an additional performance decrement on the signal.

Figure 12: Typical configuration in bidirectional communication transceiver.

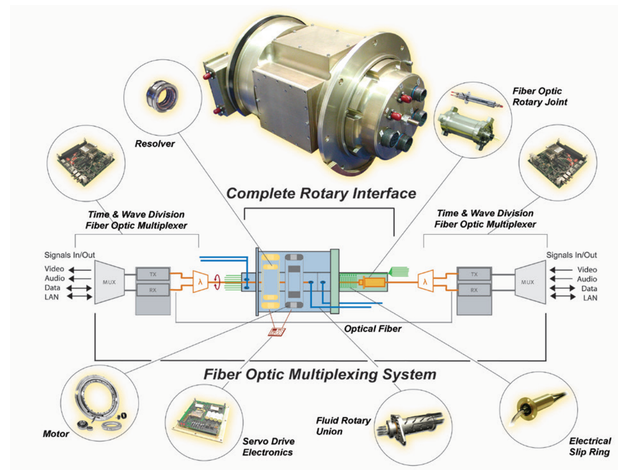

Figure 13: Rotary system integrating a FORJ.

Summary

A FORJ is typically integrated into a fairly sophisticated rotary system. One example of a rotating sensor pedestal application is shown in Figure 13. It is important to carefully consider the best trade-off of multiplexing and physical passes when establishing both the mechanical and electrical architecture of the system. For example, single pass FORJs can be quite small, but some degree of multiplexing will be required to handle a typical quantity of communication and sensor signals. On the other hand, most multiplexing can be eliminated with the use of larger, more complex multi-pass FORJs. And as Figure 13 illustrates both wave division and time division multiplexing can play a role in reducing physical pass count and simplifying systems. In the case of rotary systems, it is essential to optimize these trade-offs between channel count and physical pass count before the final system architecture is established.

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