Electro-Optic Hybrid Rotary Joint (EOHRJ)

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ABSTRACT

An advanced electro-optic hybrid rotary joint (EOHRJ) has been developed in Phase II of an AF SBIR effort with Physical Optics Corporation (POC) to replace cable wrap structure for multi-channel rotation-to-fixed (RTF) signal transmission. The EOHRJ meets AFFTC and other range special needs with a generic, high performance, rotary joint solution. At the moment, we have successfully installed and tested the EOHRJ on our KTM tracker system with the following capabilities: 1) able to accommodate hundreds of transmission channels, including electrical power, control, feedback, and low-speed signals; 2) able to accommodate multiple channel, high data rate (over gigabits per second), and bi-directional signal transmission; 3) able to be reliable for harsh environmental operation, adaptive to stringent sized requirement, and accommodating existing electrical and mechanical interfaces.

The completed EOHRJ contains three uniquely integrated functional rings. The first and the outmost one is power ring, which provides RTF transmission channels for over 50 high voltage and high current channels. The second and the middle one is low speed electrical signal ring, which provides RTF transmission for over hundred control, feedback, and low speed data signals. The third and the inmost one is optical fiber slip ring, which, incorporating with current advanced signal multiplexing technologies (either time division or wavelength division multiplexing) is able to provide multiple channel, high data rate, and bi-directional signal transmission. At the moment, the prototype module of the tree-layer EOHRJ has been successfully assembled in Air Force's tracker system, and is providing a satisfactory performance. This paper presents our joint work on this project.

[short: This paper addresses the development of a unique three-layer electro-optic hybrid rotary joint (EOHRJ). The EOHRJ is able to transmit all types of signals for rotation platform to fixed position, or vice versa.]]

Key Words: Electrical Slip-ring, Optical Rotary Joint, Tracker System, Wavelength Division Multiplexing (WDM), and Time Division Multiplexing (TDM)

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1. INTRODUCTION

The video tracker Kineto Tracking Mount (KTM) is used by the U.S. Air Force and NASA to maintain range safety, night vision, and other real-time applications. Most current KTM systems use cable wrap structures to transmit sensed data, video and audio signals, and other information from rotating platforms to control systems at fixed locations. With the rapid development of modern technology and the proliferation of applications, there is a tendency to add more sensors to existing mounts, resulting in an increased number of data stream channels and an increased data rate for each channel in a data stream. For instance, in a typical KTM system, over a hundred signal channels have to be connected from the rotating platform to the fixed center. In addition, high definition color video and infrared sensors on tracker systems will generate high-rate data streams exceeding hundreds of Mbits per second (MBPS), up to Gbits per second (GBPS). In order for modern sensing,

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control, and processing systems to operate accurately at high-speed, a reliable, speed-matched, rotating-to-fixed signal transmission technology is urgently needed.

The introduction of lightwave technology into today's communication, computer, and sensor networks [1] for both military and industrial applications has spawned numerous new photonic components that are smaller, lighter, faster, and more reliable than their purely electronic counterparts. Optics and photonics are gaining in popularity because of their intrinsic high speed, high information volume, and immunity to electromagnetic interference (EMI). At the same time, they have become affordable.

Physical Optics Corporation (POC), in corporate with Edwards Air Force Base, has developed and tested a unique electro-optic hybrid rotary joint (EOHRJ) for Air Force KTM system applications. The EOHRJ provides the following unique features. First, it includes a specially designed two-layer electrical slip-ring (ESR), which is capable of accommodating hundreds of transmission channels, including electrical power, control, feedback, and low speed data signals. Second, it includes an advanced on-axis fiber optic rotary joint (FORJ), which is able to provide multiple channel, high data rate (over GBPS), and bi-directional signal transmission. Third, the EOHRJ is compact and adaptable to the existing KTM space; rugged and reliable for harsh environmental operation; and accommodating of existing electrical and mechanical interfaces. The EOHRJ has been successfully incorporated into a typical KTM system and has demonstrated satisfactory performance.

This paper presents our joint work between POC and Edwards Air Force Base. First, we address the motivation for this development. We then review our work on FORJ, including basic architecture and major functional parts. Next, we describe our work on the three-layer EOHRJ development, including special two-layer ESR design and fabrication, ESR and FORJ integration, and EOHRJ to tracker system installation. The system test and performance demonstration is then followed. We close the paper with remarks about future applications.

2. MOTIVATION FOR THE DEVELOPMENT

Current weapons systems use a variety of sensors and testing devices to monitor and measure systemic, environmental, and operational factors. These sensors and testing devices often operate in different frequency or wavelength bands and under different environmental conditions. In many applications the sensors and testing devices are distributed on a rotating platform and the received signals have to be transmitted from the rotating platform in the test area to a fixed point at the command or process center. For example, the Air Force's mobile optical KTM tracker systems are equipped with a number of optical and electrical sensing devices, including high frame rate cameras. During space test operation, the sensor platform has to trace a fast moving target in both horizontal and vertical dimension, and send all types of signals to the base center. At the same time, the electrical power, control, and command signals have to be transmitted from the base center to the rotating platform. Presently, rotating-to-fixed (RTF) signal transmission is handled by a large number of electrical cables (up to two hundred). The use of wrapped cables as RTF connectors has limited the rotating angle of the entire tracker system to 380 degrees. That is, only one complete revolution can be made. Then the system needs to be rewound. Whenever the angle is over this limit, the wrapped cables have to be unwrapped so that they will not break. This unwrapping operation may lead to missing targets, loss of time, money, and manpower. Furthermore, using diversified cables to transmit a wide range of signals also limits system operation speed and overall data rates. To overcome such problems, a special rotating-to-fixed signal transmission structure which is capable of handling RTF transmission for all types of signals is urgently sought. It is because of this real demand that this program was initiated. The aim of the program is to develop a unique RTF joint to replace all cable wrap joints and, at the same time, to furnish additional high-speed signal channels to existing tracker systems for future use. To achieve this goal, we have pursued the following major tasks: (1) develop a unique fiber optic rotary joint (FORJ), incorporated with advanced multiplexing techniques to perform the RTF function for multiple high-speed signals; (2) develop a special electrical slip-ring (ESR) to handle the RTF function for all DC, low speed, and high power signals; (3) integrate the FORJ and ESR to form a comprehensive EOHRJ, and fit it into a modified KTM system; (4) test and demonstrate the EOHRJ-equipped KTM system. Figure 1 shows a schematic of a future KTM system which will be equipped with POC's EOHRJ.

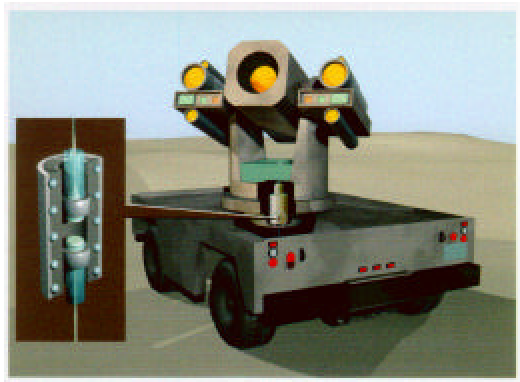


Figure 1
Air Force's KTM tracker system equipped with EOHRJ.

3. DEVELOPMENT OF FIBER OPTIC ROTARY JOINT

As will detailed addressed, the entire EOHRJ consists of three functional layers: the external electrical slip ring for power transmission, the internal electrical slip ring for low speed signal transmission, and inmost fiber optic rotary joint (FORJ) for extremely high speed signal transmission. Due to its importance, we first briefly review our work on FORJ development

Concept and Architecture

The FORJ developed consists of two compact optical and photonic components: (1) an optical RTF signal transmitting component, which includes a pair of either non-imaging-optical (NIO) elements or graded refractive index (GRIN) rod lenses, and (2) a photonic component, which contains POC's fiber data link system (including electrical TDM, optical WDM, and a transceiver (TRx) array). The concept and general architecture of the FORJ is depicted in Figure 2. The multiple signals on the rotating platform are first multiplexed through electrical TDM, and then converted to optical signals through an internal transceiver array (1, 2, ..., n). These optical signals are then mixed onto a single optical fiber through a compact, optical WDM component. The light beam transmitted through the optical fiber is then expanded, collimated, and emitted into the air gap by an NIO or GRIN component placed in the center of the rotating platform. Because of this center emitting arrangement, the output light beam propagates in the short air gap in a stationary manner without being affected by the rotation of the platform. The collimated light beam is received and focused back to a single optical fiber by an identical NIO or GRIN component. The received light is carried to the second WDM component, where the optical signals (1, 2, …, n) are demultiplexed and sent to the command base for detection, electrical time division demultiplexing, and further signal processing. In this way, multichannel signals from a rotating platform can be transmitted to the fixed ground center. Following a similar process, the signals from the ground center can be transmitted to the rotating platform, because the optical components involved in this FORJ system (optical fiber, NIO or GRIN lens, WDM, and optical transceivers) are all bi-directionally operable. In this way, not only can the control center receive sensed signals from the rotating platform for monitoring and processing, but it can also send signals (such as actuator commands, switching, or feedback signals) back to control any of the sensor arrays. In addition, because of its optical nature, the FORJ provides inherently high data rate capability.

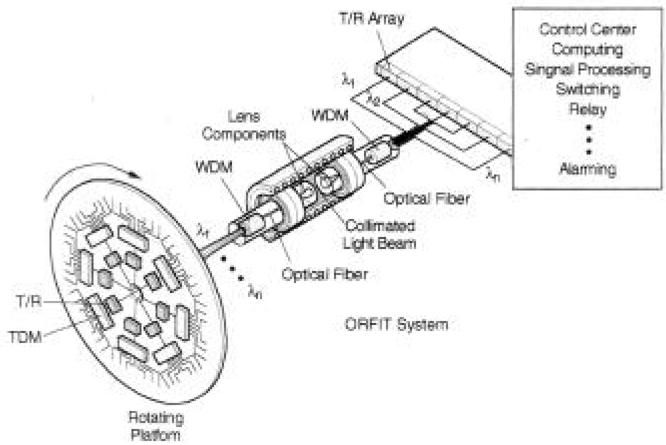


Figure 2
Schematic and Operational Principle of the FORJ.

Major Components

The developed FORJ is mainly composed of a pair of NIO or GRIN components and a pair of POC fiber data link sets, which include electrical TDM, optical WDM, and electro-optic transceivers. They are described as follows.

1. Non-Imaging-Optical (NIO) Components

Unlike conventional lenses, which function on the principle of light refraction, NIO components function on the principle of total internal reflection (TIR) and Lagrane invariant characterization of light propagation through an optical system for paraxial beams [2-4]. The structure can be realized in either a dielectric or metallic configuration. The former operates on the TIR principle (in which the reflection coefficient is exactly equal to 100%), while the latter relies on low loss reflection from finely polished metal to concentrate the beam. A typical NIO structure is shown in Figure 3.

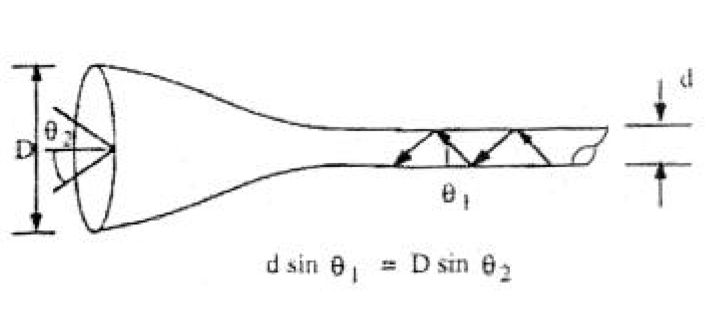


Figure 3
Schematic and Operational Principle of NIO Component.

According to Liouville's theorem, the following relation always holds true:

$$D \sin\theta_2 = d \sin\theta_1 \quad (1)$$

where D and d represent the diameters of the cross-sections at the large and small ends of an NIO component, respectively; θ_2 and θ_1 represent the light beam divergence angels at the corresponding ends. For this application, d and θ_1 (at one end) are determined by the optical fiber used, while the aperture at the other end can be decided easily by the beam collimation requirement. The transition curve (or surface morphology) between these two ends can be designed by using POC's in-house ray tracing program to achieve the peak collection efficiency allowed by Liouville's theorem.

2. GRIN Lenses

The refractive index profile of a GRIN lens is approximately quadratic; therefore, it guides light according to the index distribution [5-6]:

$$N(r) = N_a (1- A r^2/2) \qquad (2)$$

where r is the radial distance from the optical (and geometric) axis, N(r) is the refractive index at the radius r, and N_a is on the optical axis. Figure 4 illustrates light transmission through a GRIN lens.

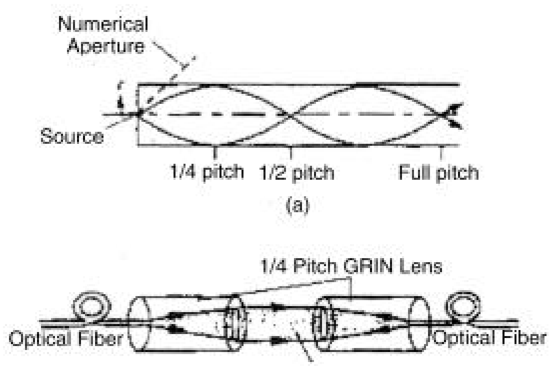


Figure 4
Schematic and Operational Principle of GRIN rod lens. (a) Guided light in a GRIN lens; and (b) a pair of 1/4 pitch GRIN rod lenses for light transmission in ORFIT system.

3. Electrical TDM

The operating principle of TDM is depicted in Figure 5. As shown, with the help of a synchronizing clock signal, N channel signals in a frame can be time multiplexed into one single transmission channel on the transmitter side, and on the receiver side, the multiplexed signal can be time demuliplexed back to N channel signals with the help of the common clock signal.

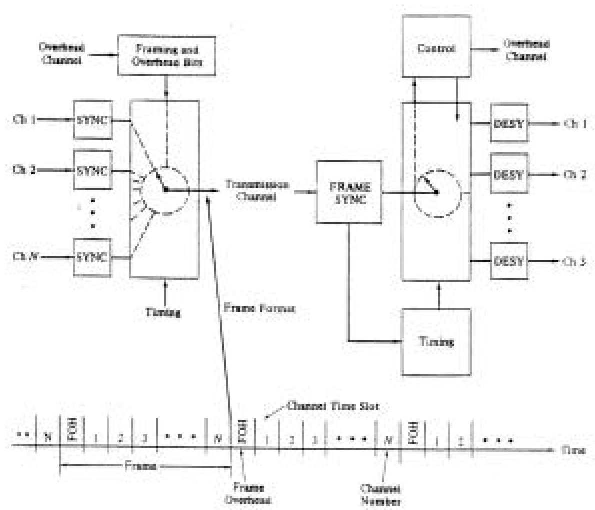


Figure 5
Schematic and Operational Principle of TDM: with the help of synchronizing clock signal N to 1 and 1, to N, channel transformation is realized.

4. Optical WDM

As mentioned, with the help of WDM components large number of high-speed signals can be finally transmitted through a single piece of optical fiber. POC's WDM component consists of only three parts: a fiber array on a silicon V-groove substrate, a molded lens, and a planar diffraction grating. As shown in Figure 6, when multi-channel optical signals with a wavelength separation of $\Delta\lambda$ are transmitted by the input fiber array, they are first collimated by the aspherical molded lens, then each of the collimated light beams is incident onto the dispersion grating and diffracted back to a pre-designated position. With proper design [7-9], the light beams from all the fibers are focused by the same lens and are received by a common output fiber.

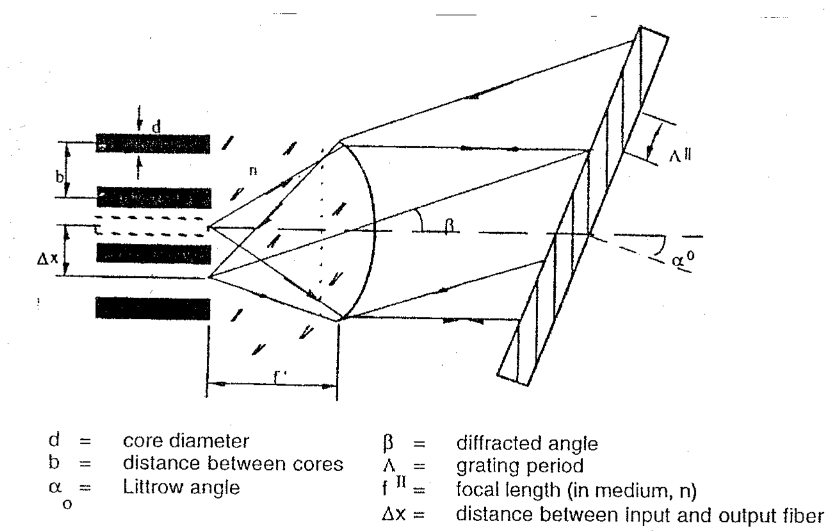


Figure 6
Schematic and Operational Principle of POC's Fiber Optic WDM Component

5. Fiber Optic Multimedia Link Set

The fiber optic multimedia link sets, developed by POC, provide simultaneous one-way or two-way transmission of multiple-channel video, audio, and sensor data signals over a single piece of optical fiber. Figure 7 shows the block diagram of a POC's typical fiber multimedia link system.

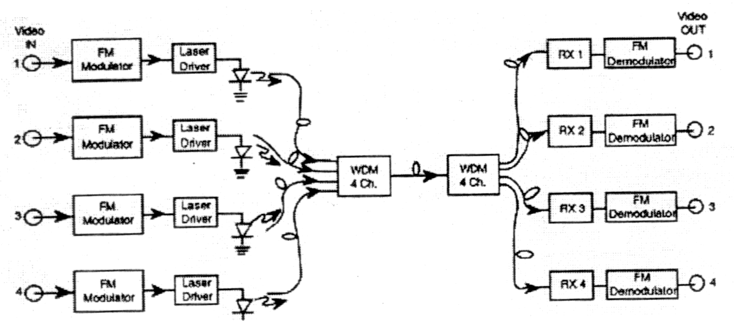


Figure 7
Schematic and Operational Principle of POC's Fiber Optic Multimedia Link System: Demultiplexers using subcarrier frequency modulation to combine audio and video electrical signals.

4. DEVELOPMENT OF TWO-LAYER ELECTRICAL SLIP RING

The FORJ developed above is able to transmit multiple-channel high-speed channels, but it is unable to handle multiple-channel high power signals. To solve this problem, a comprehensive electrical slip-ring (ESR) was developed in parallel during the course of this project. Finally, by integrating the FORJ with the ESR, a comprehensive EOHRJ has been created to handle the entire RTF function for the KTM system.

4.1 Concept and Architecture of Three-Layer EOHRJ for Tracker Use

As mentioned, we developed the ERS to solve the following very challenging problems. First, in the KTM, the number of signal channels to be transmitted is exceptionally large, up to 200 cable lines being involved. Second, the types of signals to be handled are rather disparate, from DC to RF signals, from small power to high power signals. Third, the existing space for the ESR assembly in the KTM system is rather limited. The narrowest portion is only 4.5 inches in diameter. Fourth, the FORJ developed previously has to be integrated in the on-axis position so that the resulting EOHRJ is capable of handling all types of signals. Finally, the FORJ, ESR, and the entire EOHRJ must be reliable and able to operate in harsh working environments.

In response to the above challenge, POC developed a three-layer integrated EOHRJ structure. The entire EOHRJ is composed of three integrated functional rotary joints. The outmost piece is designed to carry the power, ground, and high current rated cables. The middle piece is designed to carry all signals from feedback, shielded, and twisted pair cables. The inmost central piece is the FORJ, which is inserted at the axial position to handle high speed and low power signals. In order to meet the space demands, a concentric, drum type ESR configuration is utilized to form overlapping power and signal slip rings. Hundreds of rings are arranged adjacent to each other along the centerline. Figure 8 shows the schematic of the three-layer slip ring structure, and how it is attached to the current tracker system. The related design, fabrication, and assembly are addressed below.

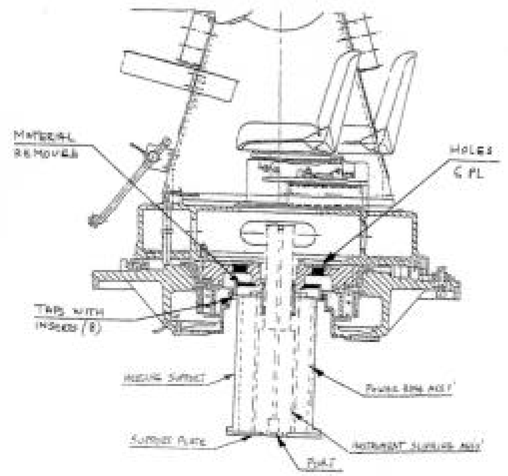


Figure 8
Schematic of three-layer integrated EOMRJ and its attachment to the KTM system.

4.2 Design and Fabrication Issues

As shown in Figure 8, ESR portion consists of two overlapping layers of slip rings -- the power slip ring and the signal slip ring. The former is shown in Figure 9 (a), it includes up to 66 rings to handle the required KTM electrical power supplies, rating from 12 V to 115 V, and 3 A to 25 A. The later is shown in Figure 9 (b), it includes up to 186 rings to handle system control, feedback, and switching signal transmission, operating from DC to lower RF bands. In the design, by matching the external diameter of the internal ring with internal diameter of the external ring, these two rings can be perfectly overlapped to form a rugged yet compact ring structure. In addition, by leaving a matched cylindrical space on bottom-center position of internal ring, the tiny FORJ unit can be attached perfectly to form a unique three-layer EOHRJ structure. Both power and signal ESRs use solid coin silver rings and silver graphite brushes. The solid silver rings arc vacuum cast with an epoxy dielectric onto a steel rotor structure as a group. They are not stacked on a rotor structure as is common with other slip ring assemblies. The silver rings are turned to be concentric with the bearing diameter and a thru bore. This method of construction produces a slip ring that is exceptionally reliable, both mechanically and electrically over the life of the system the slip ring is installed in. Solid coin silver rings cast as a group to the rotor structure eliminate the problems that are associated with plated ring surfaces and stacked slip ring rotors, making it more suitable to handle vibration and temperature extremes. This type of rotor structure eliminates virtually all paths from ring to ring and ring to ground. The dynamic resistance of this slip ring, as low as 0.010 ohm, is expected to be stable over very long periods of time because the ring surface does not change as in the case of a plated ring surface. The entire slip rings are made of stainless steel, except for the outside cover, which is aluminum. All wires are cast in dielectric epoxy for insulation, and also to prevent any movement during transport or operation. All contacts are soldered, using silver solder compound. To increase the lifetime, all bearings have been sealed and lubricated.

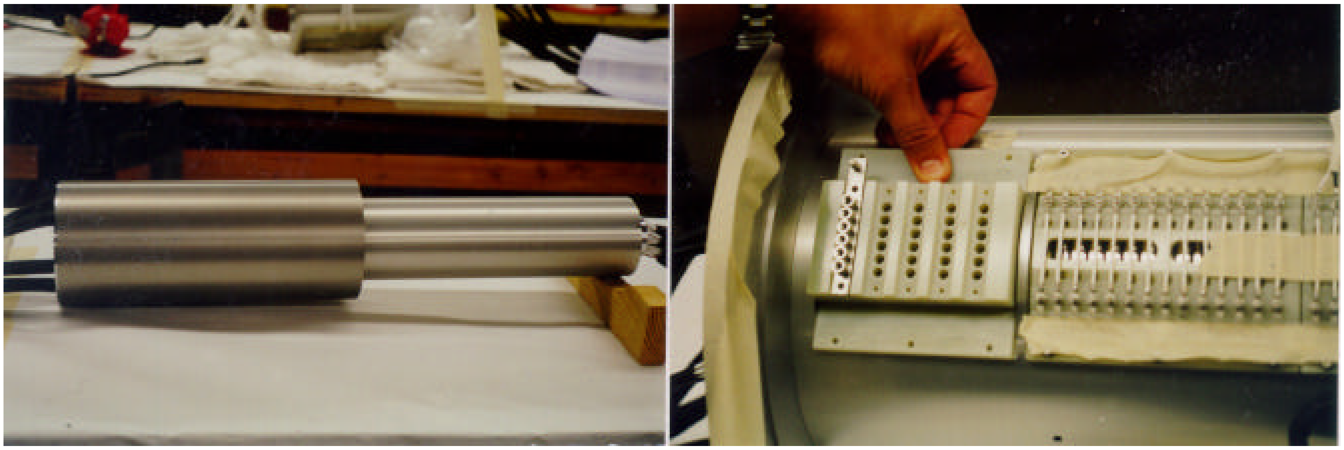
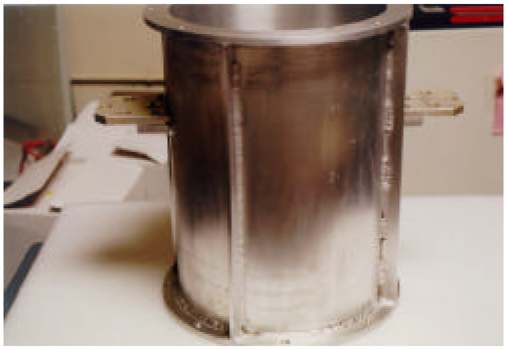


Figure 9
The KTM matched EST consists of two overlapped slip-rings: (a) the signal slipring and (b) power slipring.

4.3 Assembly and Installment Issues

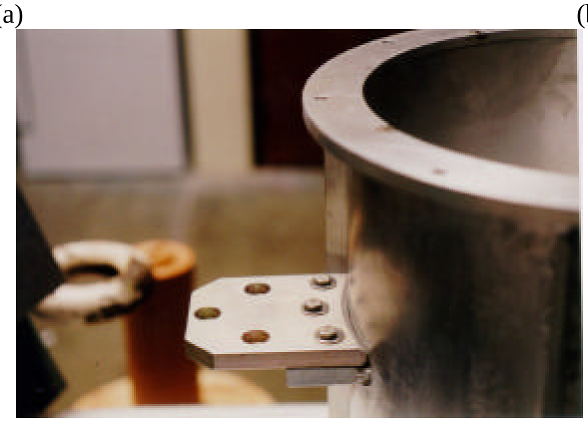
1. Installment of Three-Layer EOHRJ

In the current KTM system, the limited space available requires the extension of the bottom housing to accommodate the length of the three-layer ring structure. Both slip ring assemblies are self-contained and individually covered. To integrate the slip ring assemblies with the current KTM in the limited space, a housing support was designed to control the adverse effects of uncontrolled vibrations. The internal and external housing supports were designed and fabricated to provide the following three functions: (1) support the vertical axial position of both slip-ring assemblies; (2) provide an anchor to the stator base of the instrument slip-ring and the stator of the FORJ; and (3) environmentally shield and protect all three slip-rings. Figure 10 shows the supporting housing, consisting of a circular ring and two (top and bottom) flanges attached with pin and counter-sink bolt construction for increased mechanical strength.



(a)

(b)



(c)

Figure 10
Support Housing for ESR Attachment and Enforcement

2. Installment of Inductosyn and Resolver

Following the installation of three-layer EOHRJ, the inductosyn and relsolver (whose function is to detect and control rotation position of the tracker) were then installed. To ensure that the FORJ and its I/O fiber cables have the entire center position, a two-gear transmission system was designed and fabricated so that the originally center-positioned resolver can be shifted from center to a proper designed off-center position.

Figure 11 shows the installed EOHRJ in the KTM system. Figure 11 (a) is a top view with single mode fiber cable extended to the rotating platform. Figure 11 (b) is a bottom view with the inductosyn and resolver attached for rotation position feedback control.

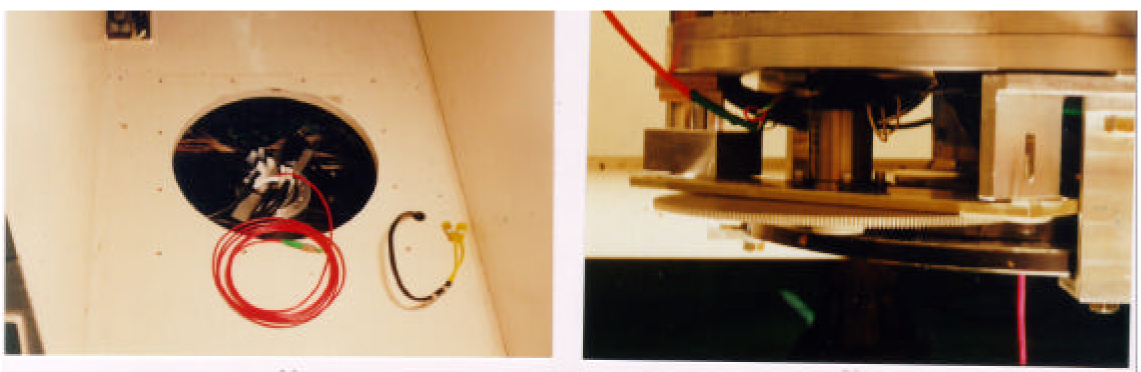


Figure 11
Installed EOHRJ in the KTM system: (a) top view with single mode fiber cable extended to the rotating platform; (b) bottom view with the inductosyn and resolver attached for rotation position feedback control.

5. SYSTEM TEST AND PERFORMANCE DEMONSTRATION

Thus far the EOHRJ equipped KTM tracker system has been tested in both laboratory and field, the assembled EOHRJ has demonstrated satisfactory performance.

5.1 ESR Test and Performance

As mentioned, the maximum rotation angle of the original cable-wrap tracker system was limited to 380 degree to avoid cable break, once the angle limit was reached, the tracker system would stop and rotate back for a new test. At the moment, the ESR equipped tracker system can rotate freely without any limit. All power, control, feedback, indicator, and ground signals are properly transmitted through the ESRs from ground center to rotating platform or vise versa.

5.2 FORJ Test and Performance

To test the performance of the FORJ in real tracker system, the following equipment were used: (1) a pair of POC's fiber optic multimedia transceivers; (2) four real-time color cameras; and (3) a color quad real-time video splitter compressor and a high quality TV monitor. First, four color cameras and one fiber multimedia transceiver were installed onto the rotating platform of the tracker; the four video signals were connected to the transceiver where the multiple image signals were transformed to optical signals, multiplexed into one singlemode fiber, and connected to the FORJ in the rotation end through FC connector. In the ground center, the FORJ fiber in the stator side was connected to the optical input of the second fiber optic multimedia transceiver where multiplexed signal was demultiplexed and transformed back into four electrical signals. These signals were connected to quad video splitter compressor and simultaneously demonstrated on a single monitor. During the tracker rotation, four sensed image signals on the rotating platform was smoothly transmitted to the fixed control center, as shown in Figure 12.

Figure 12
Four channels of real-time video signals are transmitted trough embedded FORJ
from rotating platform to the control center of the tracker

6. CONCLUSION

In this paper, we present our work in the development of a unique electro-optic hybrid rotary joint (EOHRJ) for use in ground-based electro-optic tracking system applications. By integrating a unique fiber optic rotary joint (FORJ) with a specially designed two-layer concentric electrical slip-ring structure, a comprehensive three-layer EOHRJ was produced to replace the existing wrap-cable RTF structure in current tracker systems. With the EOHRJ equipped the new tracker system can handle rotating-to-fixed signal transmission for all types of signals, including electrical power, ground, control, and feedback signals, as well as high-speed video, audio, and data signals.

Besides the tracker system application, the EOHRJ technology is expected to provide a generic electrical and optical slip-ring architecture for numerous military and commercial applications involving the transmission of large amounts of data and signals to and from moving platforms. Potential applications include robotics (used to fabricate automobiles and aircraft); surveillance systems (used for monitoring aircraft and automobile traffic); instrumentation and observation systems located on rotating platforms (such as turbines and jet engines); multi-spectral vision systems located on automobiles and aircraft; and flight data recorders.

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