Aerospace Fly-by-Light Actuation Systems

RATIONALE

This document has been reaffirmed to comply with the SAE 5-year Review policy.

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1. SCOPE:

This SAE Aerospace Information Report (AIR) has been prepared to provide information regarding options for optical control of fluid power actuation devices. It is not intended to establish standards for optical fluid power control, but rather is intended to provide a baseline or foundation from which standards can be developed. It presents and discusses approaches for command and communication with the actuation device via electro-optic means.

The development of standards will require industry wide participation and cooperation to ensure interface commonality, reliability, and early reduction to practice. To facilitate such participation, this document provides potential users of the technology a balanced consensus on its present state of development, the prospects for demonstration of production readiness, and a discussion of problem areas within this technology. The intent is to inform the user/designer of the options available for interfacing photonics (optics) to hydraulic power control actuators used in aerospace applications. Specifically, power and signal interfaces such as control, status and BIT (built in test) are considered. Mechanical interfaces such as optical connectors and fibers are also discussed. Other issues covered include the benefits of optics, reliability of components, and system architectures.

The document draws on the expertise of numerous investigators who develop demonstration hardware, are familiar with photonics and specialize in hydraulic actuation, or are cognizant of aerospace fluid control systems. Contributions and suggestions have been supplied by members and attendees of the A-6D Committee.

2. REFERENCES:

2.1 Applicable Documents:

The following publications form a part of this document to the extent specified herein. The latest issue of SAE publications shall apply. The applicable issue of other publications shall be the issue in effect on the date of the purchase order. In the event of conflict between the text of this document and references cited herein, the text of this document takes precedence. Nothing in this document, however, supersedes applicable laws and regulations unless a specific exemption has been obtained.

2.1.1 SAE Publications: Available from SAE, 400 Commonwealth Drive, Warrendale, PA 15096-0001.

ARP490	Aerospace Recommended Practice on Servovalves
ARP1281A	Servoactuators: Aircraft Flight Controls, Power Operated, Hydraulic, General Specification for
AS1773	Fiberoptics Mechanization of a Digital Time Division Command/Response Multiplex Data Bus
ARP4386	Terminology and Definitions for Aerospace Fluid Power, Actuation and Control Technologies
ARD50020	Fiber Optic Interconnection Systems for Aerospace Applications
ARD50024	Fiber Optic Coupled Sensors for Aerospace Applications

2.1.2 U.S. Government Publications: Available from DODSSP, Subscription Services Desk, Building 4D, 700 Robbins Avenue, Philadelphia, PA 19111-5094.

MIL-F-9490	Flight Control Systems, General Specification for Design Installation and Test of Piloted Aircraft
MIL-STD-461	Requirements for Control of Electromagnetic Interference Emmissions and Susceptability
MIL-STD-1773	Fiber Optics Mechanization of an Aircraft Internal Time Division Command/ Response Multiplexing Data Bus

FDA Regulation 21 CFR Subchapter "J"

DO-160	Environmental Conditions and Test Procedures for Airframe Equipment

2.1.3 ANSI Publications: Available from ANSI, 11 West 42nd Street, New York, NY 10036-8002.

ANSI Standard Z136.2

2.1.4 ARINC Publications: Available from Aeronautical Radio Inc., 2551 Riva Road, Annapolis, MD 21401.

ARINC429
ARINC629

2.2 Definitions:

APPLICATION SPECIFIC INTEGRATED CIRCUIT (ASIC): An integrated circuit designed and built for a specific application, rather than for general use.

BUILT-IN-TEST (BIT): A testing routine capable of diagnosing a suspected system fault. In some cases it is an intrusive operation that places the system outside its normal, fully operational state. There are also monitor BIT functions which are non-intrusive and are used to monitor and fault isolate system operation.

CABLE, FIBER-OPTIC: That portion of an interconnection scheme carrying photonic signals between two sub-systems, that consists of the signal carrying medium plus one or more mechanical protective members such as a sheath plus strength member and scuff jacket. A fiber or multiple fibers in a structure fabricated to meet optical, mechanical and environmental specifications.

CONTROL POWER-BY-LIGHT: Involves the conversion of optical power into electrical power for use as the primary power source for otherwise electrically isolated circuits This power is used to activate the control elements of an actuator.

2.2 (Continued):

DETECTOR: A transduction device that transforms photonic energy into electrical form (typically a photodiode).

EMITTER: A transduction device that creates and launches optical radiation; an optical source; typically a light emitting diode (LED) or laser.

FLY-BY-LIGHT: The broad term used to generally describe the use of optics to communicate with the control elements of a flight control system.

FLY-BY-WIRE: A flight control system wherein vehicle control input is transmitted completely by electrical means.

NUMERIC APERTURE: The sine of the half-angle of light acceptance and emittance of an optical fiber.

SMART ACTUATOR: A servoactuator that carries on board all its necessary loop closures and the capability to report status. Many different command signal formats are possible and are discussed in 4.3.2. A smart actuator differs from a conventional actuator where information is fed back to a remote location for summing with a command and the actuator receives only the error signal. Figure 1 shows a conceptual approach for smart actuation.

TRANSDUCER, FIBER-OPTIC: That portion of a fiber-optic based sensing system that responds to the measurand based on some defined physical law; also known as the “sensing element”. Any such mechanism, internal or external to the fiber, that causes a change to the characteristic parameters of light injected into or propagated by an optical fiber (phase, intensity, wavelength, polarization) in accord with the measurand (pressure, temperature, acceleration, displacement, velocity, etc.). It is part of a sensor mechanism; not a stand-alone device.

Additional definitions for actuation and control technology that relate to the general subject of fly-by-light may be found in ARP4386.

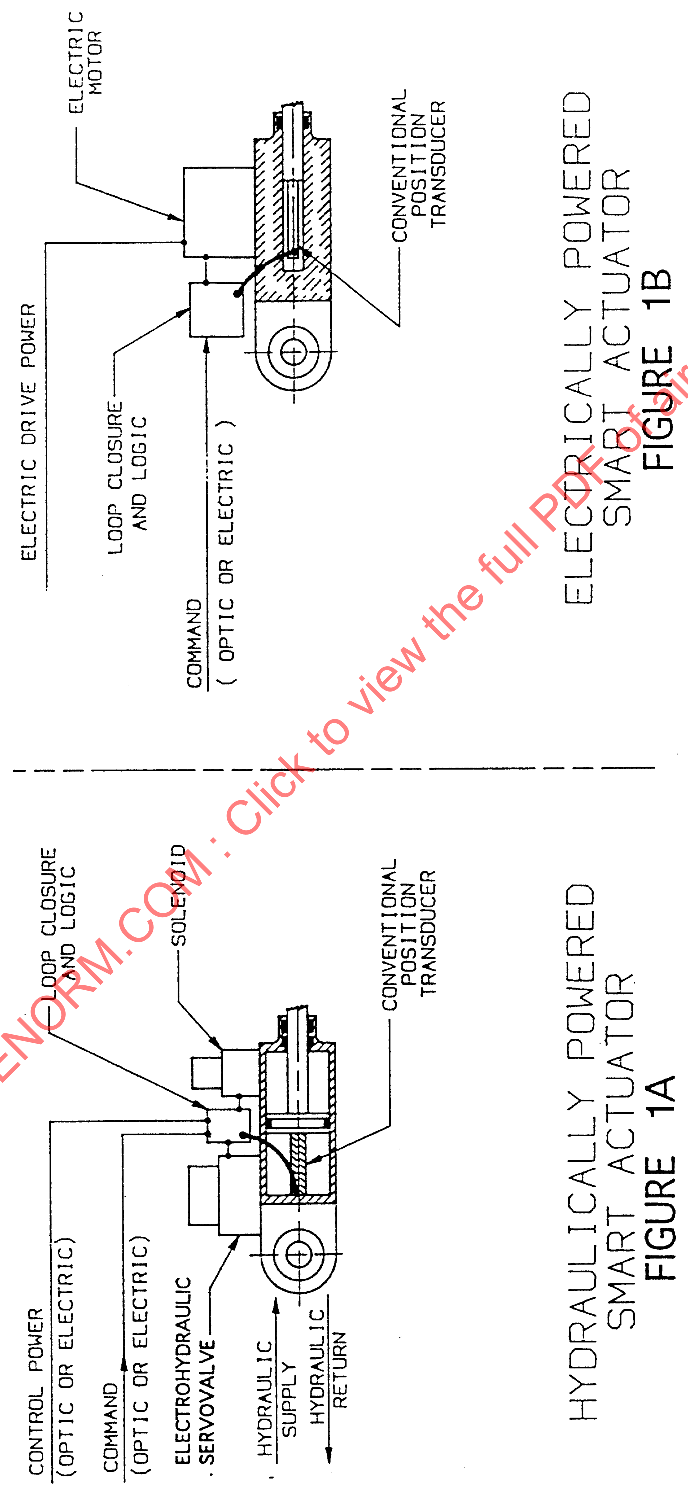

FIGURE 1 - Smart Actuator

3. BACKGROUND:

3.1 Fly-by-Wire:

Electromagnetic interference (EMI), electromagnetic pulse (EMP), lightning, high intensity radio frequency (HIRF), and other threats such as directed energy weapons are increasingly being recognized as potentially jeopardizing to the flight safety of vehicles with fly-by-wire systems. Aggravating the situation is the increasing use of non-metallic composite materials in airframes thus eliminating the shielding inherent to the metals formerly used. Fly-by-wire systems can be protected from these threats through the use of component and wire bundle shielding. Components and data transmission and electrical power distribution wires can be protected by a common shield forming a Faraday cage. These protective solutions lead to weight, system flexibility and maintenance penalties. Also, the cost of maintaining the integrity of the shielding adds significantly to the life cycle cost of the aircraft. These penalties are sensitive to an estimated threat level, which future service may show to be greater than currently expected. A problem with fly-by-wire systems, is that if the actual electromagnetic threat environment is worse than that assumed in the original design, the systems may require subsequent costly in-service modifications.

3.2 Fly-by-Light Benefit:

The introduction of photonic technology could be a cost-effective way to provide protection against EMI, EMP, lightning, HIRF, and other electromagnetic threats. The known fly-by-light benefit is the inherent high level immunity of photonic information transmission to electromagnetic threat, and the high bandwidth and multiplexing capability of optics. Optic components that are sensitive to free field EMI are readily protected inside the actuation device, which provides shielding with little or no added weight, as long as good EMI design criteria are rigorously followed. Potential benefits exist when one considers that in the future, EMI threat levels and optical bandwidth capabilities are both likely to increase. The use of optical components will substantially reduce the burden associated with electromagnetic threat immunity certification, and allow future growth in system performance.

The use of photonic devices in designing system architectures also offers possibilities that are not available with electronics. The increased bandwidth offered by optics provides benefit needed for advanced vehicle management system architectures which may use an estimated 5 to 20 Mbps. The greater information transmission capability permits the condition of the actuation device to be known more precisely by sensing additional parameters on a continuous basis. Architectures may be devised to take advantage of the added bandwidth and reduce the uncertainty of an actuator's condition by using additional monitors, possibly eliminating a redundant actuator or increasing dispatch reliability. Data transmission on optical fibers provides inherent isolation of channels. There is no concern of an electrical short causing a fire. Furthermore, there is no concern of an electrical short bringing down all channels, which is important when considering failure modes and designing redundancy. The added flexibility in system architecture design introduces the possibility of increased reliability without increased weight. In fact, studies have shown fly-by-light systems will weigh less, for the same system performance and reliability, provided reliable optical components can be developed.

3.2 (Continued):

While there is no concern about short circuits causing multiple channel failures, there has been considerable concern about externally caused physical damage. With the tendency being to take advantage of the small fiber size and combine many signal paths into one cable, a single cable cut can destroy many paths simultaneously. This must be considered at the system architecture level.

3.3 Photonic Technology Considerations:

There will be considerable similarity in the photonic technology used for commercial, military, and space applications. This is in part due to the considerable time and cost required to develop and certify new components. It will not be cost effective to develop unique devices for each specialized application and it will be necessary to establish common standards to ensure compatibility of components from different sources. Therefore, devices for a given function must satisfy the requirements of a wide range of applications. The functions and operational requirements of commercial, military, and space systems will of course, differ considerably, and this will be reflected in the differences in the system architectures, but not necessarily in the components and their interfaces.

4. OPTIC ACTUATION INTERFACES:

4.1 Optical Actuation Concepts:

The flight control, engine control, and other flight-critical control systems of aerospace vehicles contain a large number of hydraulically or electrically powered actuators. In a fly-by-light system these actuators must be interfaced with the fiber optic data buses or other photonic-based signaling networks. This must be done in a way that maintains immunity to electromagnetic threats without requiring electromagnetic shielding of signal paths and long electrical power distribution networks.

While the actuator environment is relatively severe, resulting in an increased failure rate of electronics when compared with conventional locations, the system reliability must be assessed with fault trees and other tools to determine the optimum circuit complexity of on-board electronics. Photonic interfaces which allow minimum or no electronics are generally preferred, but advances in high temperature electronics may alter the optimum architecture. Several concepts are described below.

4.1.1 Fully Optically Controlled Actuator (Fly-by-Light/Control Power-by-Light): A fully optically controlled hydraulic actuator has no electrical connections. All signaling information, data transmission and control power, to and from the actuator is provided by optical fiber. Control power refers to the power required to operate control devices such as the servovalve and solenoid valve. It is not the power to move the load. The "optic actuator" has substantial immunity to EMI, EMP, lightning and HIRF, since the electrical wiring network to the actuator is eliminated, and good EMI design will be used within the actuator to shield sensitive photodetector circuitry. The components on the actuator such as control valves, solenoids and transducers (position, pressure, velocity, etc.) all have optical interfaces. A fully optical actuator may or may not be a "smart actuator", depending on the system architecture. Figure 2 depicts a fully optically controlled actuator, and Figure 1A depicts an approach to a fully optically controlled smart actuator.

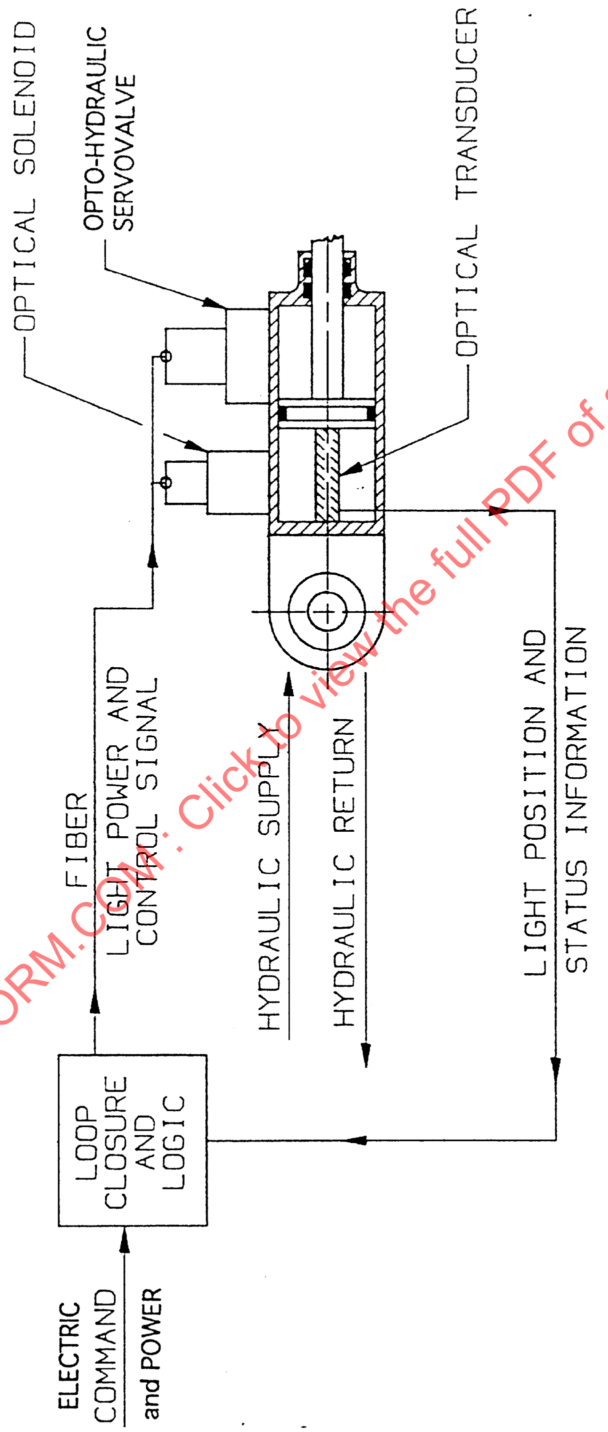

FIGURE 2 - Typical Full Optical Control
Fly-by-Light/Control Power-by-Light

4.1.2 Optoelectrical Controlled Actuator (Fly-by-Light/Control Power-by-Wire): An optoelectrically controlled actuator has modulated optical control signal interfaces with electronic circuits which demodulate the optic signals and control the actuator. The electronics may utilize ship's power or a source of locally available power such as a hydraulic powered alternator. A typical approach would be to provide the control signal by fiber optics to the actuator but provide control power via an electrical connection. This has the benefit of transmitting the low power signal that is most susceptible to EMI, EMP, and HIRF via light, yet uses ships electrical supply to directly power the control devices on board the actuator. This approach reduces the need for reliable high-powered lasers, which would otherwise be needed to provide this level of power optically. This approach is depicted in Figure 3. Note that since this approach already has an electrical connection for control power, it can be extended to using electrical power to drive the load as well. This is shown in Figure 1B. It should be noted that for actuators where there is electrical drive power, the internal EMI generation adds to shielding requirements.

4.2 Optic Actuation Components:

Fly-by-wire systems use transfer devices and sensors which are electrical components. A fly-by-light system will need components to perform similar functions, except the electrical medium will be replaced by light. The conventional components that will need an optic counterpart are the servovalve, solenoid operated valve, and transducers.

4.2.1 Opto-Hydraulic Servovalve: The electrohydraulic servovalve is the device in a fly-by-wire system that provides the transfer function between electrical command and hydraulic control. It accepts electrical input and provides proportional hydraulic output. An opto-hydraulic servovalve serves the same purpose as an electrohydraulic servovalve by providing hydraulic output in response to some type of optical input. Several different schemes have been considered to accomplish this and they are discussed in 4.2.1.1 through 4.2.1.3. Schemes to format the optical input are discussed in 4.3.2.

4.2.1.1 Direct Light Conversion: This scheme utilizes the principle of converting light directly to a position change at the quantum level by use of silicon microactuators. This is distinguished from an acoustic or thermal process which involves large ensembles of atoms in collective motion. Conceivably, the motion generated by the quantum conversion could be mechanized to drive a control valve (or other device). There have been several demonstrations of direct light operated valves, ranging from micro machined silicon devices to flapper-nozzle two stage hydraulic valves with internal spring feedback. These devices are not yet commercially practical for aerospace fluid power applications, but they are very close to achieving that practicality.

4.2.1.2 Optoacoustic Conversion: This principle involves the conversion of light to a fluid pressure by thermal means and uses the change in pressure to operate the control valve (or other device). This approach offers limited bandwidth and requires comparatively high optical operating power.

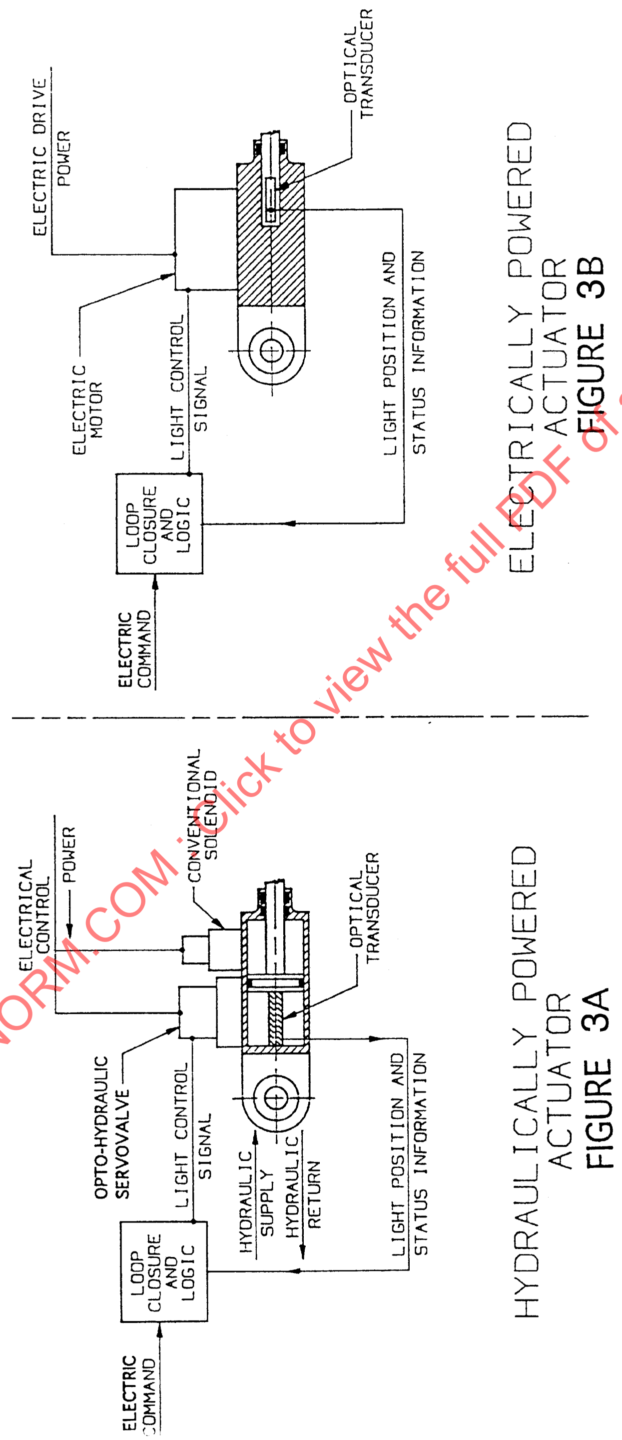

FIGURE 3 - Typical Optoelectrical Controlled Actuator
Fly-by-Light/Control Power-by-Wire

4.2.1.3 Optoelectric Conversion: This approach converts light energy to electrical energy within the control valve. An optical detector is added to a conventional electrical input control valve, and the optoelectric conversion (by the optical detector) takes place within the shielded region that already exists as part of the servovalve. The technology for this scheme is readily available since it is simply the integration of existing devices of known reliability. This type of opto-electrohydraulic servovalve can be configured to operate in either a fully optical actuator (4.1.1) or an optoelectric actuator (4.1.2).

4.2.2 Optical Direct Drive Valve: A direct drive valve (DDV) performs the same function as a servovalve, without the benefit of hydraulic amplification within the valve and as such, requires more electrical power. It is a useful device where hydraulic power is at a premium, but due to its electrical power consumption, should only be considered for fly-by-light/control power-by-wire (4.1.2) where electrical power is available and only the control signal is provided by light. Paragraph 4.3.1 provides further discussion on generating sufficient optical power to drive a DDV.

4.2.3 Optical "Solenoid" Operated Valve: An optical solenoid operated valve provides an on/off hydraulic condition depending on the presence of an optical signal. The use of a conventional electro-hydraulic solenoid is practicably limited to optoelectric actuators (fly-by-light/control power-by-wire) due to the high power consumption of conventional solenoids. When this function must be accomplished on a fully optical actuator, a low power on/off torque motor type valve should be used.

4.2.4 Optical Transducers: ARD50024 provides an in depth discussion of the different types of optical transducers and their relative merits. The system designer can select the transducer based on system requirements such as performance and reliability from a number of different approaches which are discussed in ARD50024. Most actuation devices can be designed to accommodate any of the available optical transducers, so mechanical interface is generally not an issue. Mechanical reliability however, is an issue, due to the effect contamination has on most optical transducers. The designer should understand the consequences of contamination on the transducer performance and the extent to which their design will exclude contamination from the transducing element.

4.3 Optic Actuation Operation:

4.3.1 Power: For an optoelectrical hydraulic actuator, optical power is not a significant issue since the actuator is provided a source of electrical power and light is used only to provide control signals. For a fully optical hydraulic actuator, the power for the electro-mechanical control devices must be sent down a fiber as light, and then converted to electricity within a Faraday shield which is readily provided at the actuator. There are many inefficiencies in transmitting power by light as opposed to transmitting it electrically. Optical connectors introduce losses, whereas electrical connector loss is normally insignificant. Present state of the art utilizes electrical control signals converted to optical and then necessitates that the optical power be converted back to electricity to operate the actuation device. Each component that makes the conversion also contributes to the inefficiencies. One potential alternative to eliminating the electrical conversion is to interface the optics to the hydraulics via hydro-fluidic devices and amplifiers. Approaches to reduce required optical power below source maximum rated optical power will also be helpful, as reliability and life of optical power sources (e.g., lasers) increases dramatically. Clearly, an optical system design requires engineering trades considering light budgets, cable constraints, distribution etc., but for the reasons given here, a major design goal should be to minimize the optical power required by the actuator. This dictates that the electrical power consumed by all the components within the actuator be minimized, and hence direct drive valves are not suited for fully optical (control power and signal by light) actuation devices.

4.3.1.1 Optical Power Emitters:

4.3.1.1.1 Lasers: Due to the widespread use of lasers in many different industries, there are vast quantities of literature available.. MIL-STD-1773 provides specific information relating to aerospace applications. Laser diode optical sources, developed for the telecommunication industry, have extremely good power densities and narrow spectral widths. However, readily available commercial laser diodes are too thermally unstable and show relatively low reliability in the aerospace thermal environment. The following discussion provides information on how lasers fit in a fly-by-light system.

The issues of power, temperature and reliability are all related. No one doubts that a laser can generate enough power for fly-by-light systems, but instead, the question is whether the required power levels can be reliably maintained over the life of the system. It is known that lower operating temperatures and lower power delivery increase laser life. This is why low-power control elements for actuation devices are important components in fly-by-light systems. The importance of low-power has already been discussed, but beyond that, the system designer should incorporate other features that enhance laser reliability.

4.3.1.1.1 (Continued):

One approach is to incorporate in the architecture multiple lasers to reduce the power delivered by each one. This can be integrated with a redundancy management scheme. It should be noted that lasers typically degrade in performance that is a subtle warning of impending failure as opposed to sudden and unexpected failures. This degradation generally shows itself as an increase in laser current for a constant optical power output. Therefore, many use a scheme that monitors laser current (to maintain constant optical power) to signal a maintenance action. This could be incorporated so lasers can be replaced near the end of their life.

Laser life can be extended by designing the system so that the laser is "off", or at very low power levels most of the time. A conventional servoactuator normally functions this way in that the servovalve draws current (power) only when the actuator moves. Further, the current it draws is proportional to the actuator velocity, so there is little power consumption for low velocity actuator excursions. This makes system duty cycle an important factor when considering laser life.

Designing the system so that the laser is in a "friendly" environment is also important. Lower temperatures as well as low vibration extend laser life. This can be feasibly achieved with architectures that locate the laser with other electronic components (such as the primary flight control computer) in an equipment bay, and the laser's light output brought to the actuator over a dedicated fiber. Also, lasers like many electronic components, are sensitive to electro-static discharge.

Laser safety is a concern because the human eye cannot detect the wavelength of most lasers under consideration. A person is not able to protect themselves by closing their eyes, because they don't know that they are being exposed to the laser radiation. Within the U.S., all laser products must be certified by the manufacturer to conform to the eye exposure safety standards set by requirements contained in FDA Regulation 21 CFR Subchapter "J". ANSI Standard Z136.2 may also be imposed as well as regulations of the International Electrotechnical Commission (IEC) Standard 825. The system designer may be faced with a specification which dictates that IEC Class 1 emission requirements be met through automatic emitter shutdown, when the optical interconnection path is broken for any reason, such as the de-mating of an optical connector pair.

The state of the art in lasers is changing rapidly so this document does not include reliability data. The research in strained-layer lasers threatens to make existing data obsolete. Development of laser diodes suited to aerospace applications has recently shown great promise, resulting in devices stable to 125 °C. As laser development continues, a greater variety of wavelengths are being used. Strained-layer, quantum-well laser diodes in the 1050 nm range show promise of providing the same reliability at higher power than the 870 nm GaAs lasers that were developed in the previous few years. This is just one example of how laser technology continues to grow, demonstrating that standardization for lasers at this time would leave the industry with less than optimum technology.

4.3.1.1.2 Light Emitting Diodes (LED): The LED is a low power emitter compared to the laser and typically is not used to power actuation devices, but is useful for optical data transmission. Lasers on the other hand, tend to have relatively high noise amplitude and modal interference which may limit the resolution if used with some sensors. Therefore, an LED is used where precise optical resolution is required, but optical power is not. For example, fly-by-light/control power-by-wire (where the command signal and other information are carried by light) is well suited for LED usage. It is preferred as an aerospace emitter because they degrade gracefully. There are additional discussions on LEDs in ARD50024 and MIL-STD-1773.

4.3.1.2 Optical Power Detectors: While the system designer sometimes has the option of locating the optical emitters in a friendly environment, detectors are usually located directly on the actuation device and therefore must withstand all the environments that the actuator experiences. Fortunately, they are more rugged and are more capable of such conditions. MIL-STD-1773 provides further general discussion on detectors.

4.3.1.2.1 Detector Efficiency: Development of detectors, like lasers, continues to result in performance improvements. Efficiency is the key parameter in evaluating detectors, and is defined as the electrical power output divided by the optical power launched on the photosensitive surface. It has improved from the 30% range for silicon based detectors to the 50% range for GaAs detectors. GaAs detectors are also attractive because of their operating capability at higher (200 °C) temperatures. However, their efficiency does decrease with increasing temperature.

The system designer should be aware of the importance of matching the resistance of the load with the peak efficiency point of the detector, and that changing resistance also changes the conversion efficiency. Detector efficiency varies with changes in the electrical resistive load. Also, efficiency is dependent on the light received on its surface, so alignment and positioning tolerances are important when building components with optical detectors.

4.3.2 Protocol: The physics of transmitting power and information by light offers the system designer a number of different protocol options. Selecting the protocol is an iterative process in the system design that depends on many factors that can generically be called "the architecture". At the actuator level, some of the factors that influence and/or are affected by selection of protocol include the type of transducer(s) on board the actuator, the number of fibers going to the actuator, and the electro-mechanical drive schemes. Three generic protocols for controlling the electro-mechanical devices within the actuator are discussed below.

The system designer will have the option to integrate any of these protocols (including one that is consistent with accommodating optical transducers) in the desired architecture.