A Novel Optoelectronic Interface-Circuit Design for Sensing Applications

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***Abstract*— A novel and commercially viable optoelectronic interface is proposed for sensors measuring optical attenuation. Emphasis is given to commonly neglected background-noise-interference and dynamic-range-limitation problems. A modulated laser-diode, together with optical and electrical filtering, reduces the optical noise to less than a measurable level, even in extremely bright "light-infested" surroundings. In addition, an effective approach is introduced for substantially increasing the sensor's dynamic range. The power of the light-source is monitored in a dynamic intensity-control loop designed to perform "floating-point" measurements according to the attenuation in the optical path. The sensor acquires the combined dynamic ranges of the detector and light-source circuits.**

I. Introduction

A. Motivation

Applications of optoelectronic transducers are becoming increasingly complex; a large variety of transducers have been constructed, and new and improved transducers are frequently proposed. Optoelectronic transducers that measure attenuation in an optical path, from an emitter to a reflecting surface and back to a detector, are commonly used in robotic applications including proximity sensors [1], [2], force-torque sensors [3], and tactile sensors [4]. The primary reasons for this popularity are the relatively small size of the optoelectronic transducer, its range of operation, and the fact that almost no restrictions are imposed on the intervening reflecting surface.

The performance of optical transducers, however, is limited by the electronic interface to the computer-control algorithm. In general, electronic interfaces presently available are imperfect in ways which limit achieving the sensors' goals. In this context, this paper proposes a robust and reliable computer interface for robotic transducers.

B. Interface Requirements

A sensor must be robust, deal with interference, operate reliably in the full measurement range, and supply true data with a sufficient signal-to-noise ratio (SNR). All these requirements must be addressed by the electronic interface. As a preliminary stage in our design, we have compiled a list of requirements, of which only the most important are introduced here.

1) From the interface viewpoint, the optoelectronic transducer is a communication channel connecting a transmitter to a receiver. However, data generation occurs inside the channel, and it is analogue in nature. These facts impose special demands on the receiver circuits; nonlinearities commonly used by digital-communication circuits (such as increasing the dynamic range through automatic gain control) are strictly forbidden in the analogue channel. The "1" or "0" decision of the digital case is replaced by the goal of obtaining a precise value. In addition, this value cannot be improved later by error verification.
2) Transducers may have to operate in very (highly illuminated) noisy environments, and be prone to interference from many possible sources of extraneous light in both the visible and near-infrared ranges. These light sources set the "background-noise" level in which the sensor must operate. Other sources of light may be even more disturbing. For example, light emitted by fluorescent lamps is modulated at the electric-power frequency (50/60 Hz) and its harmonics. Welders emit short bursts of light that are especially intense in the ultraviolet region.
3) While dynamic range (DR) is a very important parameter for any sensor, it is particularly critical for sensors measuring optical attenuation. In practice, the light intensity at the receiving end of such sensors is a strong function of many parameters. For example, it is inversely related to the square of the distance between the transducer's transmitter and receiver [5]. Thus, even a modest distance operating range of 10 : 1 would result in a 100 : 1 range of light intensities at the receiver. It is important to emphasize at this point that the light-detection process at the receiver involves the conversion of light intensity to current. Therefore the range of current intensities for various distances is also 100 : 1, which corresponds to a 40 dB electrical-measurement range (rather than to the 20 dB range of optical-power variation). Other important parameters that affect the DR include orientation of the reflecting-surface and its overall reflectivity.
4) Many sensor applications require measurements of the light attenuation in several paths concurrently. In order to perform this task, the interface is required to sup-

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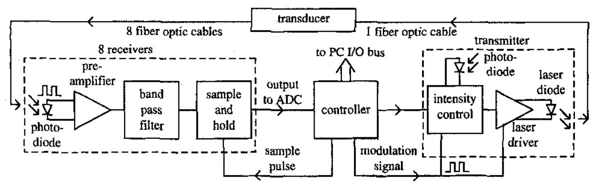

Fig. 1. Block diagram of the interface circuit.

ply synchronized multiple measurements using several receivers.

5) Finally, the electronic interface should consist, preferably, of commercially available low-cost components. It should also be constructed such that its physical connection to the transducers will be as convenient as possible.

II. Design

The proposed electronic interface comprises a controller, a transmitter, and a receiver. The transmitter is linked to the receiver through the sensor's transducer (Fig. 1). The emitted and received light signals are conducted between the interface card and the transducer via fiber-optic cables (FOC's). This appropriately facilitates the operation of the sensitive low-noise interface circuitry remote from the high currents of robots' (and other machines') motors.

Both the receiver and the transmitter were designed to achieve the required immunity to external light disturbance by using a combination of two methods: namely, the use of a narrow optical band within the transducer, and the use of modulated light.

The wavelength for transducer operation is normally chosen in the near-infrared region. This enables the use of commonly available semiconductor components while avoiding the strong background-light noise in the visible and ultraviolet wavelength ranges. At the transmitter side, the light source emitting this wavelength can be either a laser diode (LD) or a light-emitting diode (LED). The LED's cost is low, and its driver circuit is simple. However, the available light power of LD's is higher, and their optical bandwidth is narrower. This makes the LD-based light source a better choice for the general case, while the LED-based light source can serve adequately for low-attenuation transducers that are relatively protected from light noise. The transmitter-circuit design described here is based on the use of an LD. However, if desired, the driver circuit can be simplified and adapted to drive an LED instead.

At the receiver side, in order to minimize the reception of light noise, the received light is passed through an optical filter. The filter's center wavelength and the width of its optical band must correspond to those of the light source. The bandwidth tolerance is required to take into account light-source parameters such as spectral-width and wavelength-drift as functions of temperature and output power.

Additional noise immunity of both optical and electrical kinds is achieved by modulation. The transmitter's LD is modulated by a square wave, while the received signals are passed through a high-Q band-pass filter and sampled at the output sine-wave peak. As a result, optical noise is reduced to far under the electrical noise created in the circuit even in extremely bright, "light-infested" surroundings. The modulation frequency also dictates the minimum interval between measurements, since each measurement requires a complete modulation cycle for its completion.

Retrieval of the data from the modulated signal by a sample-and-hold approach in the receiver also serves to fulfill the requirement of multiple receivers capable of concurrent measurement. This allows a single A/D converter to process measurements sampled at the same time in multiple channels.

Light modulation also helps to resolve the problem of biasing, and temperature-related drift in the receiver. A receiver that is used in a nonmodulated scheme must have direct coupling from the detector to the A/D. The DC calibration of such a receiver is a complex and inherently inaccurate process: a drift in the DC bias of any part in such a receiver will be amplified and passed to the A/D converter as indistinguishable from a measurement.

As noted above, for conventional design, the DR of the electronic interface is commonly limited to the DR of the receiver circuit. This restriction, however, has been eliminated in our interface circuitry by applying a new concept of dynamic transmitter-intensity control. Unlike the situation in conventional optical communication, the transmitter and the receiver for a sensory application are both subject to the same controller. Thus, the light-source intensity can be adjusted in real time, such that the intensity at the receiver is adequate for measurement. In practice, the LD's output power is monitored with the help of a photodiode integrated with it. Using a closed-loop driver, the output intensity can be brought to the level desired by the controller. This method of dynamic intensity control results in an overall DR that is the sum of the DR's of the receiver and the transmitter circuits.

Moreover, employment of the method of dynamic intensity control at the transmitter also affects the design of the receiver. Tradeoffs exist in the design of both a transducer and an opto-electronic receiver. For a transducer, the demands for a large DR, high sensitivity, and accuracy are often contradicting; while for an optical receiver, DR is often balanced against high sensitivity and good linearity [6]. By contrast, the substantial increase in the overall DR of our new electronic interface allows us to maximize various parameters at the expense of the receiver's DR. For example, we have decided to use a high-impedance preamplifier rather than conventional transimpedance design, in order to improve the sensitivity of the receiver.

Finally, in order to create a practical and easy-to-use interface, we decided to design the interface circuitry on a PC I/O card, and to use the PC's power supply as a power source. Therefore, in the design of the interface circuits we had to take into consideration the special conditions inside the PC, and to deal with problems such as "dirty" power lines and interfering sources (such as I/O bus signals).

III. Circuit Analysis

A few pseudo-arbitrary decisions had to be made for the construction of the prototype circuit presented in this paper.

Although any near-infrared wavelength would do, we chose 830 nm as the operating optical wavelength, since a vast selection of optoelectronic components is available there. In addition, we selected 10 kHz as the modulation frequency, since it is far from the 50/60 Hz noise but not high enough to complicate real-time computer processing.

Of the many controller circuits that are commercially available, the AT-MIO-16 by National Instruments was selected for use in our interface. This is a programmable PC data-acquisition card with 16 analog input channels connected to a 12-bit A/D converter, two 12-bit D/A output channels, digital I/O, and five counters for timing of I/O operations.

The choices noted above, and the following choices of electrical components are in no way unique, nor do they restrict the design's applicability to any specific sensor. Other choices (for wavelength, modulation frequency, LD, photodiodes, operational amplifiers, etc.) can be made to suit one's needs, provided that the appropriate adjustments required by these choices are correctly made.

A. *Laser Driver*

The schematic of the laser-driver circuit was given in [7]. The LD used as the light source is the Hitachi HL8312G. It is capable of emitting 20 mW of optical power. The current driving the LD is composed of a constant biasing current and a modulated intensity current. The biasing current is driven through a transistor switch, and is set such that it induces just-above-minimal lasing from the LD (at about 60 mA for the HL8312G). This biasing scheme minimizes turn-on effects, and reduces temperature variations in the LD. The voltage signal from the intensity-control circuit is converted into a current signal (with maximum amplitude of about 70 mA for the HL8312G), and then modulated by another transistor switch. Two Zener diodes protect the LD from overdrive by limiting the maximum current through it. The commands to control the two switching transistors are converted from TTL levels and supplied by the control circuit. It is critical that the power supply connected to the receiver circuit is not affected by the high-current LD signal. Any such coupling can cause the pickup of the modulated signal by the sensitive low-noise receiver circuit. Therefore, the -5 V power source that supplies the LD current is used in the transmitter circuit only.

B. *Intensity Control*

The transmitter circuit, given in [7], operates in a closed loop for light-intensity control. A photodiode, integrated with the LD, provides feedback to the control by capturing a small portion of the generated light. A transimpedance amplifier biases the photodiode and converts its sample into a voltage signal. The transimpedance gain of this amplifier is adjusted to allow the largest voltage span that will not saturate the later stages.

A low-pass filter is used in the second stage to attenuate any high-frequency noise picked up in the transimpedance amplifier. This electronic noise includes possible interference from the PC buses. This stage also incorporates an offset adjustment to set the zero level of the output intensity. Accurate adjustment of this zero level is essential for obtaining the maximum possible DR in the transmitter.

The control loop is periodically broken in the laser-driver stage by the modulation signal. To prevent this on-off switching from affecting the intensity control we incorporated a sample-and-hold circuit (S&H) ahead of the intensity comparator. About 3 μs after the LD is turned on, the S&H becomes transparent to the feedback signal. This delay is needed to allow both the LD and the input stages to stabilize (for the components in the implemented circuit). When the LD is turned off, the S&H is switched to the hold state, and retains the "on" feedback value until the next modulation cycle.

A comparator stage is the heart of the intensity-control circuit. Here, the feedback signal is continuously compared to the desired intensity, and any disagreement causes an adjustment in the signal relayed to the laser driver. The pole frequency of a low-pass filter sets the time constant by which a new intensity command comes into effect, and therefore should not be too low. However, this frequency has to be under the modulation frequency, such that the comparator behaves as an integrator and smoothes out any intensity variations related to the light modulation.

C. *Detector and Preamplifier*

The preamplifier design (given in [7]) is based on a low-noise remote-control receiver [8]. A regulated 8 V power source is used to prevent "dirty" power lines from introducing noise to the circuit. The bias supply connected to both the detector and the preamplifier is further filtered to prevent feedback through the supply lines.

In the implemented circuit, light is detected by an MFOD71 PIN photodiode, biased at -5.3 V. Although the performance of other commercially available PIN and avalanche photodiodes may be superior, they are more costly and require special mounting hardware. As well, avalanche photodiodes require very complex bias circuits with relatively high voltages, which are undesirable for the straightforward PC card implementation originally proposed. By contrast, the MFOD71 is a low-cost plastic-encased device, designed for direct connection to a 1 mm-core FOC. Biasing this photodiode is simple and inexpensive, using voltage levels that can be derived from the power supply of the PC.

As stated earlier, in order to improve the sensitivity of the receiver, the receiver circuit uses a high-impedance preamplifier instead of a conventional transimpedance design [9]. Current-to-voltage conversion is done with a variable resistor to enable fine tuning of the receiver gain.

A high-pass filter at the input of the receiver is necessary in order to reduce the effect of ambient light on the preamplifier. The amplitude of the ambient light can in some cases be much larger than the signal's amplitude. Though this noise will eventually be filtered out in the band-pass filter, it might affect the operation of the preamplifier by changing the operating point of the transistors or even saturating their outputs. In particular, the filter is meant to block DC light and the 50/60 Hz harmonic-modulated light emitted by fluorescent lamps. The two poles, constituting the high-pass filter, are realized by two RC circuits. The connection between the detector and the preamplifier is capacitor-coupled, thereby implementing the first pole ahead of the preamplifier. The second pole is positioned at the emitter of the input transistor. The values of the filter components are selected to give a cutoff frequency in the range 350–550 Hz. This filter is designed to attenuate the 60 Hz signal by 20–30 dB. Choosing a higher cutoff frequency (with smaller capacitors at the base and emitter of the input transistor) could increase this desired attenuation, but will also further restrict the minimum modulation frequency of the LD.

A separate low-pass filter with a cutoff frequency of about 700 kHz is designed to increase the attenuation of interfering signals such as the PC bus frequency and the CPU clock. The preamplifier includes a series-shunt feedback loop that serves many purposes: it sets and stabilizes the amplifier gain, increases the bandwidth, increases the input impedance, and reduces the output impedance [10].

D. Band-Pass Filter

The band-pass filter is a second-order KHN biquad circuit [10]. The filter is designed to have its center frequency at 10 kHz, voltage gain of 10, and Q factor of 30. While the center frequency of the band-pass filter can be changed (together with the modulation frequency) according to the intended application of the interface circuit, it is recommended that the gain and the Q factor of the filter remain as indicated.

The band-pass filter uses a trimmer to fine-tune the filter center frequency to the modulation frequency of the LD. The tuning is especially important when several receivers are used within one sensor. While the signal gain hardly varies within the passband of the filter, the phase shift of the output signal can vary as much as 90–100°. Therefore, the tuning of the filters in the multireceiver sensor is directed toward obtaining the same phase shift in every channel. This will allow the signals in all the receivers to be sampled by a single controller-generated pulse.

E. Sample-and-Hold Circuit

Additional gain is applied to the signal before it is sampled. The gain is set to bring the noise level to about ±1 LSB of the A/D converter. This guarantees the obtainment of maximum sensitivity from the converted measurements. While the gain of the S&H circuit itself is unity, the circuit has an offset adjustment to correct for bias mismatch.

The duration of the sample pulse may likely be a function of the modulation frequency, but it should not be less than the time required by the S&H chip. To acquire an accurate amplitude measurement, the pulse's trailing edge must be synchronized to the peak of the signal (in all receivers). The A/D conversions of the amplitude sample from all the channels must be done during a single hold state.

IV. Circuit Performance

The performance of the implemented circuit design was analyzed by investigating the frequency response of the various parts of the complete interface circuit, noise and sensitivity of the receiver, dynamic range, and time-domain performance.

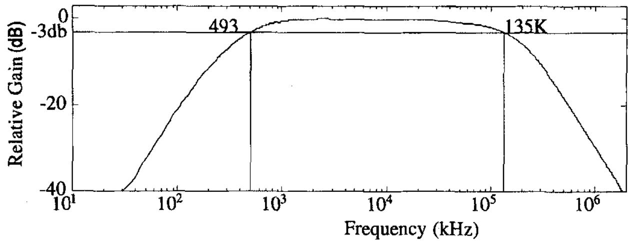

Fig. 2. Preamplifier's frequency response.

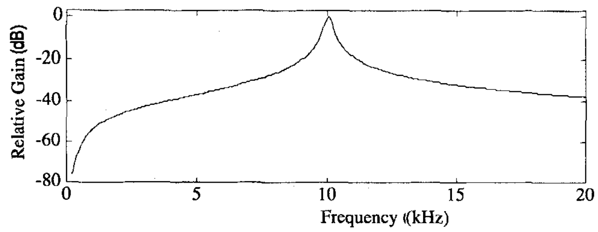

Fig. 3. Receiver's frequency response.

The frequency response of the preamplifier is shown in Fig. 2. The 3 dB points at 493 Hz and 135 kHz set the possible range for the modulation frequency. Interfering light at 60 Hz is attenuated by 29 dB by the filter at the base and emitter of the input transistor. The frequency response of the complete receiver (which includes the effect of the high-Q band-pass filter at 10 kHz) is shown in Fig. 3. The relative attenuation of the 60 Hz light signal at the S&H input is 108 dB.

The transmitter's frequency response is limited primarily by the delay and slew rate of the operational amplifiers and by the delay of the S&H chip. Although the operation of the laser driver was still possible at frequencies up to 500 kHz, the intensity control lost most of its linearity above 200 kHz. Thus, the use of a faster S&H chip and faster op-amps with a higher slew-rate is recommended for modulation frequencies above 50 kHz. The same recommendation applies to the components described in the S&H section of the receiver circuit.

The noise from the transmitter circuit proved to be negligible at any output intensity. This allowed the use of the D/A converter's full available range of 12 bits for intensity control. The 4096 : 1 range of light power emitted by the transmitter works to increase the DR of the sensor by 72 dB (for electrical measurement). An even greater improvement in the DR is possible by using a higher precision D/A converter and S&H chip. Combining the DR in both the receiver and the transmitter provides a 24-bit range of measurements. This is equivalent to a DR of 134 dB, when the minimum SNR is taken as 10 dB.

The optical background noise at the receiver also proved to be negligible. The optical filter was needed only when the receiver FOC was in a very close proximity to a modulated light source (such as less than 10 cm from a 40 watt fluorescent lamp). Thus, in many possible applications, the optical filter would not be essential. In some other cases, a broad near-infrared filter would be sufficient to eliminate optical noise.

It should be noted that a higher cutoff frequency in the preamplifier's low-pass filter can sometimes serve the same objective. However, the attenuation that is applied to low-frequency light noise changes rapidly with the modulation frequency (40 dB per decade). Therefore, an optical filter with a narrower passband is required for lower frequency sensor applications.

The noise measured at the input of the S&H circuit was projected to the preamplifier input using the measured gain and frequency response, to yield the value of 1.52 $pA/\sqrt{Hz}$. This noise is attributed mainly to the input resistors (about 0.5 $pA/\sqrt{Hz}$ and to the input transistor.

V. Application Example

In order to test the performance of the new electronic interface circuit, it was used with an experimental robotic proximity sensor [11]. This sensor uses measured optical attenuation in several paths to calculate the distance and orientation of a surface in relation to the sensor's transducer. The interface consisted of a single transmitter and eight receivers to match the transducer's requirements, and consequently required nine FOC's.

Measurements were acquired at various points within a range corresponding to variations of 1–100 mm in distance and $\pm 30°C$ in orientation (a set of five measurements at each point). A ten-minute warm-up period was allowed before taking measurements. Control of the LD output power level was aimed at obtaining maximum SNR in the measurements. Therefore, for each set of measurements the LD output power was adjusted such that the received signals were as strong as possible without being saturated. The measurements were repeated three times at roughly 24-hour intervals.

The measurements were analyzed and yielded the following results. The noise level in each set of measurements was ± 1 LSB. Thus, the SNR was 66 dB for the strong signals and as low as 32 dB for weak signals (at the 100 mm range). Comparison between measurements taken on different days gave ± 2 LSB variation, reducing the above SNR's by 6 dB. The added 1-bit noise was presumably a result of drift induced by temperature variations in the interface circuits.

A fourth group of measurements was then conducted while the transducer was exposed to intense light from both halogen and fluorescent lamps. In comparing these measurements to the three preceding groups no change in the noise pattern was noticed. Therefore, the interface circuit was proven reliable, in that its measurements are repeatable, and not affected by light noise from the environment.

VI. Conclusions

A new sensor interface was designed as a practical low-cost circuit for use by a variety of optoelectronic sensors. As shown by experimentation, the design can overcome the problem of interfering ambient light by means of electrical modulation and use of a narrow-band source. Also, the development and implementation of the "floating-point" technique introduced here more than doubles (in decibels) the dynamic range usually achieved by a conventional sensor interface.

Although interfaced to a proximity sensor in our laboratory, the new interface circuit can be used in many similar applications such as proximity sensing [1], [2], force-torque sensing [3], and tactile sensing [4].

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Adi Bonen, for a photograph and biography, see this issue, p. 546.

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