A Novel Opto-Electronics Interface-Circuit Design for Sensing Applications

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Abstract – **A new and practical opto-electronic sensor interface is presented. It consists of a transmitter and a receiver for sensors measuring optical attenuation. Emphasis is given to commonly-neglected background-noise-interference and dynamic-range-limitation problems. The design of the electronic circuitry allows sensors to operate in manufacturing environments. 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, a novel approach is introduced which substantially increases 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

The next generation of advanced robotic manipulators, working in complex and constantly-changing environments, must possess the capability of adapting to the imprecise features of their dynamic surroundings. A combination of various sensors to obtain information about the environment, together with a computer to modify the robot's action based on this sensory data, would facilitate this desired adaptivity [1,2].

Presently, opto-electronic transducers seem to be the most appropriate for a wide range of sensing tasks. In particular, opto-electronic 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: force-torque sensors [3,4], tactile sensors [5,6], and proximity sensors [7-10]. The primary reasons for this popularity are the relatively small size of an opto-electronic transducer, its range of operation, and the fact that almost no restrictions are imposed on the intervening reflecting surface.

Applications of opto-electronic transducers are becoming increasingly sophisticated; a large variety of transducers have been constructed, and new and improved transducer types commonly appear. However, the performance of all optical transducers, no matter how advanced and sophisticated they may be, is limited by the electronic interface to the computer-control algorithm. Unfortunately, there has been lack of attention to this matter in the literature; in general, electronic interfaces presently available are imperfect in ways which limit achieving the sensors' goals. The intense need to design a robust and reliable computer-interface for robotic transducers has motivated the research presented here.

II. INTERFACE REQUIREMENTS

A sensor must be robust and reliable; it has to accommodate all possible conditions, deal with interference, cover the full intended 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.

From the interface viewpoint, the transducer is a communication channel connecting a transmitter to a receiver. However, unlike other cases of optical communication, including fiber-optic communication and remote control, data generation in opto-electronic sensors occurs inside the channel and not at the transmitter. Moreover, the data itself is analogue in nature. These facts impose special demands on the receiver circuits; non-linearities commonly used by digital-communication circuits (such as increasing the dynamic range through automatic-gain-control) are strictly forbidden in the analogue channel. Furthermore, the "1" or "0" decision of the digital case is replaced by the goal of obtaining an precise value. In addition, this value cannot be improved later by error-verification schemes (e.g., parity check) since the data is not generated by the transmitter. As a result, we have found it very difficult to adapt usual digital-communication-circuit techniques to our application.

Moreover, the transducers that would use this interface cannot be restricted to operate in a closed environment, where ambient light is excluded. Instead, they may have to operate in very (highly illuminated-) noisy environments, and be prone to interference from many possible sources of extraneous light: Sunlight and illumination from hot objects (such as tungsten lamps) involve light in both the visible and near-infrared ranges. As well, other high-temperature objects, that often exist in a manufacturing environment, also emit light in the infrared region. 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 ultra-violet region. Because of all these disturbances, light-transducer-based sensors must embody explicit protective mechanisms.

Another strict requirement for the interface to such transducers is a wide dynamic range (DR). While DR is a very im-

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portant 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 [11]. 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 40db electrical-measurement range (rather than to the 20db range of optical-power variation). Another important parameter, the reflecting-surface orientation, can cause a similar variation in the measurement range. Moreover, there exist other parameters, such as overall reflectivity of the surface, that for different surfaces can vary in an even more extreme manner. In fact, so extreme are the variations that one can easily come to the conclusion that no fully-linear receiver circuit can possibly supply the required DR. Correspondingly, in practice, the DR of such sensors has, until now, been restricted by the DR of the receiver in the electronic interface. As will be described later, our design incorporates a new method by which we bypass this limitation, and allow substantial widening of the DR of the sensor system.

Many sensor applications require measurements of the light attenuation in several paths concurrently. In order to perform this task, the interface is required to supply synchronized multiple measurements using several receivers. An interface circuit that allows synchronized operation of several light transmitters can also add to the flexibility of an optical-sensor system.

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.

III. 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 1mm-core fiber-optic cables (FOCs). This appropriately facilitates the operation of the sensitive low-noise interface circuitry remote from the high currents of robots' (and other machines') motors. The FOCs can also be used as an integral part of the transducer itself.

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

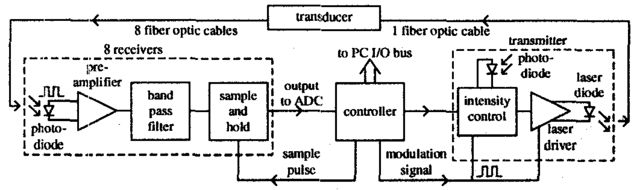

Fig 1. Block diagram of the interface circuit.

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 LDs 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 minimum width of the optical band of the filter is set by the geometric features and the tolerances of the light-source. Most critically, the center frequency of a pass-band interference filter is a function of the angle between the light beam and the filter's normal. Correspondingly, the optical bandwidth needed to cover the transducer aperture ϕ, can be approximated as:

$$\Delta\lambda = 2\lambda_{\max}\left(1-\sqrt{1-\left[\frac{n_o}{n_e}\right]^2 \sin^2\phi}\right) \qquad (1)$$

where λ_{max} is the filter's center wavelength, n_o is the refractive index of the external medium (air), and n_e is the effective refractive index of the filter.

The bandwidth tolerance is also 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 serves also 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 non-modulated scheme must have direct coupling from the detector to the A/D. 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 photo-diode 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 DRs of the receiver and the transmitter circuits.

Moreover, employment of the method of dynamic intensity control at the transmitter also affected 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 [12]. 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 pre-amplifier 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).

IV. 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 830nm as the operating optical wavelength, since a vast selection of opto-electronic components is available there. As well, we selected 10KHz as the modulation frequency, since it is far from the 50/60Hz 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 [13]

The schematic of the laser-driver circuit is shown in Fig. 2. The LD used as the light source is the Hitachi HL8312G. It is capable of emitting 20mW 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 60mA 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 70mA for the HL8312G), and then modulated by another transistor-switch. Two Zener diodes protect the LD from over-drive 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.

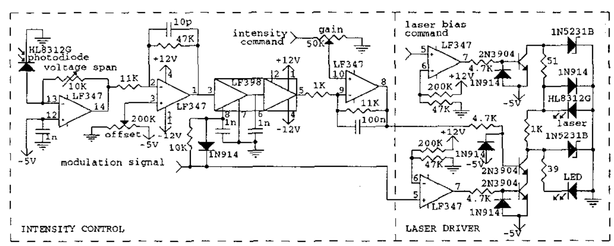

Fig. 2. Transmitter schematic.

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 pick-up of the modulated signal by the sensitive low-noise receiver circuit. Therefore, the −5V power source that supplies the LD current is used in the transmitter circuit only.

B. Intensity control [13]

The transmitter circuit, shown in Fig. 2, 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 3µsec 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.

The 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 the 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. This stage includes gain adjustment to allow a match between the maximum intensity commanded and the maximum current allowed by the laser driver.

C. Detector and preamplifier

The preamplifier design (Fig. 3) is based on a low-noise remote-control receiver [14]. A regulated 8V 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.

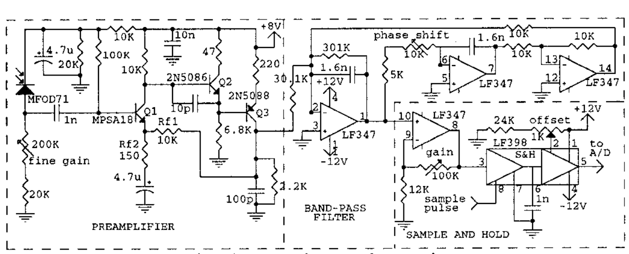

Fig. 3. Receiver schematic.

In the proposed circuit, light is detected by an MFOD71 PIN photodiode, biased at −5.3V. 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 1mm-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 pre-amplifier instead of a conventional transimpedance design [15]. Current-to-voltage conversion is done with a variable resistor to enable fine tuning of the receiver gain. This adjustment also affects the receiver's SNR and the high-pass filter implemented at the receiver's input.

A high-pass filter at the input of the receiver is necessary in order to reduce the effect of ambient light on the pre-amplifier. The amplitude of the ambient light can in some cases be far 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 pre-amplifier 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 50/60Hz-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 pre-amplifier is capacitor-coupled, thereby implementing the first pole ahead of the preamplifier. The second pole is positioned at the emitter of Q_1. The values of the filter components are selected to give a cut-off frequency in the range 350-550Hz depending on the value of the variable gain-tuning resistor. This filter is designed to attenuate 60Hz signal by 20-30db. Choosing a higher cut-off frequency (with smaller capacitors at the base and emitter of Q_1) could increase this desired attenuation, but will also further restrict the minimum modulation frequency of the LD.

As in common optical receivers, the transistor in the first gain stage (Q_1) must have low noise and high h_{fe} to minimize the electrical noise output of the receiver. The parameters of the MPSA18 make it a suitable choice. The Miller compensation-capacitor between the base and the collector of Q_2 ensures the stability of the preamplifier [16]. The transistor Q_3 serves as an output stage, supplying high current gain and low output impedance. A low-pass filter is implemented by an RC circuit at the emitter of Q_3, with a cut-off frequency of about 700KHz. This filter 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 implemented through the feedback resistors R_{f1} and R_{f2}. The feedback factor (in the pass band) is:

$$\beta \cong \frac{R_{f2}}{R_{f1} + R_{f2}} = 0.0148 . \quad (2)$$

This feedback serves many purposes: it sets and stabilizes the amplifier gain to $1/\beta$, increases the bandwidth, increases the input impedance, and reduces the output impedance[16].

D. Band-pass filter

The band-pass filter is a second order KHN biquad circuit [16]. The filter in Fig. 3 is designed to have its center frequency at 10KHz, 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 pass band of the filter, the phase-shift of the output signal varies as much as 90~100 degrees. Therefore the tuning of the filters in the multi-receiver sensor is directed towards 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 (Fig. 3). The gain is set to bring the noise level to about ±1LSB 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 6μsec as required by the LF398 used in the circuit. 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. Therefore, if obtaining all the values during a single modulation period is impossible (according to some combination of modulation frequency, number of receivers, and A/D conversion rate), the modulation-signal frequency must be divided to obtain the sample pulse.

V. CIRCUIT PERFORMANCE

The performance of the proposed 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.

The frequency response of the preamplifier is shown in Fig. 4. The 3db points at 493Hz and 135KHz set the possible range for the modulation frequency. Interfering light at 60Hz is attenuated by 29db by the filter at the base and emitter of Q_1. The frequency response of the complete receiver (which includes the effect of the high-Q band-pass filter at 10KHz) is shown in Fig. 5. The relative attenuation of the 60Hz light-signal at the S&H input is 108db.

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 500KHz, the intensity control lost most of its linearity above 200KHz. Thus, the use of a faster S&H chip and faster op-amps with a higher slew-rate is recommended for modulation frequencies above 50KHz. The same recommendation applies to the components described in the S&H section of the receiver circuit.

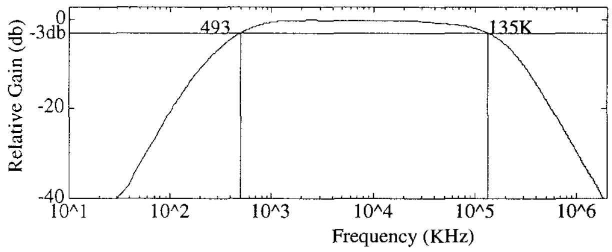

Fig. 4. Preamplifier's frequency response.

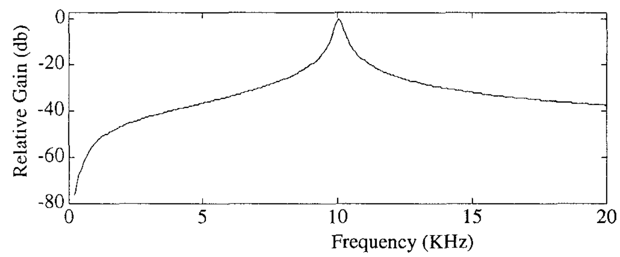

Fig. 5. Receiver's frequency response.

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 72db (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 134db, when the minimum SNR is taken as 10db.

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 10cm 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 cut-off 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 (40dB per decade). Therefore, an optical filter with a narrower pass-band 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 [17], to yield the value of $1.52\,\text{pA}/\sqrt{\text{Hz}}$. This noise is attributed mainly to the input resistors (about $0.5\,\text{pA}/\sqrt{\text{Hz}}$) and to Q_1.

VI. APPLICATION EXAMPLE

In order to test the performance of the new electronic interface circuit, it was interfaced with an experimental robotic proximity sensor [18]. 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 FOCs.

Measurements were acquired at various points within a range corresponding to variations of 1-100mm in distance and ±30° 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 ±1LSB. Thus, the SNR was 66db for the strong signals and as low as 32db for weak signals (at the 100mm range). Comparison between measurements taken on different days gave ±2LSB variation, reducing the above SNRs by 6db. 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.

VII. CONCLUSIONS

A new sensor-interface was designed as a practical low-cost circuit for use by a variety of opto-electronic 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 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 force-torque sensing [3,4], tactile sensing [5,6], orientation sensing [7], and distance sensing [8-10].

ACKNOWLEDGMENT

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