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Liquid Crystal based optical telemetry applied to 4–20 mA current loop networks

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ABSTRACT

We report on a novel way to interface a liquid crystal based optical telemetry system to existing 4–20 mA sensors and apply it to the specific case of gas sensors. We prove that existing sensor networks can be retrofitted with passive electro-optical transducers and low-power Voltage to Frequency (V-F) converters without any loss of accuracy. In particular, we show that resolutions of 16 bits can be achieved even for short acquisition times and low sampling rates, limited only by the V-F specifications. The proposed approach allows harnessing all the benefits of optical networks, such as increased transmission distance of up to several tens of kilometres and intrinsic safety, without having to redesign the actual sensors.
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1. Introduction

4–20 mA current loops are the dominant industry standard for sensor measurement and control. There are numerous advantages to using a current loop for control and measurement, such as minimal signal losses when compared to voltage signals and the fact that varying loop impedance or supply voltage does not affect the signal. Such loops can, in principle, run over distances as far as several kilometres, but are more commonly used in the range of several hundreds of metres dependent on the wiring, power supply and loop components. Additionally, the live-zero signal (4 mA), verifies that the sensor or transmitter is electrically functional. Zero current implies that there is a break in the loop. Such advantages have seen this measurement standard embraced almost universally across a range of industries. [1–3]

In this work, we demonstrate an optical telemetry system based on novel electro-optical transducers applied to 4–20 mA analogue sensors. We chose an industrial oxygen sensor from the mining industry, which uses the 4–20 mA current loop regime, to demonstrate our approach. The proposed optical telemetry could equally be applied to other sensor networks such as flow measurement for example [4]. The Deformed Helix Ferroelectric Liquid Crystal (DHFLC) based transducer we use can confer numerous further advantages to existing 4–20 mA sensors, by connecting them to an optical network. By leveraging the benefits of the optical domain we can add benefits such as: intrinsic safety in flammable or explosive environments, the ability to multiplex multiple distributed sensor signals onto a single optical fibre, as well as allowing for transmission across much longer distances than conventional copper loops, in the order of several tens of kilometres. Additionally, the electro-optical transducer allows for high resolution measurements with short acquisition time.

Many types of fibre-based sensors are in widespread use, and employ a range of deployment methods such as: point, integrated, distributed or quasi-distributed arrangements. In many cases though, such sensors are used to directly interrogate the measurand through intrinsic measurements techniques or extrinsic ones [5–10]. We do not seek to describe a new measurement method in this work, but rather to demonstrate a method of interfacing with existing 4–20 mA sensors so that we can leverage the benefits of the optical domain without having to design a whole range of new optical sensors.

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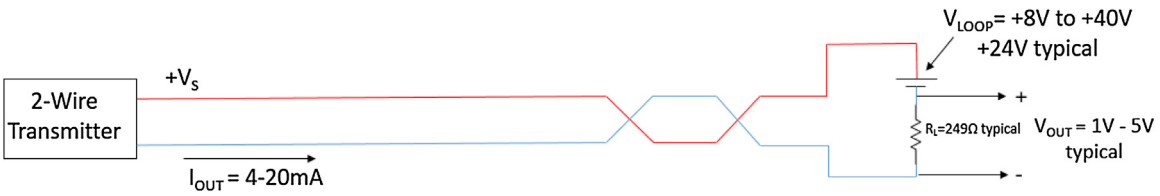


Fig. 1. Two-wire current loop architecture showing the power supply with transmitter (sensor) and output voltage for the receiver.

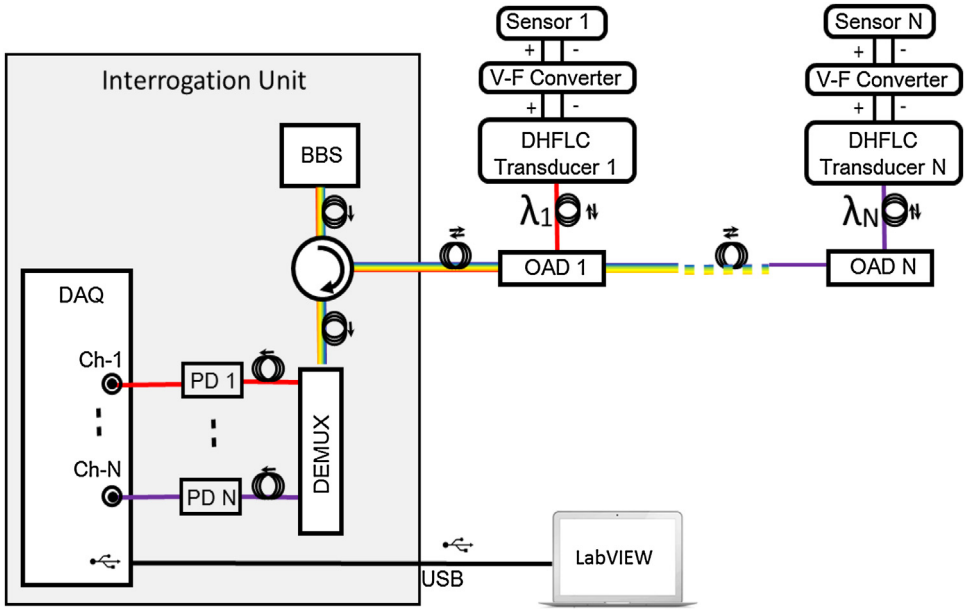


Fig. 2. System schematic showing the interrogation unit containing the Broad-Band light Source (BBS), optical circulator, de-multiplexing unit (DEMUX), photodetectors (PD) and data acquisition card (DAQ), as well as the 4–20 mA sensors, V-F converters, electro-optical transducers (TR) and Optical Add/Drop filters (OAD). Wavelength Division Multiplexing channels are represented as colours.

The theory and functionality underlying the operation of the liquid crystal (LC) transducer has been described in previous work [11,12]. Here we show a specific application along with experimental data supporting the benefits and advantages in coupling this technology with the ubiquity of existing 4–20 mA current loop sensors.

Fig. 1 shows a typical two – wire current loop.

2. Approach

2.1. Overview

A diagram of the system setup is shown in Fig. 2 for reference. An interrogation unit containing a light source, optical hardware, photo detector array and data acquisition card (DAQ), sends broadband light downstream to a sensor node. Wave Division Multiplexing (WDM) allows us to use standard telecommunications Optical Add/Drop filters (OAD) along the single mode fibre backbone to drop off specific bandwidths of the transmitted light to each sensor node. At each node, we have a 4–20 mA sensor connected to a custom built V–F converter which accepts either a 2–10 V or 4–20 mA input. We interface the 4–20 mA sensor output directly with the current input of the converter. The converter outputs an AC voltage at a frequency directly proportional to the input current from the sensor. This AC voltage is used to drive the optical transducer, causing the liquid crystal to modulate the reflectance of the cell at the same frequency [12]. Light delivered to the transducer is thus modulated and reflected back into the fibre up to the interrogation unit, where it is de-multiplexed and analysed by photodetectors. The signal is then processed by software to measure the frequency of the optical signal and finally obtain the sensor measurement.

2.2. Interrogation unit

The interrogation unit contains the essential hardware for the functioning of the system. The light source is an Erbium Doped Fibre (EDF) Amplified Spontaneous Emission (ASE) source, pumped by a 980 nm fibre-coupled pump laser (Gooch and Housego). The source has an optical output power of approximately 200 mW and a broadband output with a wavelength that ranges between 1535 and 1565 nm. An optical circulator allows source light to be directed to the fibre backbone with attached sensors, whilst modulated light returning along the same path is directed to the de-multiplexing unit rather than back to the source. The intensity of the de-multiplexed light is measured by an InGaAs photodetector (OE Market PIN-TIA-155), converted to an electrical signal and then filtered to remove DC and high frequencies (> 20 kHz). A National Instruments DAQ (USB-6009) with a maximum sampling rate of 48 kHz and 14 bit input resolution takes care of the analog to digital conversion and outputs the data via a USB connection to a laptop running LabVIEW software for analysis.

Using a Virtual Instrument (VI) in LabVIEW we are able to adjust acquisition time and sampling rate. Data collected during the acquisition time is fed to an in-built “Extract single tone Information” VI in LabVIEW to measure the signal frequency. The algorithm uses a Fast Fourier Transform (FFT) analysis and improves the result by using a Hanning Window function to reduce aliasing. In particular,

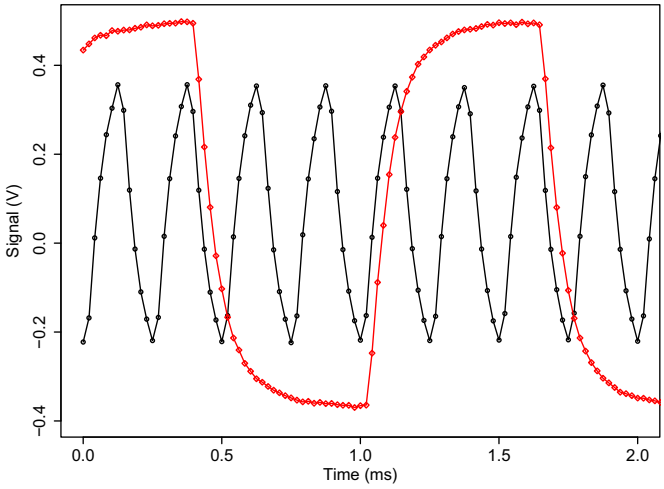


Fig. 3. Raw optical signal at 0.8 kHz and 4 kHz captured over 2 ms. Note how the original square wave shape from the V-F converter is modified due to the finite bandwidth of the LC transducer.

the frequency is calculated from the highest and second highest value of the magnitude of the discrete FFT according to an analytical formula. The algorithm can dramatically increase the accuracy of the frequency measurements even when a small number of periods is sampled, especially if the DAQ has a high input resolution. This approach works better with pure sine waves, while in the case of square waves the presence of higher order harmonics can still produce aliasing. Since in our experiments the information is carried by square waves, we expect the accuracy of the frequency measurements to depend on the ratio of the frequency to the sampling rate in a periodic way, giving rise to extra noise in the data when these two parameters are changed (see Sections 3.2 and 3.4). Typical raw signals as measured at the interrogation unit are shown in Fig. 3.

2.3. Optical transducer

The optical transducers are based on LC cells that act as variable reflectance mirrors when coupled with a polariser [11]. Essentially, the cell consists of two substrates with conductive inner surfaces acting as electrodes, sandwiching a thin layer of liquid crystal. This has been aligned with respect to the polariser in such a way as to induce a linear optical response to the input voltage. Deformed Helix Ferroelectric LC's are unique in their combination of fast switching speed (approximately 20 μs), and low driving voltage [11,12]. The substrates are made of borosilicate glass, one with a transparent conductive film of Indium Tin Oxide (ITO), whilst the other is coated in gold, which acts dually as a mirror, and electrode, (Fig. 4a). Infrared light is delivered to the cell by single mode optical fibre. It passes through a polariser, the top substrate and the LC layer before undergoing reflection off the back surface of the cell.

The two conductive substrates (or electrodes) are connected to the output of the V-F converter. The V-F converter output signal is used to drive the optical transducer such that the oscillating voltage across the LC cell causes the LC to modulate the reflected light being coupled back into the fibre.

2.4. V-F converter

The variable 4–20 mA current from the gas-sensor connected to the input of the V-F converter is converted to an AC voltage with a fixed amplitude and a variable frequency that ranges between 800 Hz and 4 kHz. Note that using an AC voltage to drive the optical transducer is necessary to avoid degradation of the LC. The output frequency range emulates the current input range of 4–20 mA and maintains the 'live-zero' characteristic of a 4–20 mA current loop. The output waveform is a simple square wave with 50% duty cycle. The amplitude of the signal can be adjusted if necessary, but stays fixed for the duration of the data acquisition. For simplicity we used a 2 V peak amplitude for the output signal. The V-F converter has been custom made and is specified to have frequency resolution of 16 bits. In particular, the voltage across the sense resistor is sampled by a 24 bit ADC and the frequency output is from a pulse width modulator with a 16 bit count value. Thus, the best resolution is only at very low output frequencies, corresponding to very low input voltages. As the input voltage increases, the resolution of the output decreases. To counter this effect, we keep a running average of the frequencies of the output cycles and jitter them either side of the ideal frequency. Our electro-optical transducers are passive, requiring no power to operate. The V-F converter however does require a 12 V power supply to power the board. In our experimental setup, we used a powered oxygen sensor and therefore supplying the V-F board with power was relatively trivial. However, for completeness, we quantified the power consumption of the V-F converter for a range of output signal amplitudes in order to give some indication as to the power requirements for this essential part of the system in the case that a different sensor is being transduced and battery power is required. The power was calculated by measuring

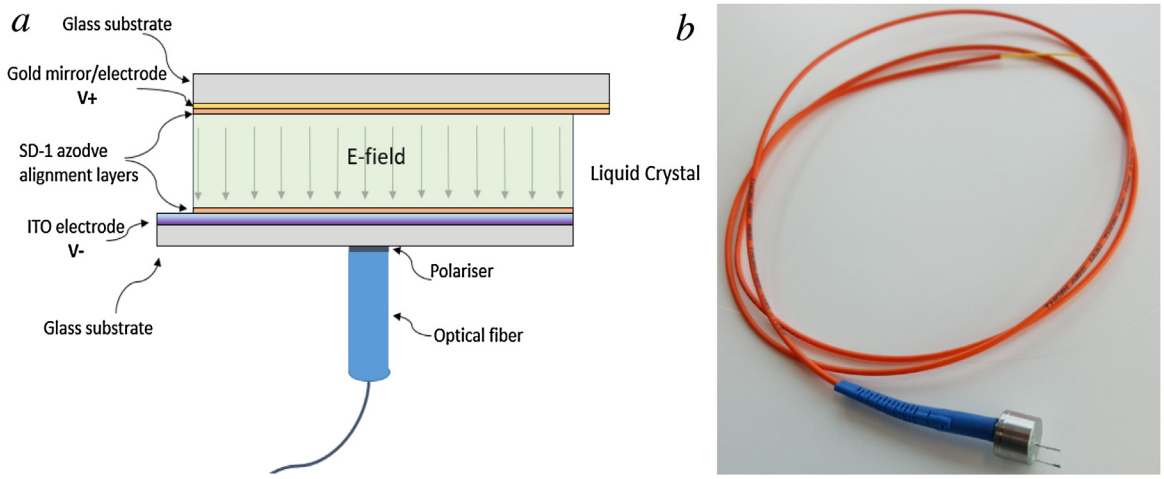


Fig. 4. (a) Daiagram showing the architecture of a typical liquid crystal (LC) transducer cell. And (b): A packaged transducer with two electrical inputs (signal) and a single mode fibre input/output.

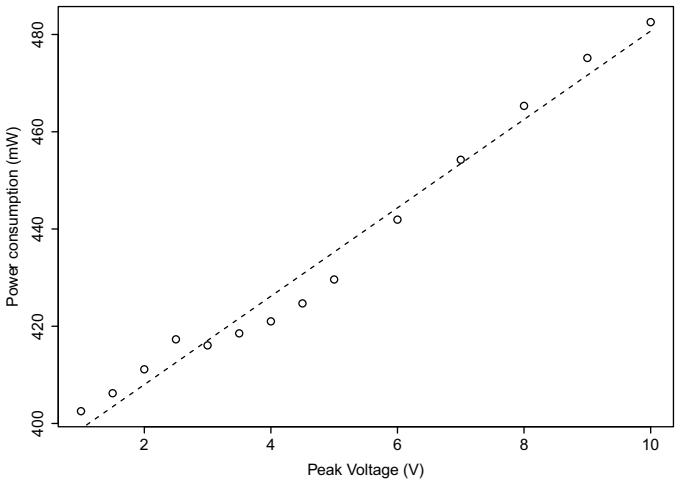


Fig. 5. Power consumption of the V-F converter board at a range of output signal amplitudes. Most of the data presented in this paper had a peak amplitude of 2 V, corresponding to a power consumption of approximately 0.41 W.

the input current to the board for several amplitudes. The input voltage was 12.31 V. The results are shown in Fig. 5 below:

2.5. Gas sensor

Our primary goal is to show that we can interface to any existing 4–20 mA sensor and obtain extremely high levels of transduction accuracy, much higher than most sensors require. To use a real world example though, we chose a 4–20 mA oxygen sensor manufactured by Ampcontrol (Gasguard O_2 gas detector/transmitter Series 65-6550), commonly used in underground mining and tunnelling operations (Fig. 6). The unit contains a galvanic oxygen cell (CiTicel 7OX-V,) with associated electronics to output the 4–20 mA current range for oxygen concentrations from 0% to 25%. The stated accuracy of the Gasguard sensor is 0.1%, an accuracy achievable with 8-bit resolution. Where normally, the distance between the transmitter (sensor) and receiver in a 4–20 mA current loop may be several hundreds of metres long; in our approach, we effectively run the current loop over a very short distance, from the sensor output to the V-F converter input, a distance of only a few centimetres. The sensor and the V-F converter are acting as the transmitter and receiver respectively in Fig. 1.

3. Experiment and discussion

In the first instance, we omitted the V-F converter from the experimental setup and replaced it with a signal generator (Stanford Research Systems DS340, 15 MHz), so that we could directly modulate the LC transducer with known frequencies of exact amplitudes. In particular, we applied a square wave signal with 50% duty cycle and 2 V peak voltage to a LC transducer connected to the first channel of the telemetry system. The aim of this setup was to vary the input parameters in order to establish the resolution of the optical telemetry system (LC transducer and interrogation unit). In the real system, the V-F converter outputs a frequency range from f_{min} = 800 Hz to f_{max} = 4 kHz which corresponds to the 4–20 mA range of the sensor to which it is connected, so this is the range we investigate. The resolution of the optical telemetry system depends on various parameters, such as sampling rate, acquisition time, signal frequency and attenuation. In this section we characterise the optical telemetry system and investigate how the various parameters affect its resolution. We used the standard deviation, σ, of a set of 100 measurements as a measure of the system precision. Resolution is then expressed in bit according to the following formula:

$$bitresolution = log_2\left(\frac{f_{max} - f_{min}}{\sigma}\right).$$

3.1. Attenuation

It is important to understand the effects of signal attenuation on the resolution, because, as fibre length increases, the system suffers losses. In addition to that, in the case where multiple transducers are 'daisy-chained' and their signals multiplexed onto the same fibre backbone, there are losses associated with each time the

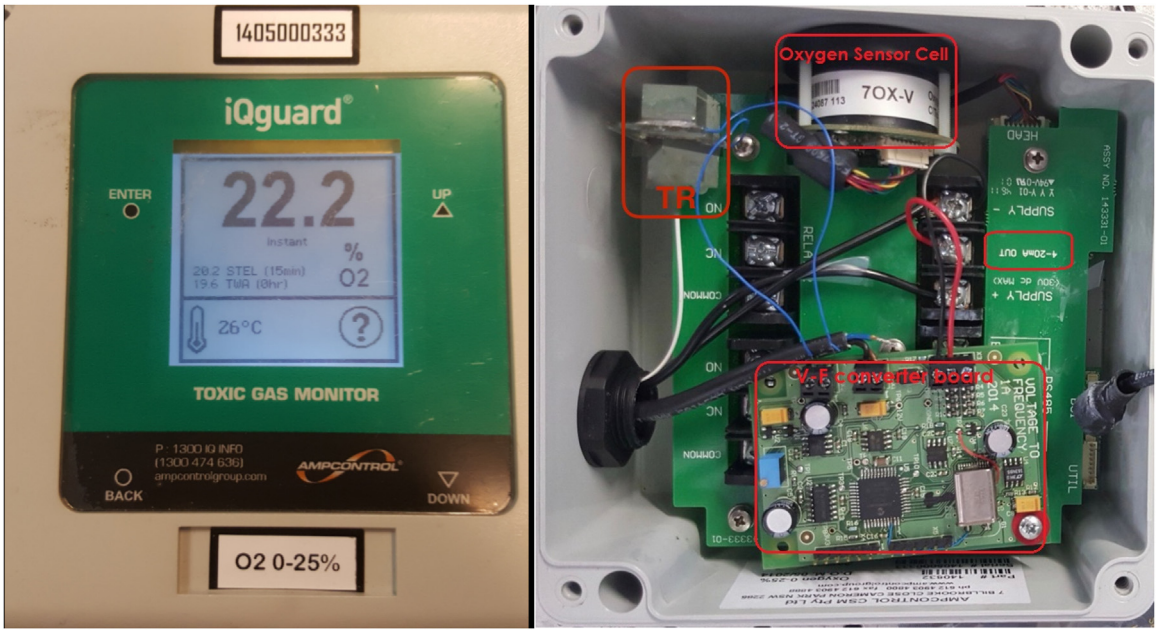


Fig. 6. 4–20 mA O_2 sensor showing ambient O_2 concentration (left). Inside of gas sensor with V-F converter PCB visible at bottom, interfaced directly with gas sensor output. The unpackaged LC transducer (TR) is visible top left with white fibre attached.

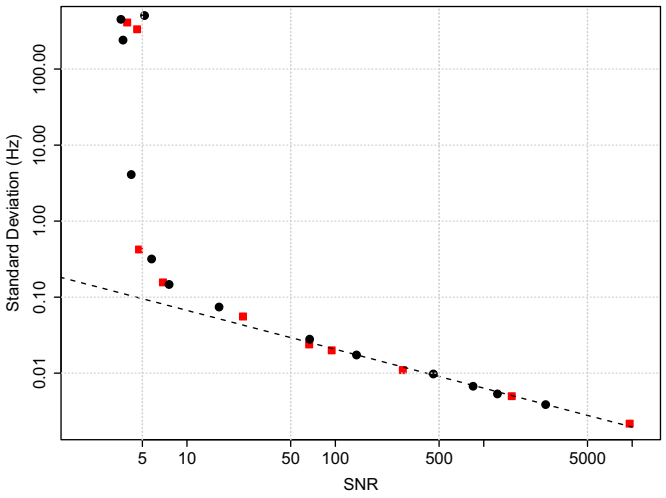


Fig. 7. Standard deviation of the measured frequency as a function of the signal to noise ratio (SNR) at the interrogation unit (logarithmic scale). Two different frequencies have been applied to the LC transducer: 800 Hz (squares) and 4 kHz (circles). The dashed line is a linear fit for SNR > 50, with slope −0.51.

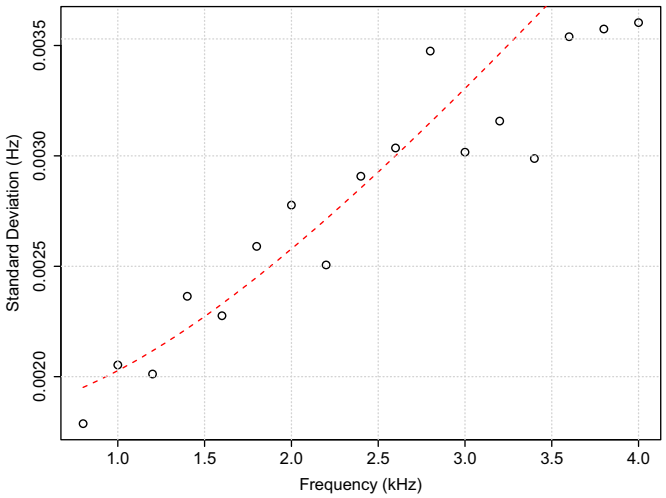


Fig. 8. Standard deviation of the measured frequency as a function of the signal frequency (open circles). The dashed line has been calculated from the data in Fig. 7 assuming that the 3 dB bandwidth of the LC transducer is 2 kHz (see the text for more details).

light passes through an add/drop filter on the way down the chain. The amount of light reaching the transducer furthest away from the interrogation unit is much less than that arriving at the first transducer in the chain, (refer to Fig. 2). The losses are completely quantifiable and are typically specified per component. Single mode optical fibre for instance is specified to have losses of 0.18 dB/km [13]. In traditional 4–20 mA current loops, the power source needs to supply enough voltage to overcome all the system losses. Though current loops are advantageous precisely for the reason that Kirchhoff's current law stipulates, that measured current at any point on a single loop must be the same everywhere along the loop, it is also true that the power supply must supply enough voltage to overcome all the voltage losses along the loop as well, including the voltage drop incurred by the wire in the loop itself. Longer loops require higher and higher voltage sources. For this reason, traditional loops cannot be arbitrarily long. In the optical domain, losses are still present, but the distances over which the losses occur is much greater than in the electrical domain.

We measured the standard deviation σ of the frequency measurements as a function of the signal to noise ratio (SNR) at the interrogation unit. The SNR was calculated as the ratio of the power of the measured signal and the power of the background noise, measured with no voltage applied to the transducer. The two extreme frequencies, 800 Hz and 4 kHz have been used for this experiment, while the acquisition time was 0.1 s and the sampling rate 48 kHz. The SNR was varied by using a variable attenuator placed along the backbone fibre, thus simulating additional optical losses of the system. The results are reported in Fig. 7. As expected, σ strongly depends on the SNR. At high SNRs, greater than about 50, it scales roughly with $SNR^{-1/2}$, until the measurements become less accurate and completely meaningless as SNR approaches a value of 4. However, we point out that the corresponding resolution is still close to 13 bits, for an SNR of 5. Such a low SNR corresponds to additional optical losses of about 18 dB, equivalent to about 49 km of extra fibre (we used a value of 0.36 dB/km for the fibre losses because light travels both ways). Finally, it is important to note that the trend is identical for both frequencies.

3.2. Frequency

For this set of measurements, the sampling rate was kept at 48 kHz and the acquisition time at 0.1 s, the same as in the previous experiment, but the frequency of the voltage applied to the LC transducer was varied across the whole range from 800 Hz to 4 kHz. The results are shown in Fig. 8. The precision of the measurements decreases as the frequency increases, the standard deviation at 4 kHz being about twice the one at 800 Hz. This result is not surprising and it is due to the finite bandwidth of the LC transducer, which is about 2 kHz at room temperature. For this reason, the amplitude of the signal received by the interrogation unit is smaller at high frequencies and the corresponding SNR poorer. Using the linear fit from Fig. 7 and a Lorentzian shape for the dependence of the signal intensity from the frequency [11], we obtain the dashed line in Fig. 8 that correctly reproduces the trend of the experimental data. The explicit formula for the standard deviation as a function of the frequency, f, is

$$\sigma(f) = a\left[\frac{SNR_0}{1+\left(f/f_c\right)^2}\right]^b,$$

where a = 2.17 Hz and b = −0.51 are fitting parameters from Fig. 7, SNR_0=11600 is the SNR at low frequencies and f_c=2 kHz is the bandwidth of the LC. The fact that the experimental data are fairly scattered is a consequence of the fitting algorithm used by the LabVIEW VI "Extract single tone Information", which is very sensitive to both the signal frequency and the sampling rate.

3.3. Acquisition time

In Fig. 9 we show two curves, demonstrating the relationship between the precision of the optical telemetry and the acquisition time, *T*, used in the processing software. Two frequencies were chosen at each end of the signal frequency range, 800 Hz and 4 kHz, while the sampling rate was kept constant at 48 kHz. We note a clear correlation indicating that as acquisition time increases, the standard deviation decreases, giving a higher bit resolution. The linear fit of the log-log plot in the figure suggests that the standard deviation scales as $\sigma \propto T^{-3/2}$. One possible reason for this behaviour is that at longer acquisition times the amount of noise in each frequency bin of the Fourier Transform decreases, leading to more accurate measurements than the expected 1/T scaling would predict. By showing the two extreme ends of the signal frequency range we note that the highest signal frequency is always more difficult to resolve, due to the lower SNR, as already discussed in the

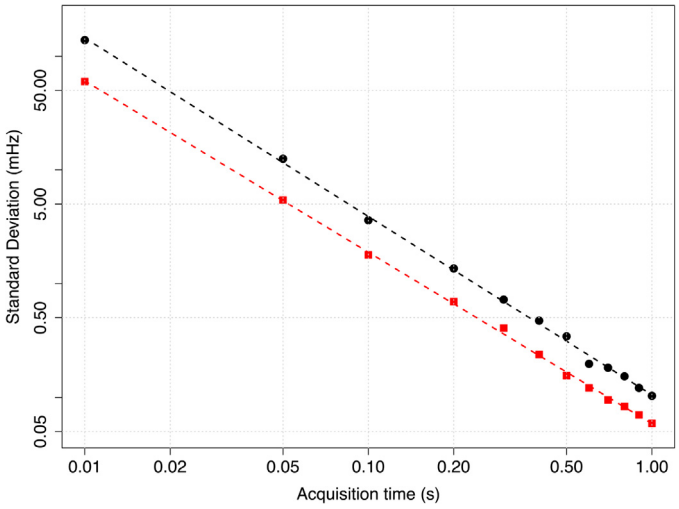


Fig. 9. Standard deviation as a function of the processing software's acquisition time for signals at 800 Hz (squares) and 4 kHz (circles). The dashed lines represent the best linear fit to the data, with a slope of −1.51 for 800 Hz (squares) and −1.57 for 4 kHz (circles).

Table 1
Bit resolution of the optical telemetry system for a range of acquisition times.

Acquisition Time (s)	0.01	0.05	0.1	0.2	0.3	0.4	0.5	0.6	0.8	1.0
Bit resolution	14	17	19	21	22	22	23	23	24	24

Table 2
Bit resolution of the optical telemetry system for different sampling rates and acquisition time 0.1s.

Sampling rate (kHz)	8	12	16	20	24	28	32	26	40	44	48
Bit resolution	12	18	18	18	19	19	18	19	19	20	19

previous section. Table 1 shows the bit resolution of the system, calculated using the standard deviation measured at 4 kHz, i.e. the largest across the whole range of signal frequencies. We note that 24-bit resolution is possible with 0.8 s acquisition times and that we still have 14 bits with the fastest acquisition time of only 0.01s.

3.4. Sampling rate

Next, we varied the sampling rate, F_s, of the DAQ from 8 kHz to 48 kHz. As expected, the 4 kHz signal frequency is not able to be resolved with as great an accuracy compared to the rest of the measurements when the sampling rate is set to 8 kHz, due to this signal frequency corresponding exactly to the Nyquist limit. However, the standard deviation of the measurement decreases rapidly once the sampling rate is increased beyond this fundamental limit. Acquisition time was maintained at a constant 0.1 s for every data set. As can be seen in Fig. 10, the experimental data are quite scattered due to the nature of the fitting algorithm implemented in LabVIEW. By once again analysing the worst case scenario (4 kHz signal frequency), we can calculate the bit resolution of the optical telemetry system, which is reported in Table 2. Please note that we still obtain 12-bit resolution down to the sampling rate of 8 kHz.

3.5. Gas sensor

In order to demonstrate that the approach that we have described applies equally well to a real world sensor, we now drive the V-F converter with the gas sensor output signal. We also wrote a Labview VI to convert the measured optical signal frequency back to an oxygen concentration. As mentioned in the previous section,

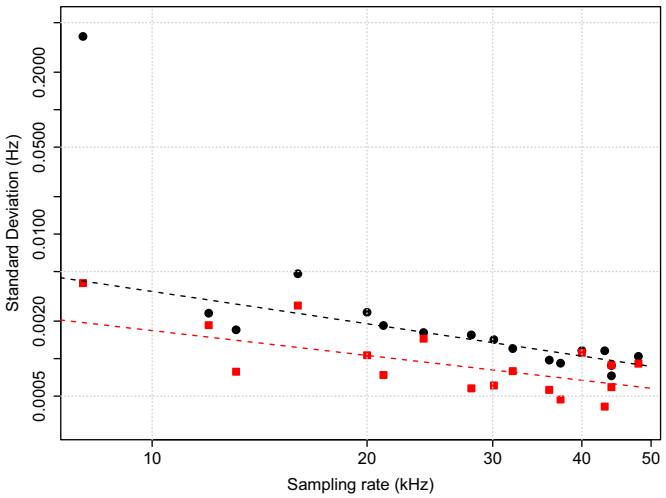


Fig. 10. Standard deviation as a function of the DAQ sampling rate for signals at 800 Hz (squares) and 4 kHz (circles). The dashed lines represent a guide to the eye.

the gas sensor outputs a 4–20 mA signal, corresponding to 0–25% O_2 concentration in increments of 0.1%, the full sensor range thus being able to be represented by an 8-bit number. Obviously, given the much higher resolution of our optical telemetry, the optical signal we read was very steady and accurate. By directing a nitrogen flux on the sensor, we were able to test the range of the Gasguard from ambient levels, around 20.6%, down to 0% O_2 concentration. In all cases the reading on the gas sensor display, and the reading on the laptop screen matched perfectly. We can thus confidently say that the system behaves with 100% agreement between the real signal and the transduced signal value for this particular example.

4. Conclusions

In this work we demonstrate a novel way to interface an existing 4–20 mA current loop sensor network with an optical telemetry system. By doing so we allow for the existing sensors to be read optically without having to re-fit the whole network with new optical sensors, which in many cases do not even exist. We can thus leverage all the benefits of moving into the optical domain, such as even longer transmission distances in the order of several kilometres, intrinsic safety in flammable environments and well as a very high measurement precision.

We summarise the analysis section by pointing out that the bit-resolution of the optical telemetry system is very high, much higher than most commonly used sensors, as we proved by using a signal generator to emulate the V-F converter. As a matter of fact, in many of our experiments the limiting factor was the V-F converter itself, which is specified to 16-bit accuracy. Overall, we can demonstrate a telemetry system which, although dependant on several parameters, displays high resolution across all sampling frequencies including down to the Nyquist frequency (8 kHz), where we still obtain 12-bit resolution. At full sampling rate (48 kHz), we are able to achieve very high accuracies for longer (>0.05 s) acquisition times. Even at 0.01 s, 14-bit resolution is achieved and up to 24-bits is achieved with a 1.0 s acquisition time. This corresponds to a 4–20 mA current resolution of less than 1 μA.

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Biographies



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