Digital Control of a White Light Interrogation System for Optical Fiber Interferometers

Eduardo Velosa, Carlos Gouveia, Orlando Frazão, Pedro A. S. Jorge, and José M. Baptista, *Member, IEEE*

***Abstract*—A system to interrogate optical fiber interferometric sensors with digital control is presented. The system is based on a receiving white light Mach–Zehnder interferometer and is capable of operating with four distinct synthetic and pseudo-heterodyne signal detection schemes. A differential phase detection scheme was implemented and system performance with the different processing schemes was compared using fiber Bragg grating based Fabry–Pérot cavity strain sensors. With a lock-in time constant of 1 s, most digital techniques were able to nearly match the performance of a standard hardware system, demonstrating the feasibility of low-cost high-resolution interferometric systems operated with virtual instrumentation.**

***Index Terms*—Digital signal processing, interferometric sensors, optical fibers, pseudo-heterodyne, synthetic-heterodyne, virtual instrumentation, white light interferometry.**

I. Introduction

THE FIBER-OPTIC sensor industry is becoming increasingly important, employing presently different techniques to sense a large variety of parameters in demanding applications [1]–[3]. Interferometric techniques are particularly important providing, simultaneously, very high sensitivity and high dynamic range, benefiting also from general advantages of fiber-optic sensors, such as electrical passivity, reliability, and multiplexing ability. White Light Interferometry (WLI) techniques, in particular, are widely used for interrogation of interferometric sensors. This technique uses low coherence optical sources providing high measurement accuracy and insensitivity to optical power fluctuations in the fiber link [4]. In spite of these advantages, such techniques typically require the use of bulky, heavy and expensive instrumentation, hindering system portability and operation in remote environments. Using virtual instrumentation and digital signal processing techniques reduces the need for hardware, increasing miniaturization and the portability of these systems [5].

Manuscript received November 12, 2010; revised April 08, 2011; accepted April 09, 2011. Date of publication April 21, 2011; date of current version December 01, 2011. This work was supported in part by Fundação para a Ciência e Tecnologia (PTDC/SAU-BEB/102247/2008, Hybrid). The associate editor coordinating the review of this paper and approving it for publication was Prof. Ignacio Matias.

E. Velosa, C. Gouveia, and J. M. Baptista are with Unidade de Optoelectrónica e Sistemas Electrónicos, INESC Porto, 4169-007, Porto, Portugal, and also with the Centro de Competências de Ciências Exactas e da Engenharia, Universidade da Madeira, 9000-390 Funchal, Portugal (e-mail: eduardo_velosa@hotmail.com; carlos.j.gouveia@inescporto.pt; jmb@uma.pt).

O. Frazão and P. A. S. Jorge are with Unidade de Optoelectrónica e Sistemas Electrónicos, INESC Porto, Rua do Campo Alegre 687, 4169-007, Porto, Portugal (e-mail: orlando.frazao@inescporto.pt; pedro.jorge@inescporto.pt).

Color versions of one or more of the figures in this paper are available online at http://ieeexplore.ieee.org.

Digital Object Identifier 10.1109/JSEN.2011.2144579

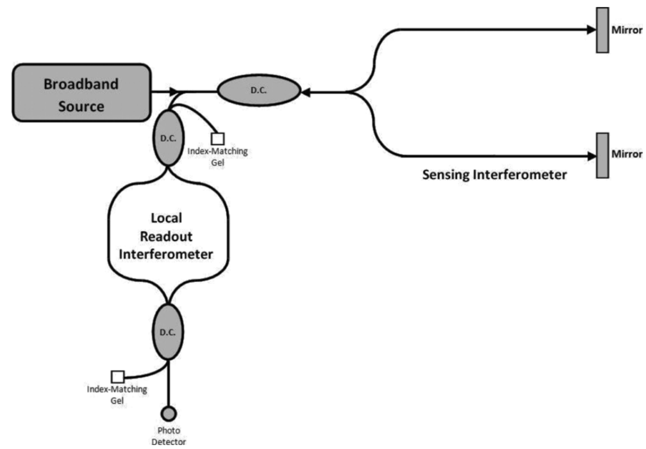

Fig. 1. Basic white light interferometry interrogation scheme.

In this paper, the development of a digital control system for operation of a WLI setup with different synthetic heterodyne and pseudo-heterodyne detection schemes to interrogate interferometric fiber sensors is presented. A Mach–Zehnder interferometer is used to interrogate two FBG based Fabry-Pérot cavity sensors in a differential scheme. The digital control system is evaluated and compared with standard hardware while performing strain measurements.

A. White Light Interferometry

White light interferometry has been used for remote measurement of diverse parameters such as strain, temperature and refractive index [6]. The basic configuration of a WLI interrogation scheme is shown in Fig. 1. It uses a wideband optical source, with a coherence length Lc, to feed the system, which is composed by a remote sensing interferometer, exposed to the measurand, and a readout interferometer, that should be isolated from any undesired environmental effects.

The optical path difference (OPD) of each interferometer (X_1 for readout interferometer and X_2 for sensing interferometer) must be much larger than L_c. In order to obtain meaningful interference at the system output, the condition $|X_1 - X_2| < L_c$ must be attained [4]. Although there is also interference at the output if the OPD of the readout interferometer alone is approximately null ($X_1 = 0$), in such a situation there is no information about the measurand in the phase of the generated carrier. To recover the measurand information, the OPD of the readout interferometer must closely match the OPD of the sensing interferometer ($X_1 = X_2$), in order to obtain the condition $|X_1 - X_2| = 0 < L_c$. A simulation of the behavior of the optical intensity at the output of such a system as a function of X_1 is shown in Fig. 2. To recover the measurand information,

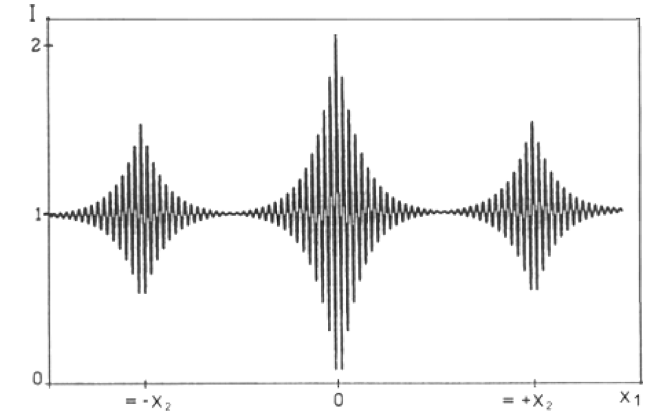

Fig. 2. Simulated optical intensity at the output of a white light system connected to a sensing interferometer as a function of the interferometric path imbalance of the receiving interferometer.

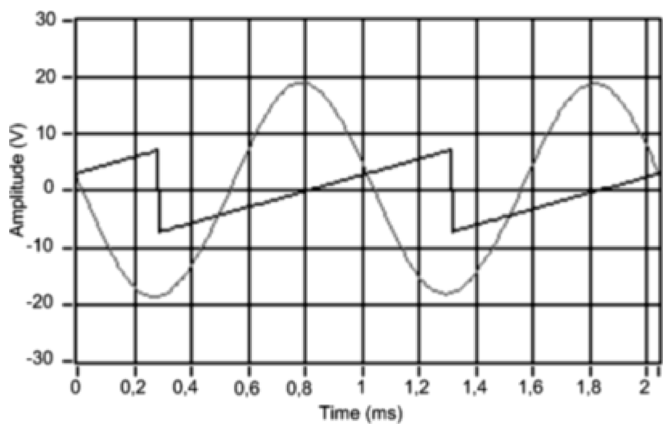

Fig. 3. Modulation waveform (sawtooth) and waveform at the output of WLI system (sinusoid). Real measurements taken from the developed LabVIEW application.

which is contained in the phase of the interference pattern, it is necessary to implement a suitable signal detection scheme.

B. Signal Detection Schemes

The pseudo-heterodyne detection scheme is widely used in WLI systems. It consists in sweeping the readout interferometer phase using a sawtooth waveform. This sweeping can be done using a piezoelectric element to stretch one of the fiber interferometer arms or using an electro-optical phase modulator. The later approach was used in this work.

Modulating the path imbalance of the readout interferometer with an amplitude suitable to produce a 2π excursion in its phase, it can be obtained at the output of the system a quasi-sinusoidal waveform (carrier), like it is shown in Fig. 3.

The information of the measurand can then be retrieved from the phase of the generated carrier, that can be monitored using a lock-in amplifier or other phase tracking techniques [7]. This particular approach has the disadvantage of having a phase measurement error associated with the finite flyback time of the modulation waveform. In order to avoid the flyback effect, the use of synthetic heterodyne detection schemes is usually recommended [8]. In such an approach, a sine waveform is used instead to modulate the phase of the readout interferometer. This

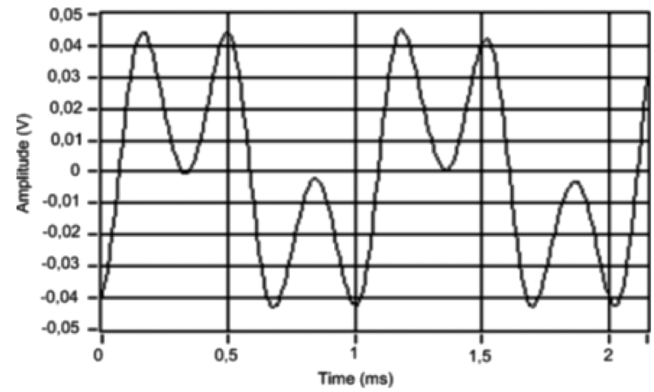

Fig. 4. Waveform obtained at the output of readout interferometer (synthetic heterodyne detection). Real measurements taken from the developed LabVIEW application.

results in a more complex waveform being obtained at the output of the system (shown in Fig. 4).

Therefore, in this case, in order to recover the measurand information, it is necessary to apply more complex signal processing that involves obtaining a carrier with a frequency three times higher than the modulation waveform. The synthetic heterodyne detection scheme, however, has the disadvantage of having limited compatibility with traditional techniques, such as phase tracking or lock-in amplifiers. Moreover, it is more demanding from the computational point-of-view since it comprises a higher number of operations and bandpass filters, being the simplified schemes processed faster.

Simplified synthetic heterodyne schemes, presented by Lo *et al.* [9] and by Misas *et al.* [10], [11] both generate a sinusoidal carrier with the same frequency as the sinusoidal modulation waveform. Although they use different signal processing configurations, both are able to avoid the undesirable flyback phenomena and to provide a straightforward phase difference read-out. Another important feature is that these simplified schemes, when implemented in software, require significantly less computing processing when compared to full synthetic heterodyne scheme.

II. Experiment

Presently, digital tools and computation power are available that enable the implementation of complex modulation and processing schemes in a more straightforward fashion. In order to demonstrate such versatility, a WLI interrogation system controlled digitally by virtual instrumentation was developed in which the user can choose to operate using any of four distinct signal processing schemes.

A. Physical Setup

The experimental setup of the interrogation system is shown in Fig. 5.

A standard fiber-optic Mach–Zehnder interferometer was assembled using two 50/50 power couplers. In one of the interferometer arms, an electro-optical phase modulator (APE from JSDU) was inserted for carrier generation. On the other arm, an adjustable air path was inserted, to allow tuning of the path imbalance, using GRIN lens and a translation stage. The system was illuminated by an erbium-doped broadband source

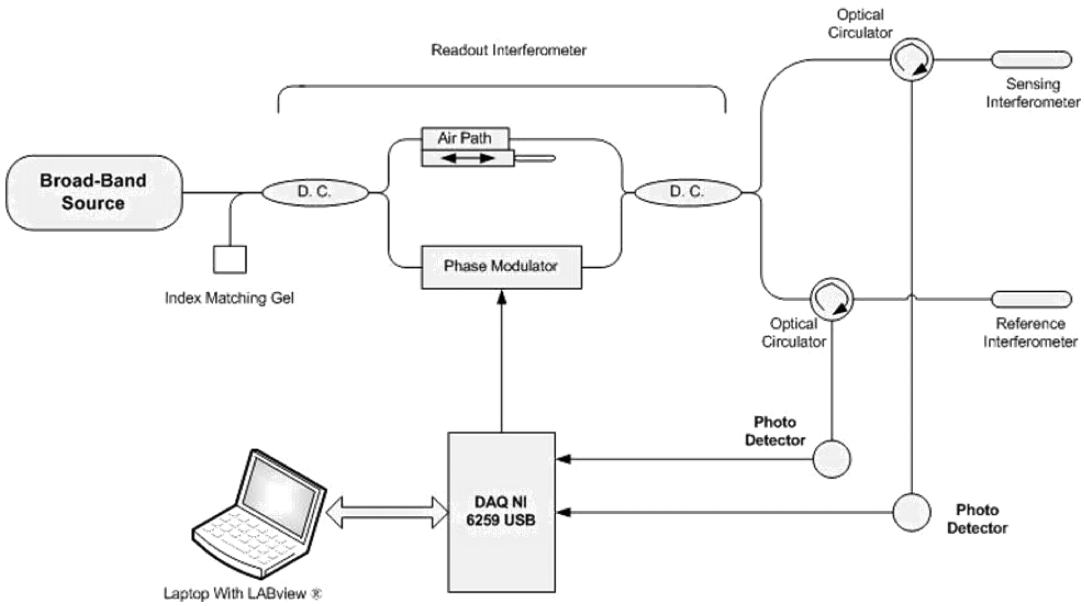

Fig. 5. Setup of the interrogation scheme.

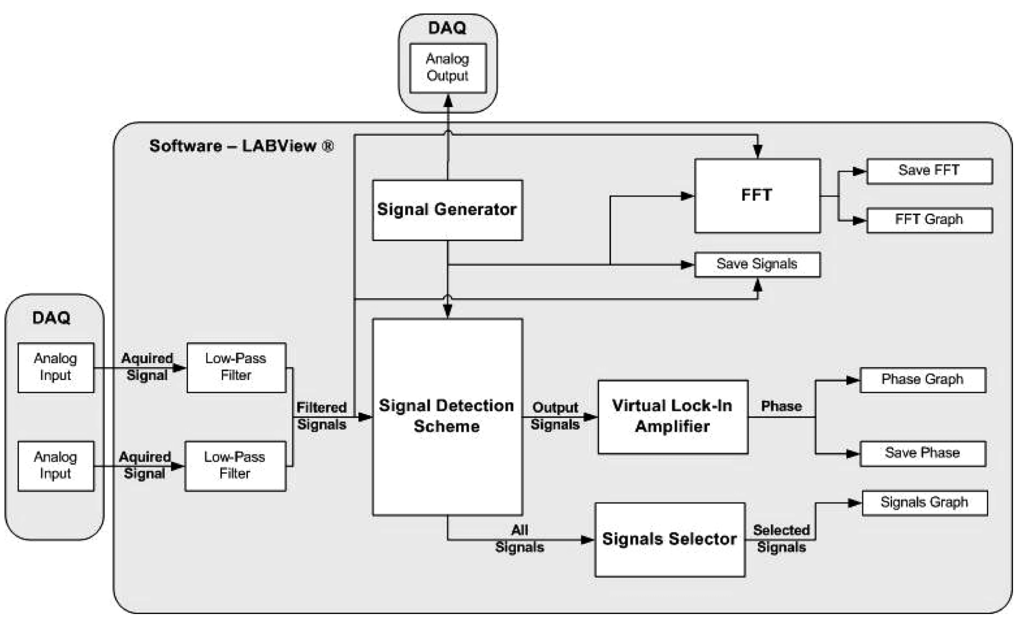

Fig. 6. Block diagram of the virtual instrumentation setup.

($\sim$ 60 nm spectral bandwidth and Lc $\sim$ 40 μm), and used to interrogate interferometric sensors. In-fiber Fabry–Pérot cavities, built by splicing two identical FBG separated by a small fiber segment, were used as strain sensors. By using two identical Fabry–Pérot sensors, each connected to one of the Mach–Zehnder outputs, a differential scheme could be implemented [12]. Using one of the sensors as reference and the other as measuring probe, and since the Mach–Zehnder outputs are in phase opposition, most environmentally induce phase drifts can be canceled out allowing a very stable and accurate phase measurement. The sensors output was directed by optical circulators towards two photodetectors plugged into a signal acquisition board (DAQ NI 6259 USB). For comparison purposes, in some instances a standard hardware setup was used to operate the system using standard lock-in amplifier, a function generator and filters.

B. *Virtual Instrumentation Setup*

The virtual instrumentation was developed in LabVIEW, and included a signal generation for modulation, filtering stages, signal processing, and phase reading blocks (virtual lock-in). A simplified block diagram is shown in Fig. 6.

All the measured signals, amplitude, phase, its FFT, can be represented graphically or saved in a file by the user. The modulation waveforms (sawtooth and sinusoidal) are generated by the signal generation module and are automatically applied according to the chosen signal detection scheme. The signal processing associated to each detection scheme is done also by this

Fig. 7. Screenshot of main interface of the developed software.

module. It is possible to implement the pseudo-heterodyne technique, and three distinct synthetic heterodyne techniques. The original synthetic heterodyne technique is identified as "Synthetic Heterodyne," the technique presented in [9] as "Synthetic Heterodyne Simplified I" and the technique presented in [10] and [11] as "Synthetic Heterodyne Simplified II."

It was also developed for a user-friendly interface in order to facilitate the use of the system. Fig. 7 shows a screen shot of the main interface of the system.

III. Results

A comparison between the digital system and its physical equivalent (using standard lock-in, filters and signal generators) was carried out. For both systems, the same optical source, the same readout interferometer, and the pseudo-heterodyne technique were used. Performance was evaluated based on the measured signal standard deviation. The results obtained are shown in Fig. 8.

The system performance is very similar for both systems. The largest difference occurs when the lock-in time constant (TC) has a value of 1 ms, where a standard deviation of 2.37° was obtained. However, for values of TC longer than 100 ms, the performance of the digital system is in very good approximation to the results obtained with the hardware system.

The performance of the digital system was also analyzed for the different signal detection schemes. The results obtained for

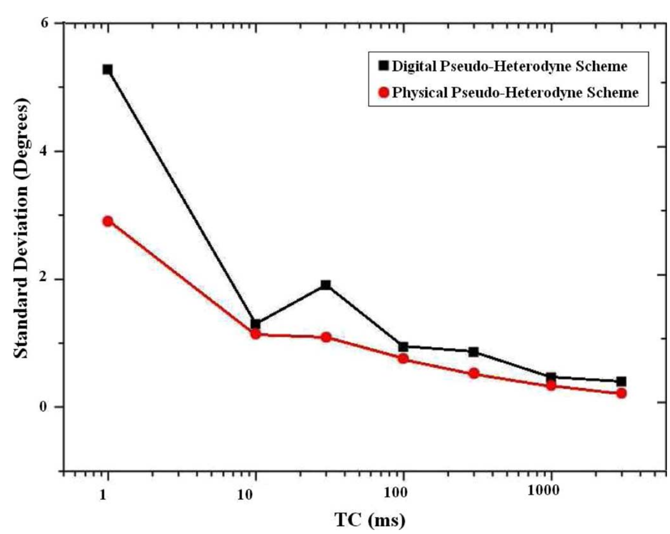

Fig. 8. Standard deviation for different lock-in TC values for the digital and the physical (hardware) system, respectively.

all schemes are presented in Fig. 9. The physical lock-in amplifier response is also present for reference. The best performance was obtained with the pseudo-heterodyne technique and the worst for the synthetic heterodyne. Overall, it can be observed that at long TC, all the techniques present a very similar performance. As the TC decreases, however, the differences between the techniques tested become more apparent. Shorter TC result in larger filtering bandwidths, increasing the noise level

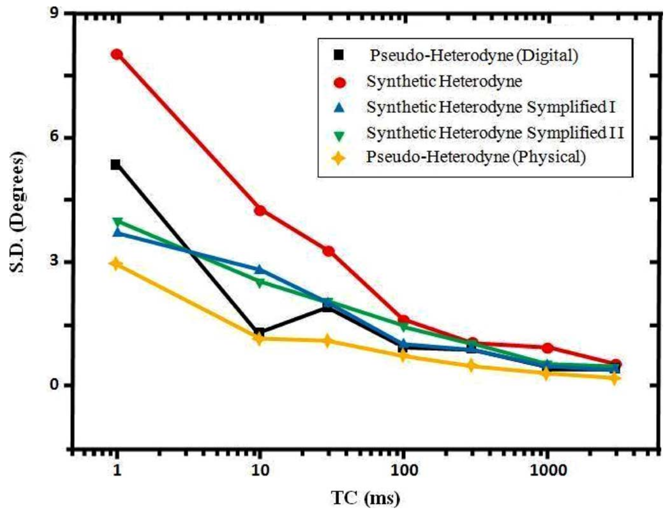

Fig. 9. Standard deviation for different virtual lock-in TC values for the developed digital detection schemes and for a standard hardware (physical) system.

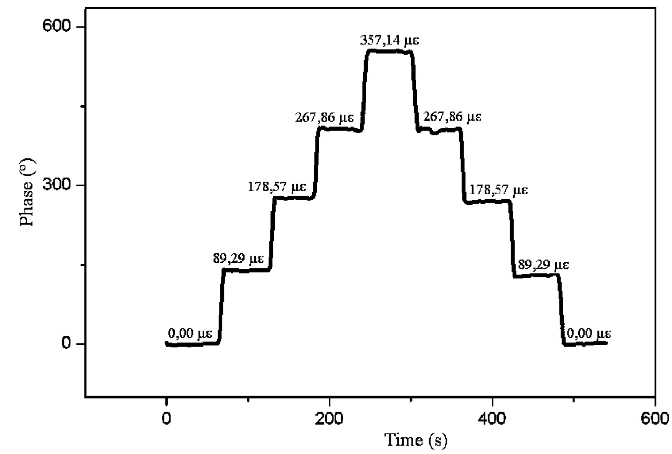

Fig. 10. Strain levels applied to strain cavity.

of the signals. Therefore, even with the standard lock-in, an increase in the standard deviation is observed. Nevertheless, observing the behavior of the digital techniques, it is evident that the impact of shorter TC is different for each technique. The main reason for this discrepancy is related with the computational time needed to process the signals in each case. With shorter TC, certain operation blocks of the processing schemes are run more often. Therefore, processing schemes that are more demanding in terms of computational time are more penalized by the reduction in the TC. This can be confirmed by the fact that the most complex technique in terms of processing operations, the "Synthetic Heterodyne" was indeed the one where performance was more degraded as TC was decreased. This might have resulted from computational overload caused by the high amount of signal processing required by the synthetic heterodyne technique. The simplified synthetic heterodyne techniques presented better performance than the "full" technique.

Overall, in the digital domain, the pseudo-heterodyne technique presented the best performance, in spite of the flyback effect. In classical systems, using function generators and piezoelectric modulators very often flyback times caused non-negligible measurement errors. However, in this particular case, the digital system associated with a high bandwidth phase modulator was able to generate a sawtooth waveform that, from the point-of-view of the sampling rate used, presented almost zero flyback time. Therefore, negligible flyback error together with shorter computational times explains the better performance of the pseudo-heterodyne technique in the digital system. Such feature further justifies the use of digital control system that enables high performance using simple techniques

In order to validate the digital interrogation system developed, strain measurements were made. Two identical Fabry–Pérot interferometers were mounted (reference and sensing), with 9 mm of cavity length, formed by two Bragg gratings with a 40% reflection and central wavelength around 1570 nm, and interrogated with the system in differential mode. Each sensor was connected to one of the outputs of the Mach–Zehnder and their differential phase was measured. The use of FBG for the sensor fabrication, resulted in a limited spectral bandwidth ($\Delta\lambda \sim 200$ pm) that effectively increased the coherence length of the system to the millimeter range. In this situation, the system dynamic range can easily be extended to thousands of $\mu\varepsilon$. Nevertheless, for the purpose of testing the validity of the digital interrogation systems, the phase output was monitored for different strain levels, in a limited range, from zero to $\sim 350\ \mu\varepsilon$. The resulting phase response is shown in Fig. 10.

It is clear that the differential scheme effectively removes any phase drift resulting in very stable phase steps that accurately correspond to the applied strain steps.

From this data, it was calculated the resolution of the system for all signal detection schemes. The resolution can be obtained by the following relation, $Res = 2\sigma/(B)^{1/2}$, where σ identifies the standard deviation of the measured phase, and B the bandwidth of the system, which is limited by the virtual lock-in amplifier bandwidth. For the FIR filter used in the tests, the virtual lock-in amplifier bandwidth is given by $0.35/(TC)^{1/2} = 0.35$ Hz. In the standard lock-in, on the other hand, a time constant of 1 s and a filter roll off of 6 dB/oct resulted in a 250 mHz bandwidth. The limiting factor for the sensor response time was the lock-in TC which was 1 s in all cases.

All tested digital schemes used the same operating parameters: modulation frequency: 1 kHz, sampling frequency: 100 kHz, number of samples per sinusoid period: 1000. The sensitivity, resolution and minimum detectable value obtained for each signal detection scheme implemented are shown in Table I.

The best resolution was obtained with the pseudo-heterodyne scheme with $1.91°/\sqrt{Hz}$, which nearly matched the performance of the hardware system. It followed the Synthetic Heterodyne Simplified I with $1.95°/\sqrt{Hz}$ and the Synthetic Heterodyne Simplified II with $1.96°/\sqrt{Hz}$. The worst resolution was obtained by the Synthetic Heterodyne Scheme ($2.07°/\sqrt{Hz}$). As discussed earlier, these discrepancies can be ascribed mainly to the computational weight of each technique. In spite of all, for quasi-static measurements, where response times in the range of seconds are satisfactory, the differences between different techniques were relatively small. In addition, increasing the sampling rate of the DAQ board used will allow the application

TABLE I
SENSITIVITY, RESOLUTION AND MINIMUM DETECTABLE VALUES OBTAINED WITH THE DIFFERENT INTERROGATION SYSTEMS

Detection Scheme	*Sensitivity (°/ $\mu\varepsilon$)*	*Resolution (°/√Hz)*	*Minimum Detectable Value ($\mu\varepsilon$)*
Pseudo Heterodyne (hardware)	1.55	1.84	1.19
Pseudo Heterodyne (Digital)	1.55	1.91	1.21
Synth.-Heterodyne Simplified I	1.52	1.95	1.29
Synth.-Heterodyne Simplified II	1.52	1.96	1.29
Synth.-Heterodyne	1.52	2.07	1.37

of the presented system to the measurement of faster changing parameters.

IV. CONCLUSION

A digital control system to interrogate fiber optic interferometers based on WLI was developed and tested with a readout Mach–Zehnder interferometer in a differential configuration, to interrogate Fabry–Pérot strain sensors. The system performance is similar to the equivalent hardware for time constants $TC > 100$ ms. Strain was measured with a resolution of 1.21 $\mu\varepsilon$. The results obtained demonstrate the possibility of implementing advanced interrogation systems for optical sensors in the virtual domain maintaining high performance and enabling miniaturization and portability.

REFERENCES

[1] K. T. V. Grattan and T. Sun, "Fiber optic sensor technology: An overview," *Sens. Actuators A: Phys.*, vol. 82, no. 1–3, pp. 40–61, 2000.

[2] Li H.-N, Li D.-S, and G.-B. Song, "Recent applications of fiber optic sensors to health monitoring in civil engineering," *Eng. Structures*, vol. 26, no. 11, pp. 1647–1657, 2004.

[3] P. Rolfe, F. Scopesi, and G. Serra, "Advances in fibre-optic sensing in medicine and biology," *Meas. Sci. Technol.*, vol. 18, no. 6, pp. 1683–1689, 2007.

[4] Y.-J. Rao and D. A. Jackson, "Recent progress in fibre optic low-coherence interferometry," *Meas. Sci. Technol.*, vol. 7, no. 7, pp. 981–989, 1996.

[5] C. T. Nadovich, *Synthetic Instruments: Concepts and Applications*. Boston, MA: Newnes, 2005.

[6] L. A. Ferreira, A. B. L. Ribeiro, J. L. Santos, and F. Farahi, "Simultaneous displacement and temperature sensing using a white light interrogated low finesse cavity in-line with a fibre Bragg grating," *Smart Materials and Structures*, vol. 7, no. 2, pp. 189–198, 1998.

[7] D. Jackson, A. Kersey, M. Corke, and J. Jones, "Pseudoheterodyne detection scheme for optical interferometers," *Electron. Lett.*, vol. 18, no. 25, pp. 1081–1083, 1982.

[8] P. A. S. Jorge, L. A. A. Ferreira, and J. L. Santos, "Analysis of the flyback effects on the serrodyne interferometric demodulation on fiber optic Bragg grating sensors," *Opt. Eng.*, vol. 39, no. 5, pp. 1399–1404, 2000.

[9] Y.-L. Lo and C.-H. Chuang, "New synthetic-heterodyne demodulator for an optical fiber interferometer," *IEEE J. Quantum Electron.*, vol. 37, no. 5, pp. 658–663, May 2001.

[10] C. J. Misas, F. M. Araújo, L. A. Ferreira, J. L. Santos, and J. M. López-Higuera, "Fiber Bragg sensors interrogation based on carrier generation by modulating the coupling length of a wavelength-division multiplexer," *IEEE J. Sel. Topics in Quantum Electronics*, vol. 6, no. 5, pp. 750–755, Sep./Oct. 2000.

[11] C. J. Misas, F. M. Araújo, L. A. Ferreira, J. L. Santos, and J. M. López-Higuera, "Interrogation of low-finesse Fabry-Pérot cavities based on modulation of the transfer function of a wavelength division multiplexer," *J. Lightw. Technol.*, vol. 19, no. 5, pp. 673–681, 2001.

[12] A. D. Kersey and T. A. Berkoff, "Fiber-optic Bragg-grating differential-temperature sensor," *IEEE Photon. Technol. Lett.*, vol. 4, no. 10, pp. 1183–1185, Oct. 1992.

Eduardo Velosa received the M.S. degree in telecom engineering from the Madeira University, Madeira, Portugal, in January 2010. From February 2009 to July 2009, he worked at INESC Porto, where he worked on his M.S. thesis, entitled "Automatic Control of an Interferometer to Monitor and Characterize Interferometric Sensors."

Since September 2009, he has been with Telecom Engineer, Portugal.

Carlos Gouveia graduated with a Degree in electronics and telecommunication engineering, in 2007, and received the M.Sc. degree in telecommunications and networks, in 2008, from the University of Madeira, Madeira, Portugal. Currently, he is working towards the Ph.D. degree at the University of Madeira.

He works in the Optoelectronics Group of INESC Porto. His research interest are in optical fiber sensors and interrogation systems for chemical and biochemical applications

Orlando Frazão received the Degree in physics engineering (optoelectronics and electronics) from the University of Aveiro, Aveiro, Portugal and the Ph.D. degree in physics from the University of Porto, Porto, Portugal, in 2009.

From 1997 to 1998, he was with the Institute of Telecommunications, Aveiro. Presently, he is a Researcher at the Optoelectronics and Electronic Systems Unit, INESC Porto. He has published about 250 papers, mainly in international journals and conference proceedings. His present research interests included optical fiber sensors and optical communications.

Dr. Frazão is a member of the Optical Society of America (OSA) and SPIE.

Pedro A. S. Jorge graduated with a Degree in applied physics (optics and lasers) from the University of Minho, Minho, Portugal, in 1996, and received the M.Sc. degree in optoelectronics and lasers from the Department of Physics, University of Porto, Porto, Portugal, in 2000, with a thesis on optical current sensors for high voltage operation, and the Ph.D. degree from the University of Porto and in collaboration with the Department of Physics and Optical Sciences, University of Charlotte, Charlotte, NC, in 2006, with work developed in luminescence-based optical fiber systems for biochemical sensing applications. The work involved studies of the applicability of luminescent nanoparticles as tools for biochemical sensing.

He is currently a Senior Researcher at INESC Porto, where he leads a small team in exploring the potential of optical fiber and integrated optic technologies in the development of biochemical sensors for environmental and medical applications. He has published more than 100 works in journals and international and national conferences and holds one patent.

José M. Baptista (M'03) graduated with a Degree in electrical and computer engineering (telecommunications and computers) from the University of Porto, Porto, Portugal, in 1991, and received the M.Sc. degree in physics of laser communications from the University of Essex, Colchester, U.K., in 1992, and the Ph.D. degree in electrical and computer engineering from the University of Porto, in 2002.

Currently, he is an Associate Professor at the University of Madeira and a Senior Researcher in the Optoelectronics and Electronics Systems Unit at INESC Porto. He is author of 45 journal publications and author of two patents. His research interests are in the area of fiber-optic sensors, fiber-optic communications, and fiber-optic technologies.