**Journal of Technological Operations** 8[21]1-8: e2821108
Article

# Optical fiber encoder based on phase shifting interferometry

# Encoder de fibra óptica basado en interferometría de cambio de fase

López-Álvarez, Yadira Fabiola*[a], Peña-Lecona, Francisco Gerardo[b], Muñoz-Maciel, Jesús[c] and Rodríguez-Franco, Martín Eduardo[d]

[a] Universidad de Guadalajara, CULagos(EPM) and Universidad Tecnológica del Norte de Aguascalientes • T-1555-2018, • 0000-0002-9041-1908 • 375952
[b] Universidad de Guadalajara, CULagos • 0000-0002-9537-8633 • 122563
[c] Universidad de Guadalajara, CULagos • 0000-0001-7091-6573 • 123153
[d] Universidad Tecnológica del Norte de Aguascalientes• T-1539-2018 • 0000-0002-6804-4777 • 660892

**CONAHCYT classification:**

Area: Physics-Mathematics and Earth Sciences
Field: Physics
Discipline: Optical
Subdiscipline: Physical optics

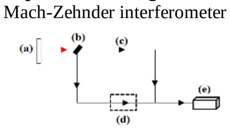
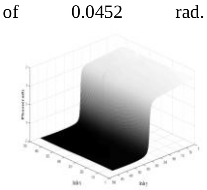
https://doi.org/10.35429/JTO.2024.8.21.1.8
**History of the article:**
Received: September 19, 2024
Accepted: December 30, 2024

* ✉ [yadira.lopez@utna.edu.mx]

## Abstract

In an automated industrial system monitoring and controlling the position of moving objects represents a crucial element in processes that have rotating systems.This is regularly in robots that use internal sensors to monitor the position of their joints. In this work we present the study of an optical encoder based on a Mach Zehnder interferometer. To determine the phase, the Phase Shift Interferometry algorithm was use, using five steps. The optical fiber encoder used the rotation matrix, and the results were correlated with those obtained by the optical technique, the reported behavior shows a wide similarity between the optical encoder and the simulated. The experimental design showed a differential distance of 0.0452 rad between the initial and that obtained after deformation. We report an encoder capable of recovering the initial phase, showing a difference in the correlation of 0.0000925 u.a.

**Optical fiber encoder based on phase shifting interferometry.**

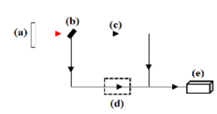
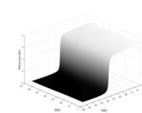
| Objective | Methods | Results |
|---|---|---|
| Demonstrate the interferometric encoder capability. Check the sensor behavior demonstrated by simulation. | Optical technique: Phase shifting interferometry. Use of optical fiber interferometer as transducer. **Experimental design** Mach-Zehnder interferometer  | The encoder is highly robust, capable of recovering its initial phase, with a differential distance of 0.0452 rad.  |

**Optical encoder, optical fiber, Mach Zehnder interferometer**

## Resumen

En un sistema industrial automatizado el monitoreo y control de la posición de objetos en movimiento representa un elemento importante en los procesos que cuentan con sistemas giratorios. Esto se presenta con regularidad en los robots que utilizan sensores internos para monitorear la posición de sus articulaciones. En este trabajo presentamos el estudio de un encoder óptico a base de un interferómetro Mach Zehnder. Los resultados se analizaron utilizando la técnica de interferometría por desplazamiento de fase de cinco pasos. El encoder de fibra óptica se simuló a través de la matriz de rotación y los resultados se correlacionaron con los obtenidos por la técnica óptica de cinco pasos, mostrando un comportamiento en la fase óptica similar. El diseño experimental mostro una distancia diferencial de 0.0452 rad entre la fase inicial y la obtenida después de la deformación, el encoder mostrado fue capaz de recuperar la fase inicial, mostrando una diferencia en la correlación de 0.0000925 u.a.

**Optical fiber encoder based on phase shifting interferometry.**

| Objetivo | Metodología | Resultados |
|---|---|---|
| Demostrar la capacidad de encoder interferométrico. Comprobar el comportamiento del sensor mostrado mediante simulación. | Técnica óptica: Phase shifting interferometry. Uso de interferómetro de fibra óptica como transductor. **Diseño experimental** Interferómetro Mach-Zehnder  | Se muestra encoder con alta robustez, es capaz de recuperar su fase inicial, con una distancia diferencial de 0.0452 rad  |

**Encoder óptico, fibra óptica, Interferómetro Mach Zehnder**

**Citation:** López-Álvarez, Yadira Fabiola, Peña-Lecona, Francisco Gerardo, Muñoz-Maciel, Jesús and Rodríguez-Franco, Martín Eduardo. [2024]. Optical fiber encoder based on phase shifting interferometry. Journal of Technological Operations. 8[21]1-8: e2821108.

## Introduction

The development of systems for measuring physical variables, such as rotation, has applications in the automotive, marine and aerospace industries [1,2]. The first mechanical devices to record the angular changes of an object are reported as gyroscopes [3]; later, electromechanical devices such as the encoder emerged. However, technological advances force such devices to present greater advantages over everyday mechanical and electromechanical instruments, so the implementation and development of optical sensors has been increasingly accepted [4].

An encoder can be linear or angular, depending on the application; they base their operation on changing codes depending on the angle of rotation of the object and can provide a measurement with nanometric resolution, they are used in a wide range of control systems, manufacturing, robots, among many others [5-9]. Among the techniques for the use of optical encoders, the phase recovery of two wavefronts through cross-correlation techniques, diffraction and polarisation, these techniques have been able to recover the phase and correlate with angles of 0.031 degrees, other studies have proposed the measurement in a range of 18 degrees, even measurements have been made with 100 degrees, obtaining an accuracy of 0.2 degrees [10-16].

On the other hand, the advances in the field of interferometric encoders based on optical fibre compared to optical encoders is their high resolution, a construction focused directly on the robustness of the transducer, electromagnetic immunity, high sensitivity and its measurement is non-destructive, allowing its incorporation in systems where space is reduced, Its operating principle is based on the modulation of light by means of the length of the optical fibre and considering the output response of the sensor, monitoring the disturbance at a single point of the fibre and obtaining a correlation with the phase, amplitude, frequency and polarisation. However, to obtain an interferometric signal it is necessary to use optical arrays called interferometers, among these are Sagnac, Fabry-Perot and Mach-Zehnder, their difference lies in the ranges of measurement of the displacements caused by the induced deformation.

If, in addition to using interferometric systems, the use of fibre optics is incorporated, what would be obtained is a device that is not dependent on environmental changes and external vibrations [20-27].

Despite the advances that have been made so far, having a robotic system that works and is monitored 360 degrees can be a complicated task, due to the type of sensors that are being used, even the mechanical design itself can mean a limitation in the working range of the robot, this fact makes it necessary to add links to the robotic system, as well as specialised sensors, involving a high monetary cost.

Another problem presented in the navigation of robotic systems is their localisation, both in the uncertainty of estimating the position of a robot, as well as in the accumulated error in its movement [28 ,8], due to this, the use of an encoder capable of monitoring the complete rotation of a robotic joint functioning directly as a transducer, that can provide fast and reliable localisation of the system, that works in hostile environments, with high precision, repeatability in measurement, with a reduced size and that also helps new designs of reliable instruments, are the reasons for the study of the behaviour of a fibre optic encoder based on interferometry.

The main contribution of this work lies in showing an interferometric encoder capable of measuring full angular movements without restrictions, recovering its initial position, as well as verifying the behaviour of the sensor shown by simulation. The interferometer encoder shows high measurement stability, high repeatability, low differential distance (hysteresis) and low cost; it is conditioned according to the ranges of rotation, due to the characteristics of the rotating mechanical element. It can be used in robotic systems, as its design characteristics allow it to monitor 360 degrees of joint rotation.

## Methodology

### Model development

When light propagates through an optical fibre, it is required that the wave equation and Maxwell's equations are satisfied, obtaining an electromagnetic field pattern transverse to the direction of propagation [29,30].

ISSN: 2523-6806.
RENIECYT-CONAHCYT: 1702902


López-Álvarez, Yadira Fabiola, Peña-Lecona, Francisco Gerardo, Muñoz-Maciel, Jesús and Rodríguez-Franco, Martín Eduardo. [2024]. Optical fiber encoder based on phase shifting interferometry. Journal of Technological Operations. 8[21]1-8: e2821108.
https://doi.org/10.35429/JTO.2024.8.21.1.8

If the intensity at the output of the optical fibre is directly linked to the field distribution, it can be expressed by equation 1.

$$I_i(x,y) = A(x,y) + B(x,y)\cos(\varphi(x,y) \quad [1]$$

Where $A$, $B$ and $\varphi$, are the background intensity, intensity modulation and phase, respectively. If the intensity detected by a sensor shows disturbances, Equation 1 shall be modified in the cosine argument by the term $\alpha_f$, equation 2.

$$I_f(x,y) = A(x,y) + B(x,y)\cos\big(\varphi(x,y) + \alpha_f\big) \quad [2]$$

The difference between the two intensity states $I_i$ and $I_f$, the initial and final, respectively, result in a geometrical arrangement known as interference fringes, with spatial coordinates (*x*, *y*), these stripes are reciprocal to the two states of deformation, as the deformation of the object changes, so does the distribution of these stripes. The absolute value of the difference between $I_i$ and $I_f$, can be written as follows:

$$\left|I_f - I_i\right| = I_M\left|\cos\varphi_f - \cos\varphi_i\right| \quad [3]$$

To monitor the system disturbances, it is necessary to perform an analysis of the geometrical distribution of the interference fringes, as well as the extraction of the phase resulting from these two deformation states.

The demodulation of these interference fringes results in the characteristic parameters of the measurement; filtering and phase unwrapping are necessary [31].

One of the most widely used techniques that shows great acceptability is *Phase shifting interferometry*, in which a series of interferograms with phase differences is recorded, as shown in equation 2. To perform the phase reconstruction process, in general, algorithms are applied with a combination of the interferograms; the analysis can be done with interferograms [32]

$$tan\varphi = \frac{\sum_{n=1}^{M} b_n I_n}{\sum_{n=1}^{M} a_n I_n} \quad [4]$$

With $a_n$ and $b_n$, as real coefficients.

To obtain the pase $\varphi$, con the phase shift technique, it was considered that the optical path shift is determined by equation 5 where θ is given in intervals of $\frac{\pi}{2}$.

$$R(\hat{z},\theta) = \begin{pmatrix} \hat{x}\cos\theta - \hat{y}\sin\theta \\ \hat{x}\sin\theta + \hat{y}\cos\theta \\ \hat{z} \end{pmatrix} \quad [5]$$

Taking five interferograms with [33,34]:

$$\alpha_{f1} = \hat{x}\cos\theta - \hat{y}\sin\theta \quad [6]$$
$$\alpha_{f2} = \hat{x}\sin\theta + \hat{y}\cos\theta \quad [7]$$

Using trigonometric identities we arrive at the wrapped phase equation with five interferograms given by [35]:

$$\varphi_w = \tan^{-1}\left(\frac{2(I_3(x,y) - I_1(x,y))}{I_4(x,y) + I_0(x,y) - 2I_2(x,y)}\right) \quad [8]$$

Finally, the method for unwrapping the phase consists of modifying ±2π to the pixel being unwrapped.

**Development of experiments**

For the development of the encoder, a Mach Zehnder interferometer based on single mode fibre optics was built, Figure 1. A Helium-Neon laser light source at 632.8 nm and a microscope objective at 20X was used.

**Box 1**

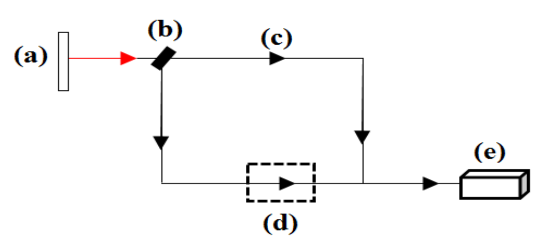



**Figure 1**
Mach-Zehnder interferometer for interferometric encoder (a) Source, (b) Beamsplitter, Fibre optics: (c) Reference, (d) External disturbance and (e) CCD
*Own elaboration*

**Experimental results**

A set of interferograms with a phase difference of π/2 were obtained, Figure 2 shows the interferograms obtained with the arrangement in Figure 1.

ISSN: 2523-6806.
RENIECYT-CONAHCYT: 1702902

Figure 2 shows for (a) 0, (b) 90, (c) 180, (d) 270 and (c) 360 degrees of rotation in one of the interferometer arms, showing an increase in the number of fringes..

## Box 2

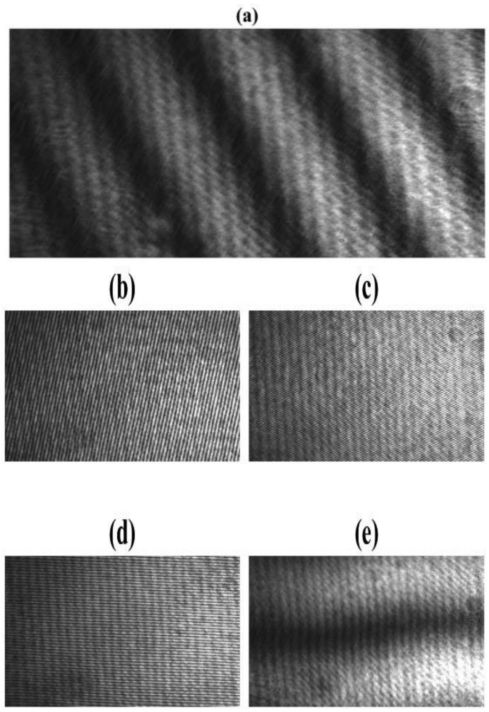



**Figure 2**

Encoder interference fringes using Mach-Zehnder interferometer, with θ: (a) 0, (b) 90, (c) 180, (d) 270 and (c) 360 degrees.

## Box 3

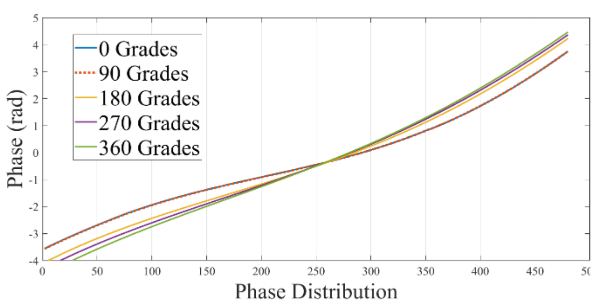



**Figure 3**

Encoder phases using Mach Zehnder interferometer, from 0 to 360 degrees

*Own elaboration*

Figure 3, shows the phase distribution resulting from the demodulation of each interferogram, the behaviour suggested by these phases is ascending, in the centre of the phase maps an intersection point is observed, to later show a descending behaviour.

Figure 4 illustrates the behaviour of the phase map unwrapped from the resulting values with , and using the algorithm represented by equation 8.

To check the robustness of the encoder, as well as its behaviour, rotation angles were chosen randomly, as indicated in equations 6 and 7, the behaviour of the unwrapped phase map is shown in Figure 5, which shows a sigmoid function, around 50% of the phase distribution.

## Box 4

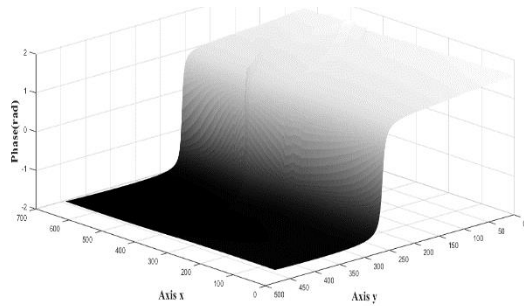



**Figure 4**

Experimental encoder phase map, using Mach Zehnder interferometer, I_n,n=5

## Box 5

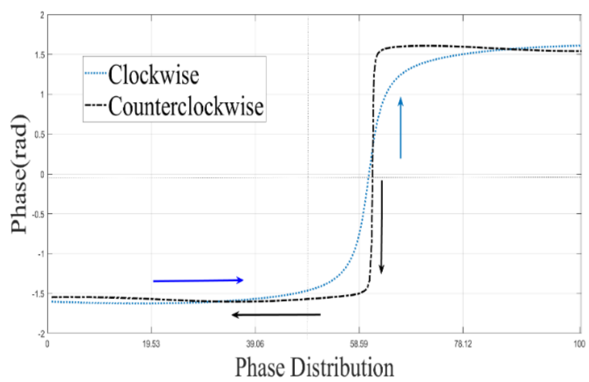



**Figure 5**

Title Phase map using Mach Zehnder interferometer with I_n,n=5.

To check the results the system was simulated equations 2, 6 and 7, the phase profile of the rotation is shown in Figure 6, (a) indicates the behaviour for , while (b) shows the phase behaviour for , both using five interferograms.

ISSN: 2523-6806.
RENIECYT-CONAHCYT: 1702902

**Box 6**

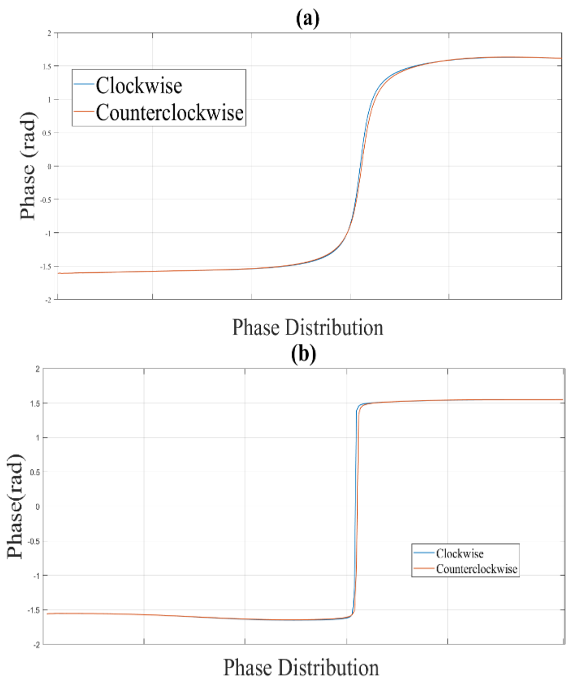



**Figure 6**
Phase map profile, interferometric encoder simulation with: (a) equation [6] and (b) equation [7]

To verify that the encoder is able to recover its initial position, in addition to comparing the experimental and simulated results, the differential distance of the initial phase, zero degrees, as well as the Pearson correlation coefficients were calculated for equations 5 and 6.

Figure 7 shows the behaviour of the Pearson correlation coefficients, the behaviour of the encoder shows for the case of the initial position a coefficient of 0.99990, as the fibre optic encoder is rotated the behaviour of the coefficients show an upward trend, where the maximum correlation is obtained in the phase map obtained at 320 degrees.

The sensitivity of the encoder is dependent on the rotation of the fibre.

**Box**

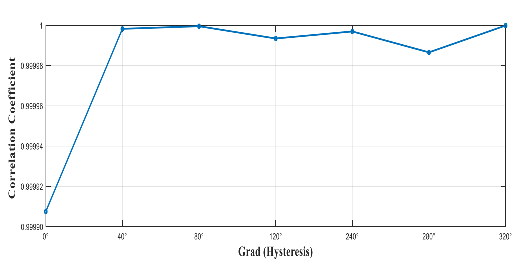



**Figure 7**
Correlation coefficients between turns with hysteresis
*Own elaboration*

## Acknowledgement

This research was carried out with support from the Consejo Nacional de Humanidades, Ciencia y Tecnología, (CONAHCYT, CVU:375952).

## Conclusions

This work shows the results obtained in the study of the behaviour of an interferometric encoder, a comparison was made between the experimental and simulated development using the concepts of rotation matrix that govern the behaviour of a rotating robotic system.

For the analysis of the phase maps the PSI technique was used, the interferometric model for the phase wrapped with .

The encoder shown, in addition to its robust design, is capable of recovering its initial phase, with a very small differential distance, where the behaviour of the correlation coefficients is dependent on the rotation.

The interferometric encoder shown is capable of being conditioned to measurements of very small degrees, as it is able to adjust to the rotating system being used. These results provide a guideline for analysing its use in the navigation and localisation of robotic systems.

## Declarations

## Conflict of Interest

The authors declare that they have no conflict of interest.

## Authors' contribution

*López-Álvarez, Yadira Fabiola*: Experimentation, analysis of results and mathematical modelling.

*Peña-Lecona, Francisco Gerardo*: Experimental design, previous studies

*Muñoz-Maciel Jesús:* Demodulation of interference fringes

*Rodríguez-Franco, Martín Eduardo*: Research and review.

**Funding**

This research was carried out in the optics and photonics laboratory of the CULagos, UDG and with the support of CONAHCYT.

**Acknowledgements**

To the Consejo Nacional de Humanidades, Ciencia y Tecnología CONAHCYT, Initial postdoctoral stay (2023), CVU: 375952.

To the Universidad Tecnológica del Norte de Aguascalientes, UTNA, for support in the realisation of stage 1 of prototypes of optical sensors in educational robotic systems.

**References**

**Background**

[1] Huggins, R. W., Abbas, G. L., Hong, C. S., Miller, G. E., Porter, C. R., & Van Deventer, B. (1992). Fiber-coupled position sensors for aerospace applications. Optics and Lasers in Engineering, 16(2–3), 79–103

[2] A. R. Missie, P. L. William, L. Antonio, and D. B. Alexandre. (2017). Angular velocity estimation from incremental encoder measurements in the presence of sensor imperfections, IFAC-PapersOnLine, 50: 5979–5984

[3] Passaro, V. M. N., Cuccovillo, A., Vaiani, L., De Carlo, M., & Campanella, C. E. (2017). Gyroscope Technology and Applications: A Review in the Industrial Perspective. *Sensors*, *17*(10), 2284. https://doi.org/10.3390/s17102284.

[4] Giallorenzi, T. G., Bucaro, J. A., Dandridge, A., Sigel, G. H., Cole, J. H., Rashleigh, S. C., & Priest, R. G. (1982). Optical Fiber Sensor Technology. IEEE Journal of Quantum Electronics, 18(4), 626–665,

[5] M.V. Shishova, S.B. Odinokova, D.S. Lushnikova, A.Y. Zherdeva, O.A. Guryleva. (2017). Mathematical modeling of signal transfer process into optical system of a linear displacement encoder, Procedia Engineering 201, 623–629

[6] R. J. Tansey and S. Holly. (1988). Development Of An Interferometric Encoder For High Resolution Angular Measurements, Proc. SPIE 0887, Acquisition, Tracking, and Pointing

[7] Ji-hua Zhang and Lilong Cai. (1998). Autofocus laser rotary encoder, Appl. Opt. 37, 2691-2695

[8] Haoxiang Lang, Ying Wang and C. W. de Silva. (2008). Mobile robot localization and object pose estimation using optical encoder, vision and laser sensors, *IEEE International Conference on Automation and Logistics*, Qingdao, pp. 617-622.

[9] Lafolla, L., Filipozzi, M., Freund, S., Zam, A., Rauter, G., & Cattin, P. C. (2020). Proof of concept of a novel absolute rotary encoder. Sensors and Actuators, A: Physical, 312

**Basics**

[10] Percival F. Almoro, Giancarlo Pedrini, Arun Anand, Wolfgang Osten, and Steen G. Hanson (2009).Angular displacement and deformation analyses using a speckle-based wavefront sensor, APPLIED OPTICS / Vol. 48, No. 5

[11] Yamaguchi, I., & Fujita, T. (1989) Laser speckle rotary encoder. Applied Optics, 28(20), 4401

[12] Yamaguchi, I. (1989). Encoder and strain gauge using laser speckle. Optics and Lasers in Engineering, 11(4), 223–232.

[13] Fernando Perez Quintián, Ariel Lutenberg, and María Aurora Rebollo. (2006). Study of an incremental optical encoder using speckle, Proc. SPIE 6341, Speckle06: Speckles, From Grains to Flowers, 634121,

**Support**

[14] Angelika Taubner, Hans-Jürgen von Martens. (1998). Measurement of angular accelerations, angular velocities and rotation angles by grating interferometry, Measurement 24 21–32

ISSN: 2523-6806.
RENIECYT-CONAHCYT: 1702902

[15] Nathalie Mancier, Ayoub Chakari, Patrick Meyrueis, and Michel Clément. [1995] Angular displacement fiber-optic sensor: theoretical and experimental study, Vol. 34, No. 28, APPLIED OPTICS

[16] Mertz, L. N. (1991). Interferometric angle encoder. *Review of scientific instruments*, *62*(5), 1356-1360.

**Diferences**

[17] D. Felekis and E. Papadopoulos. (2010). Design and development of a low-cost interferometric device for nanoscale position and velocity feedback, *IEEE/ASME International Conference on Advanced Intelligent Mechatronics*, Montreal, QC, Canada, pp. 611-616.

[18] P. Drabarek and R. M. Kennel Fiet. (2008), Are interferometric encoders a reasonable alternative in servo drive applications, *4th IET Conference on Power Electronics, Machines and Drives*, York, pp. 149-153.

[19] D. Gardner, T. Hofler, S. Baker, R. Yarber and S. Garrett, (1987). A fiber-optic interferometric seismometer, in *Journal of Lightwave Technology*, vol. 5, no. 7, pp. 953-960.

[20] Kurzych, A., Kowalski, J., Sakowicz, B., Krajewski, Z. & Jaroszewicz, L. (2016). The laboratory investigation of the innovative sensor for torsional effects in engineering structures monitoring. *Opto-Electronics Review*, *24*(3), 134-143.

[21] Wang, L., & Fang, N. (2017). Applications of Fiber-Optic Interferometry Technology in Sensor Fields. InTech. doi: 10.5772/66276

[22] Kidwell, R., Miller, R., Bennett, S., Dyott, R., Allen, D., & Brunner, J. (1998). Fiber optic rate gyros as replacements for mechanical gyros. Guidance, Navigation, and Control Conference and Exhibit.

[23] Budinski, V., & Donlagic, D. (2019). A Miniature Fabry Perot Sensor for Twist/Rotation, Strain and Temperature Measurements Based on a Four-Core Fiber. *Sensors*, *19*(7), 1574.

[24] S. -H. Hsu, C. -Y. Tsou and J. -C. Hsu. (2012). Interferometric fiber strain sensor, *2012 IEEE 3rd International Conference on Photonics*, Pulau Pinang, Malaysia, 2012, pp. 114-115,

[25] H. W. Chow, N. C. Cheung and W. Jin. (2010). A Low-Cost Submicrolinear Incremental Encoder Based on 3 ×3 Fiber-Optic Directional Coupler, in *IEEE Transactions on Instrumentation and Measurement*, vol. 59, no. 6, pp. 1624-1633,

[26] Kurzych, A. T., Jaroszewicz, L. R., Krajewski, Z., Dudek, M., & Kowalski, J. K. (2019). Interferometric optical fiber sensor set for angular velocity recording: Allan variance analysis in practice. In K. Kalli, S. O'keeffe, & G. Brambilla (Eds.), Seventh European Workshop on Optical Fibre Sensors (Vol. 11199, pp. 1–4).

[27] Elvira-Ortiz, D. A., Romero-Troncoso, R. D. J., Jaen-Cuellar, A. Y., Morales-Velazquez, L., & Osornio-Rios, R. A. (2016). Vibration suppression for improving the estimation of kinematic parameters on industrial robots. *Shock and Vibration*,(1), 6954012

**Discussion**

[28] Munoz-Barron, B., Rivera-Guillen, J.R., Osornio-Rios, R.A. *et al*. (2015). Sensor Fusion for Joint Kinematic Estimation in Serial Robots Using Encoder, Accelerometer and Gyroscope. *J Intell Robot Syst* **78**, 529–540.

[29] Luis Ramos, A., Martí Panameño, E., & Díaz, H. R. (2001). Cálculo de los modos electromagnéticos en una fibra óptica mediante soporte computacional analítico. *Revista Mexicana de Física*, *47*(4), 386-391.

[30] Freund, I. Joseph W. Goodman. (2008). Speckle Phenomena in Optics: Theory and Applications. *J Stat Phys* **130**, 413–414.

ISSN: 2523-6806.
RENIECYT-CONAHCYT: 1702902


López-Álvarez, Yadira Fabiola, Peña-Lecona, Francisco Gerardo, Muñoz-Maciel, Jesús and Rodríguez-Franco, Martín Eduardo. [2024]. Optical fiber encoder based on phase shifting interferometry. Journal of Technological Operations. 8[21]1-8: e2821108.
https://doi.org/10.35429/JTO.2024.8.21.1.8

[31] Kjell J. Gåsvik, (2002). Optical Metrology, John Wiley & Sons Ltd, 3ed, 316

[32] J. Schwider, R. Burow, K.-E. Elssner, J. Grzanna, R. Spolaczyk, and K. Merkel. (1993). Digital wave-front measuring interferometry: some systematic error sources, Appl. Opt. 22, 3421-3432

[33] Milligan, T. (1999). More applications of Euler rotation angles. IEEE Antennas and Propagation Magazine, 41(4), 78-83.

[34] Bajd, T., Mihelj, M., Munih, M. (2013). Rotation and Orientation. In: Introduction to Robotics. SpringerBriefs in Applied Sciences and Technology. Springer, Dordrecht.

[35] P. Hariharan, B. F. Oreb, and T. Eiju. (1987), Digital phase-shifting interferometry: a simple error-compensating phase calculation algorithm, Appl. Opt. 26, 2504-2506.

ISSN: 2523-6806.
RENIECYT-CONAHCYT: 1702902