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Fiber optic coiling system prototype

Prototipo de sistema enrollador de fibra óptica

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Abstract

In this work, a completely automated fiber optic coiling machine for any fiber diameter is presented. This prototype is capable of measuring the length of the fiber while it is coiled, allowing not only to coil large fibers but also to take control of diverse parameters, such as operation speed, and fiber-to-fiber separation. Our own mathematical model was implanted to the brain of the prototype that is based on a pair of stepper motors coupled to spinning rods that control the coiling process. The operation control (brain) is performed by an Arduino microcontroller with its corresponding free software for programming. The mechanical and electrical components selection makes it a low-cost prototype whose functions can be customized depending on the properties of optical fibers through different coiling conditions. Furthermore, we believe it has a good future regarding commercial projection as our approach was conceived independently from any other already registered and/or patented highlighting once again the low cost that would have as a manufactured commercial machine.

Optical fiber coiling, Prototype, Programming Arduino

Resumen

En este trabajo se presenta una máquina enrolladora de fibra óptica completamente automatizada para cualquier diámetro de fibra. Este prototipo es capaz de medir la longitud de la fibra mientras es enrollada, lo que permite no solo enrollar fibras largas sino también controlar diversos parámetros, como la velocidad de operación y la separación fibra a fibra. Nuestro propio modelo matemático se implantó en el cerebro del prototipo que se basa en un par de motores paso a paso acoplados a varillas giratorias que controlan el proceso de bobinado. El control de funcionamiento (cerebro) lo realiza un microcontrolador Arduino con su correspondiente software libre para la programación. La selección de componentes mecánicos y eléctricos lo convierte en un prototipo de bajo costo cuyas funciones se pueden personalizar dependiendo de las propiedades de las fibras ópticas a través de diferentes condiciones de bobinado. Además, creemos que tiene un buen futuro en cuanto a proyección comercial ya que nuestro enfoque fue concebido independientemente de cualquier otro ya registrado y/o patentado destacando una vez más el bajo costo que tendría como una maquina comercial ya terminada.

Enrolladora de fibra óptica, Prototipo, Programación con Arduinos

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Introduction

A fiber optic coiling system is a machine capable of properly placing, in terms of position and alignment, large specific lengths of optical fiber on a spool. Some commercial instruments that fulfill this function can also calculate the length of the coiled fiber. The difficulty of this process relies in precisely knowing the involved variables in order to estimate the fiber length. These variables include fiber diameter, spool diameter and spool width. In addition, for long fiber lengths the calculations become complicated due to the “spool diameter variations” that result when layers of coiled fiber are completed. In order to accomplish this, it is necessary to have a highly functional mechanical system that places one fiber next to the previous one in each revolution; hence, it is possible to obtain homogeneous layers of optical fiber along the entire width of the spool. As a consequence, the lengths of the corresponding coils of the subsequent layers become precisely known as the compensated spool diameter relies on the number of completed layers.

As a reference, there is a commercial fiber-optic or fine-wire spooler capable of measuring lengths, the Showmark´s DigiSpooler II model (Showmark, 2020). This system offers controlled coiling with adjustable separation between fibers from 10 µm to 100 µm with 1 µm resolution; an adjustable winding speed of approximately 0 rpm -100 rpm, bidirectional winding, fiber break detection, etc. It has a market value of around $40,000 USD to $70,000 USD. On the other hand, a patent search was carried out in the Mexico and the United States databases, searching for systems with similar functions to the prototype presented in this work. In Mexico there are no records of such systems whereas in the US we found two patents, one of them adds on a plastic coating to the fiber and then coils it on the spool (Okada, 2020); the other one is used in telecommunications and spools fiber optic cables of much larger diameters (Kowalczyk et al., 2020). This search for approaches similar to ours was carried out after we completed our work, as our system departed from a particular necessity that we usually have during our regular laboratory work; hence, we minimized possibilities concerning plagiarism from patented approaches.

The description of our work begins by detailing the general structure of our prototype that includes the mechanical parts as well as the programmed and controlled movements. It also describes our mathematical model that was written in the program and allows to estimate the coiled fiber after each spool revolution; it includes experimental results and discussions of the associated errors. Finally, the advantages and future adequations to the prototype are discussed and we conclude with the corresponding section. It is important to highlight that this work represents an improved version, with important functions added, of the previous one that was presented at the *4to Congreso Nacional de Investigación Interdisciplinaria* (Ramírez et al., 2020).

Prototype Structure

On the upper part of the scheme of Figure 1, the main mechanical components are depicted and consist on the rotating spool that receives the fiber (empty spool) which is supported and rotated by Motor 2; the motor is mounted on a sliding platform whose longitudinal movement is produced by a threaded rod that pushes or pulls the platform by means of two parallel rods; at the same time, Motor 1 provides the rotation to the threaded rod that provides the displacement of the empty (fiber receiving) spool; in other words, the Motor 2 provides the rotation of the receiving spool whereas Motor 1 provides the displacement that allows to coil one fiber next to the other. The fiber to be coiled comes from a second spool that is mounted on a slight-friction bearing system; the fiber becomes aligned by means of a pulley that freely rotates on a soft fixture, acting as a strain relief and minimizing in this way the possibility of breaking the fiber. In order to add more fiber alignment, the distance between the strain relief and the feeding spool has to be as long as possible; usually one meter or more is enough. The components were chosen from commercial consumables whose regular use is intended for the 3D-printing industry. Given that the optical fibers are usually very flexible and light in weight, all the system tends to also be very light in weight and, as a consequence, it uses low torque stepping motors and consequently low powers in all the components; i.e., control has preference over power.

There is a great variety regarding types of motors used in mechanical systems; however, stepper motors are widely used in systems that require high precision such as ours; based on this, the bipolar stepper motors that we used were the 17HS440-Model (Bello & Luna, 2004) with 200 steps by revolution and 1.8 degrees per step; these resulted very adequate during our tests.

In order to properly control the polarity reversal in both electrical coils of each motor, it is necessary to use an H-bridge per coil since the they demand more current than the maximum that the microcontroller can provide. There are different integrated circuits that include different amounts of H-bridges inside. In our case, a pair of L293b integrated circuits was used, since each one contains 2 H-bridges (Bello & Luna, 2004).

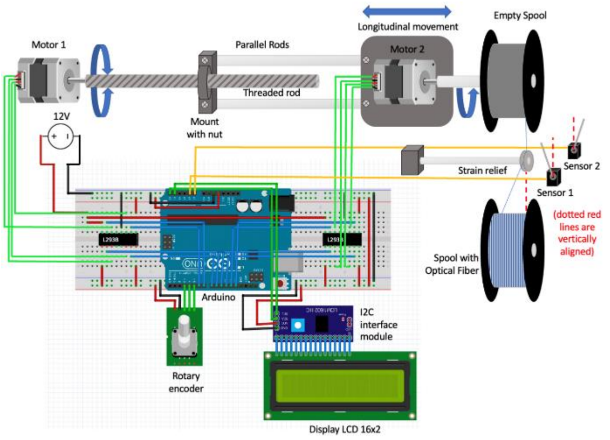

Figure 1 General scheme of the coiling prototype

For controlling the motors through the H-bridges as well as for the general operation of the fiber coiling, we used an Arduino-based programming microcontroller that has an open-source platform that covers our necessities. This is used in multiple electronics projects due to its low cost, ease of use as it is programmed by a C++ simplified version. The model that we used was the ATmega328, which is capable of being programmed and erased/re-programmed with instructions through its free access software. In addition to its simplicity and easy interfacing, it offers the advantage of having multiple independent sensors and other input devices for different purposes (Badamasi, 2014).

In regard to the improvements realized to our previous reported system (Ramírez *et. al.*, 2020), we added a pair of limit switches (see Fig. 2) that operate as complete layer indicators; these allow a more automated operation that allows counting layers and reverse longitudinal displacement to start coiling the next layer, and so no. This function was realized manually in the previous version, implying a more human assistance at the end of each layer. Before these sensors were adapted, the operator had to a push bottom at the end of each layer.

The visual interface between the coiling system and the user is a 16x2 LCD display that exhibits a programmed menu as part of the interface for controlling in two operational modes: a) coiling a piece of fiber to determine its length or b) coiling a specific length of fiber. An I2C serial interface board module was used to simplify the programming process as well as the connections.

Once a fiber layer has been completed, the directional change is provided by Sensor 1 or Sensor 2. These are activated by the walls of the receiving spool and command the microcontroller to reverse the rotation of Motor 1 and hence to activate the opposite longitudinal displacement. In this way, with the appropriate number of steps, it is possible to place one fiber next to the other after each turn during the coiling process. On the other hand, while transferring the fiber from the feeding spool to the receiving one, a pulley is used to always feed the fiber in the same place and orientation regardless of the feeding parameters. Additionally, the pulley has a second function as it serves as a strain relief; i.e., the fiber is always tense but not sufficient as to be broken (Ramírez, 2020).

Mathematical model

The method to obtain an equation to calculate any total coiled fiber length starts from an analysis for the simplest case, up to the most complex in which all the variables involved are considered.

In order to know the fiber length in a single revolution on the spool, the expression for the perimeter of a circle $l = \pi d_s$ is used, where l is the length and d_s the spool diameter. This expression can be generalized for any revolution number N obtaining a fiber length L:

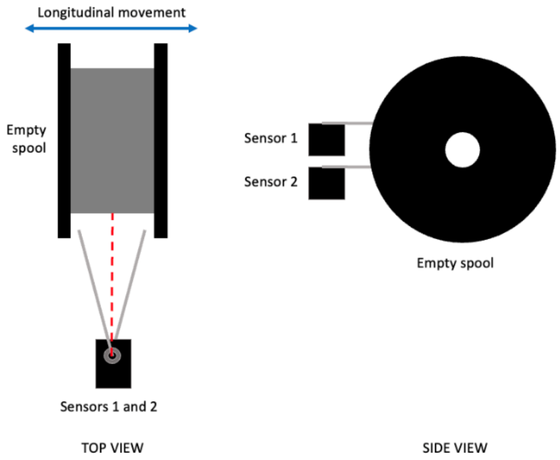

Figure 2 Top and side view of the limit switch sensors

$$L = N\pi d_s \tag{1}$$

However, this expression is only valid within a single layer of coiled fiber. For any subsequent layers, corrections have to be made as follows. As the diameter to perform the calculations will not be the spool diameter but, it will also include twice the diameter of the fiber d_f. Thus, depending on the number of complete layers n, the diameter will increase according to the relation:

$$d_n = d_s + 2nd_f \tag{2}$$

On the other hand, considering a proper tight fiber-to-fiber placement at each revolution on the spool, for each layer of fibers the number of revolutions N can also be represented as the number of fiber diameters that fit in the spool width w_s:

$$N = \frac{w_s}{d_f} \tag{3}$$

Substituting (3) in (1) and considering the diameter increase for each layer of (2), a layer-by-layer analysis can be performed in the form:

$$L_1 = \frac{w_s}{d_f}\pi d_s, \quad 1st\ layer \tag{4}$$

$$L_2 = \frac{w_s}{d_f}\pi[d_s + 2d_f], \quad 2nd\ layer \tag{5}$$

$$L_3 = \frac{w_s}{d_f}\pi[d_s + 2(2d_f)], \quad 3rd\ layer \tag{6}$$

$$L_n = \frac{w_s}{d_f}\pi[d_s + 2(n-1)d_f]. \quad layer\ n \tag{7}$$

Where L_1, L_2 and L_3 are the lengths for the first, second and third complete fiber layers respectively, up to a layer n with length L_n. In this way, to obtain the length of complete layers, L_c for a layer's number n, all the calculated lengths $L_c = L_1 + L_2 + L_3 + \cdots + L_n$ must be added, obtaining:

$$L_c = \frac{w_s}{d_f}\pi \sum_{i=1}^{n}[d_s + 2(i-1)d_f] \tag{8}$$

Equation (8) allows us to calculate the fiber length considering only layers filled with fiber. However, in the case of requiring an arbitrary length to be coiled, the length will correspond to a number of complete layers, plus a remaining length L_r as:

$$L_r = N\pi(d_s + 2nd_f) \tag{9}$$

Then, the total fiber length L_T is:

$$L_T = L_c + L_r \tag{10}$$

Experimental Results

Once defined the physical parameters of the receiving spool and the optical fiber diameter, the total revolutions number N_T is obtained by numerically solving (10) with N as unknown, by substituting (8) and (9). Such formulae were introduced in the program in order to obtain the revolutions. Although several tests were realized for calibrating the system, in an example we programmed the prototype for coiling 1km of optical fiber, the system calculated the revolutions (2897.73) and took approximately 2 hours and 10 minutes. For coiling hundreds of meters that are common on experiments with optical fiber in laboratories it does not represent a problem; however, sometimes it is necessary to coil several km and in such a case, the amount of time becomes important. In this sense, further improvements will be necessary to speed up the system.

Associated error

Considering two magnitudes x and y that are obtained through a direct measurement and with associated uncertainty Δx and Δy, respectively; if you want to calculate the uncertainty of an indirect measurement z that is given by $z = x + y$ or $z = x - y$, that is, the sum or subtraction of these measurements, then the uncertainty associated with this variable is the sum of the uncertainties associated with x and y, namely:

$$\Delta z = \Delta x + \Delta y \qquad (11)$$

On the other hand, if you want to calculate the uncertainty of an indirect measurement w, which can be calculated using the product $w = x \cdot y$, the uncertainty associated with w is given by:

$$\Delta w = |y|\Delta x + |x|\Delta y \qquad (12)$$

From (11), the uncertainty or associated error with the coiled length given by (10) can be obtained, then:

$$\Delta L_T = \Delta L_c + \Delta L_r \qquad (13)$$

To calculate the fiber length L_c, in (8), the ratio w_s/d_f corresponds to the number of fibers that fit within the spool width used to fill it completely. However, there is an error associated with the limit switch sensors pressing changing the direction of longitudinal movement when completing a full layer of fiber on the spool, this error causes the number of fibers inside the spool not to exactly correspond to the mentioned ratio. Therefore, the ratio w_s/d_f must be substituted as an independent variable c. One way to measure this variable is to perform a statistical analysis for a sample of at least 30 measurements of the number of fibers of a certain diameter (d_f) within a spool of width w_s, in order to obtain the final value associated with the average ($\bar{c}$) of the measurements made, as well as its uncertainty associated with the standard deviation (σ_c) in the form $c \pm \Delta c = \bar{c} \pm 1.96\sigma_c$, to obtain a 95% reliability (Blaine). Thus, by (12), the associated error ΔL_c is:

$$\Delta L_c = c\pi \sum_{i=1}^{n} [\Delta d_s + 2(i-1)\Delta d_f] +$$

$$+\Delta c\pi \textstyle\sum_{i=1}^{n} [d_s + 2(i-1)d_f] \qquad (14)$$

On the other hand, the associated error ΔL_r is:

$$\Delta L_r = N\pi\left(\Delta d_s + 2nd_f\right) \qquad (15)$$

Finally obtaining:

$$\Delta L_c = c\pi \sum_{i=1}^{n} [\Delta d_s + 2(i-1)\Delta d_f] +$$
$$\Delta c\pi \textstyle\sum_{i=1}^{n}\left[d_s + 2(i-1)d_f\right] + N\pi\left(\Delta d_s + 2nd_f\right) \qquad (16)$$

From (16), the statistical analysis for c and considering the resolution of the measuring instrument with which the spool diameter and the fiber diameter were measured as uncertainty associated with d_s and d_f respectively, for 1km of fiber, the associated error is 2.94% (29.4 m).

Advantages

Among the main advantages offered by this device are: its low total cost (~$3500 MXN, compared to commercial devices, around $40,000 USD to $70,000 USD), its compact design compared to the large devices that are found in the market, the multifunctional operation due to access to the programming of the prototype microcontroller, and its performance versatility, due to its ability to coil different fiber diameters and specific lengths, compared to the limited operation of patent-registered devices. In summary, there is a prototype that, even with multiple improvements to be implemented in the future, offers a functional and reproducible coiling service.

Future improvements

The most important aspect to improve is to minimize error as for larger fiber diameters it is higher and hence represents economic issues; for example, when selling a 1-km of optical fiber, the seller must coil at least 1029.4 m to ensure that the fiber is not shorter than promised. Another aspect would be the coiling speed as for several km fibers the time represents up to more than ten hours which represents several risks such as difficulty for human supervision. Several parameters can be induced to the optical properties of the fiber by coiling with certain patterns; loss, birefringence and scattering among other optical properties may be induced in such way. Also, this device can be implemented for more applications such as electrical conductors or even cable coiling of any type (electrical or optical); although, in general, the latter would require much more powerful motors as well as a more heavy and robust mechanical systems. However, thin electrical wires may be coiled and measured with our system as physical properties are similar to the tiny optical fibers.

Conclusions

It was possible to develop a prototype fully automated capable of coiling and measuring large amounts of optical fiber while transferred from one spool to another in a controlled, uniform and homogeneous manner. Due to having control over parameters such as the coiling speed and the separation distance between fibers, it can be programmed to calculate the coiled fiber length. In this way, an adaptable system with adjustable functions is obtained for fiber optics laboratories and industries that require to induce or reduce values of some parameters in coiled optical fibers.

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References

Showmark. (2020). *DigiSpooler I & II*. https://www.showmarkcorp.com/product/digispooler/

Okada, K. (2020). *Bare optical fiber coating device and bare optical fiber coating method* (Patent Application No. 20160083293). https://www.patentsencyclopedia.com/app/20160083293

Kowalczyk, S., Smith, T., Kaml, J., LeBlanc, T., & Beck, R.. *Fiber optic enclosure with external cable spool* (Patent Application No. 20080292261). https://www.patentsencyclopedia.com/app/20080292261

Ramírez, M. (2020). *Desarrollo, diseño e implementación de un prototipo estrechador de micro-fibra óptica (Master's thesis)* [Centro de Investigaciones en Óptica]. https://bibliotecas.cio.mx/tesis/17887.pdf

Bello, I. I. H., & Luna, C. O. (2004). *Control difuso y construccion de un mecanismo capaz de golpear con distintos efectos una bola de billar (Bachelor's thesis)* [Universidad de las Américas Puebla.]. http://catarina.udlap.mx/u_dl_a/tales/documentos/lep/hernandez_b_ii/

Badamasi, Y. A. (2014, December 23). The working principle of an Arduino. *Proceedings of the 11th International Conference on Electronics, Computer and Computation, ICECCO 2014*. https://doi.org/10.1109/ICECCO.2014.6997578

Ramírez, M., Mejía, E., & Juárez, M. (2020). Enrolladora de fibra de bajo costo hecha en casa. In Memories of *4to Congreso Nacional de Investigación Interdisciplinaria. Instituto Politécnico Nacional*. Publication pending.

Blaine. *Understanding Precision Statements for Standard Reference Materials*. http://www.tainstruments.com/pdf/literature/TN061%20Understanding%20Precision%20Statements%20for%20Standard%20Reference%20Materials.pdf.