Development of micro optical accelerometers for Structural Health Monitoring

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Abstract—Structural Health Monitoring (SHM) is a feature of great importance that contributes to assure the safety of a given infrastructure’s behavior, as well as extending its given life span. The main objective of this thesis consists in the development, construction and testing of a two-dimensional optical accelerometer for SHM applications. The optimized design of the sensor using 3D printing technology, polymer optical fibers (POF) and light emitting diodes (LED) allow the achievement of a low-cost solution. The operating principle of this accelerometer is based on the motion detection of an inertial mass attached to a single optical fiber coupled to a red LED, which emits a light beam that is projected along the vertical plane of a POF bundle disposed in a hexagonal configuration. The cantilever’s position variations are then captured by a webcam that is lined up with the other sensor components and connected to a computer. The information registered by the camera is then analyzed using a digital image processing technique conceived in a script file using the MATLAB software, which allows the integration of the optical signal’s intensity levels detected in each fiber core and the estimation of the applied acceleration.

Starting from a basic model for the accelerometer, we then developed an optimized version, increasing the optical sensor’s accuracy and its configuration flexibility.

After conducting a series of manual tests to ensure the correct functioning of the accelerometer, we then shifted to laboratory experiments using a pendulum configuration, analyzing, discussing and comparing the obtained results.

Keywords—Accelerometers, Plastic Optical Fibers (POF), 3D Printing, Structural Health Monitoring (SHM).

I. INTRODUCTION

In the last decades, the fiber optic industry was target of a constant evolution and significant improvements. The development of optical fiber based sensors, where accelerometers are inserted, are used for various purposes, ranging from physical activity monitoring [1] to Structure Health Monitoring (SHM) of various civilian infrastructures, like bridges, dams, buildings, and tunnels, among many others.

In 2012, the optoelectronic sensor’s global market was evaluated in approximately 4 billion dollars, from which, the fiber optic’s sector alone was responsible for more than 175 million dollars [2].

In the United States of America (USA), more than 11% of the 607380 existing bridges are damaged and possess flaws in their structures, implying repairing costs of about 76 billion dollars [3]. This is a strong indicator that good maintenance of civilian infrastructures of a nation can contribute substantially to its competitiveness level in terms of global economy and help preventing the occurrence of adverse circumstances [3].

One of the SHM approaches consists in the vibration analyses of infrastructures, caused by traffic and large industrial machines that can be found in our society or even from nature, like strong winds and earthquakes [4].

The vibration’s resonant frequencies of a given structure are proportional to its stiffness, whose eventual reduction values are a good indicator of potential structural damage [4] [5] [6].

The use of optical sensors, including sensors based on optical fibers present several competitive advantages when compared with electronic and electromechanical sensors, such as immunity to electromagnetic interference, electrical insulation, light weight, small size, minimal aesthetic impact, corrosion resistance, large bandwidth, possibility of operation in extreme temperatures, high sensitivity and high signal to noise ratio [3], [7].

A wide variety of optical sensors based on different principles of operation are currently available. Among these, the ones that stand out are those that are based on variations of intensity, phase, frequency, polarization or spectral content of the propagated optical signal, from which the most promising technology is the Fiber Bragg Gratings (FBG) [6].

The optical accelerometer presented and discussed throughout this work is a sensor which operates by analyzing the variations in intensity of a light signal. This technique is suitable for the analysis of frequency vibration measurements, revealing itself as one of the pioneering methods and probably the most basic and cost effective type of sensor with direct use in SHM [8].

The type of sensor here implemented makes use of standard Polymer Optical Fibers (POF) which have large cores and a high numerical aperture value, which allows the propagation, transmission and capture of optical signals between fibers that are not perfectly aligned, making this fiber the ideal type to be
implemented in sensors based on the intensity modulation of a light signal [8].

A. State of the Art

The first reports on the emergence of optical sensors date from the first half of the twentieth century, when they were first used in endoscopes [3]. However, the early development of fiber optic sensors in the modern era began more sharply in 1977, boosted by the development of telecommunications over long distances, which have shown an exponential growth in the last four decades [3].

Taking into account the progress made in the last twenty years, particularly in the optical sensors sector, we present an analysis of various solutions that stand out in the literature.

One of the most common solutions for the implementation of such optical sensors present an operating principle based on the intensity modulation of the light signal.

Morante et al. [9] and Lopez-Higuera et al. [10] demonstrated the feasibility of using an optical fiber suspended as a key element in the detection of low-frequency accelerations, without resorting to an inertial mass. This configuration simplifies the manufacturing process of the sensor, since the absence of a mass contributes to a better symmetry in the ends of the fiber with no degradation taking place. The accuracy of the accelerometer is also improved because it prevents the influence of factors such as the exact location of fixing the mass onto the suspended fiber, the mass value, the level of symmetry and the fixing process in the fiber itself [9]. A differential detection technique is used with the intensity modulation in order to convert the mechanical movement into an electrical signal, reflecting an instantaneous acceleration value [10].

Kalenik and Pajak [11] also started from this principle to develop an optical sensor of simple construction, low-cost and good sensitivity, to measure direct and low-frequency accelerations. They also concluded that the maximum operating frequency of the accelerometer is strongly dependent on the length of the suspended emitting fiber.

Kuang et al. [12] studied the concept of optical sensors making use of POF fibers and have presented two different designs. One of them based on a tunneling sensor soaked into a liquid and the other in air. They concluded that the encapsulated liquid approach is more sensitive to deformation, but both produce very favorable results for possible use in SHM applications [12].

Vallan et al. [13] proposed another solution also based on POF exploiting the method of analysis of the fiber sensitivity to micro deformations transducing the displacement of the suspended fiber in changes of the optical power. In order to increase the sensitivity of the fiber to mechanical deformations, they made small incisions in the fiber using a cutting tool [13].

Llobera et al. [14] implemented an optical sensor using three waveguides, whose misalignment produced by an external acceleration causes increased losses of the optical signal, whose modulation is the operating principle of the sensor.

This solution also possesses a system for self-alignment of the optical fibers along the waveguides [14].

Antunes et al. [7] developed an innovative optical accelerometer based on POF fibers, which combines the advantages of optical technology with the low costs of its interrogation mode. The sensor makes use of simple connectors with high numerical aperture values, coupled to simple Light Emitting Diode (LED) sources and photodetectors. The operating principle of this sensor is based on the misalignment between two POF fibers, with an inertial mass mounted on its structure, supported by a short beam of aluminum leaning on a spring steel sheet. Under the influence of an external acceleration, the inertial mass moves, imposing a misalignment between fibers, resulting in a change in the transmitted power. Consequently, the acceleration is coded in the intensity of the transmitted optical signal. The main advantage of this solution compared to accelerometers based on FBG technology is its low cost, as well as the respective interrogation unit simplicity [7].

B. Contributions

The optical accelerometer developed along this thesis aims to promote the use of resources at the lowest cost possible, making use of the POF technology (polymer) as a sensing element, light-emitting diodes as sources of the light signal, and the construction of the support structure using a 3D printer. As the accelerometer is subjected to external accelerations, the intensity variations of the light signal is distributed in a two dimensional plane, more specifically, along a bundle of fibers. The light distribution is then captured through a webcam installed on the opposite side of the fiber bundle.

C. Objectives

The main objective of the work presented in this dissertation is the study and development, implementation and characterization of an optical accelerometer using POF fibers, to be used in SHM of civil structures in order to ensure their operational safeness and life extension. A summarized list of the key objectives of this project are:

- Develop an accelerometer based on a POF bundle and a pendulum with an inertial mass;
- Develop an image processing algorithm using MATLAB software;
- Carry out a set of tests in laboratory environment and register the main results and conclusions reached.

II. THEORETICAL FOUNDATIONS

An accelerometer is a device designed to measure speed changes of a given mass or body along time. These sensors can be based on mechanical technology, electronics, optics or even in hybrid solutions between these technologies. The accelerations that a given object is exposed, may have its source from vibrations that occur in nature or caused by human activity. The accelerometer referred in this work is inserted in the optical range, which is subdivided into several subcategories defined by the respective sensor’s working principle.
In general terms, an optical sensor typically consists of a transducer device, a communication channel and a subsystem used for generating and/or detecting, processing and conditioning the acquired signal. These components may all be integrated or not [15].

A. Fundamentals of Fiber Optics

Among the various transmission parameters in optical fibers, the refraction phenomenon occurs when light passes from an isotropic homogeneous medium to another with a different index of refraction, changing the path angle of the beam on the boundary between the two adjacent mediums [2].

Fig. 1 shows a scheme where multiple reflections of a beam inside an optical fiber segment are represented [2].

![Fig. 1. Internal reflections of a light beam in an optical fiber segment.](image)

The Numerical Aperture (NA) is an indicative measure of the maximum capacity of an optical fiber to capture/couple light, which directly influences the respective input or output acceptance cone [2]. The coupling efficiency of a fiber increases for larger dimensions for the core [2].

Fig. 2 shows the influence of the distance and the numerical aperture parameter in the coupling of a light signal between two POFs and its respective cone of acceptance.

![Fig. 2. Dispersion of a beacon at the end of an optical fiber, adapted from [12].](image)

The coupling efficiency of a light signal between two fibers is subject to possible losses/attenuation due to misalignments between the optical fibers. These misalignments can be lateral, angular or longitudinal [16].

In addition to the losses that can occur in the coupling between fibers due to misalignments, the transmission of a given light signal is also attenuated due to multiple factors that are located within the optical fiber.

Usually, POF have high values of diameter and numerical aperture when compared to common glass fibers. POF fibers have a core around 1 mm diameter and are much less expensive compared with the cost of typical silica fibers, and still present higher levels of strength and flexibility [7]. The wide range of sensors based on POF, available in the different types of developed accelerometers, currently meet the necessary requirements and demands of a more modern and economically viable solution, making possible its use in SHM applications [7].

B. Fiber Optic based Sensors

The sensors conceived from optical fibers can be divided into five categories: the intensity-modulated sensors, phase-modulated, wavelength-modulated, polarization-based and scattering-based [2].

The operating principle of the intensity modulated sensors is generally associated with physical disorders such as displacements which interact directly with the fiber or with the transducer coupled to the fiber [2]. The loss of a light signal can be associated with the transmission, reflection, micro bending of the fiber, or other phenomena such as fluorescence, absorption or scattering, that may be incorporated into the fiber itself or at a reflective/ transmissive target [2].

This type of optical sensors usually requires higher intensity levels of the optical signal to operate when compared to phase modulated sensors, and for this purpose, multimode fibers with large cores sizes or even a fiber bundle may be used [2].

Compared to optical sensors based on phase and wavelength modulated solutions, the intensity modulated accelerometers are the alternative that present a greater cost relation [17]. Its operating concept is simple and the components necessary for its implementation are already available in the telecommunications industry, such as photodetectors and LEDs [17].

C. Structural Health Monitoring

Since most civil infrastructures have fundamental frequencies located in the range of 0-20 Hz, accelerometers should typically exhibit a resonant frequency which is well above this range of values, but low enough to maximize sensitivity and to maintain the levels of reduced noise [4].

Concrete is currently the most used material in the construction of various structures of a society, which is basically composed of cement, water and aggregates (sand or gravel), mixed in proper proportions. The SHM of an infrastructure, reflects in the supervision and control of changes in the composition of this material, internal deterioration, and changes in its properties caused by the influence of external factors [18].

The deterioration of concrete structures is due to several factors, foremost among them are two fundamental causes: disturbances from external sources and problems initially present during its construction phase [18]. A wide set of circumstances may have impacts of extreme significance in concrete infrastructures, such as the low level of funding, population growth, installations without taking proper precautions, irregularities in the structure’s design and the lack of appropriate periodic inspections [18]. Similarly, the aging of
concrete structures may be accelerated due to the increased overload from the number of users along the years [18]. For instance, concrete bridges constructed several decades ago, were not designed for the nowadays city traffic.

III. DESIGN AND CONSTRUCTION OF THE ACCELEROMETER

The sensor developed and implemented along this work, consists in a POF accelerometer based on the principle of light signal intensity modulation framed in the transmissive concept of a fiber bundle. In order to achieve better results and focus on continuous improvements of the developed product, we developed multiple solutions/versions for the optical accelerometer, presented in the next subsections.

A. Initial Version of the Accelerometer with a 7 POF Bundle

The basic concept of the optical sensor’s structure here developed is given by the emission of light by a red LED through a suspended optical fiber, supported by a small plastic U-shaped base. This fiber is aligned with the center of a fiber bundle that routes the signal to a webcam. This support structure was designed using 3D printing (3rd Generation Cube from 3D Systems Inc), making use of Plastic Jet Printing (PJP) technology. The design is shown in Fig. 3.

Fig. 3. Structure dimensions for the initial version of the accelerometer.

In order to begin with the practical and laboratorial component of this work, a study was done to find out what would be the ideal number of POFs to insert in the bundle to be mounted on the initial version of the accelerometer.

The best found solution for the optimal number of fibers composing the bundle was of seven elements. With this number of fibers, it is possible to cover six directions in the two-dimensional space by positioning, equidistantly, a fiber at every 60º adjacent to the bundle’s central fiber.

Using a POF (Avago Technologies - HFBR-RUS100Z) and with the aid of a suitable cutting tool (Omron E39F4 Fiber Optic Cutter), seven fiber segments of 15 cm each were sectioned and fixed in the desired format using small plastic clamps. After mounting the final bundle, a hole was made in the sensor's plastic base with a total diameter of three POFs (3 × 2.2 mm = 6.6 mm) allowing the insertion and fixation of the fiber bundle to support structure. At the opposite end, the emitting fiber with 7.5 cm in length was inserted through a hole with the diameter of a single POF (2.2 mm) and connected to a LED with red emission (Industrial Fiber Optics - IF- E96) that emits a light signal centered at 660 nm, with an optical power of 0.2 mW. To power up the LED, at an early stage a DC power supply (model: GPC-3030DQ) was used, placing a voltage across its terminals of 1.8 V and a current of 20 mA. The voltage and current values were based on the parameters recommended by the LED manufacturer itself, and with some fine current tuning aided by visual inspection, up to an optimum brightness level for further testing at a later stage.

The light projected by the LED into the emitting fiber is guided to its opposite end where it is then dispersed according to the value of the numerical aperture parameter of the fiber. This causes the dispersion of the light intensity throughout the various receiving bundle fibers, and a certain portion of the luminous signal is inevitably lost to the outside region of the POF bundle. This portion of intensity of the light signal, which is projected beyond the receiving POF bundle range, increases with the angle of the emitting fiber in relation to its static position, in other words, when it’s aligned with the bundle’s central fiber.

In order to minimize the amount of stray light outside the reception range of the receiving fiber bundle, we estimated the optimal distance at which we should position the end of the emitting fiber with the vertical plane of the POF bundle.

Since the bundle’s diameter is approximately the sum of the diameter of three POFs (3 × 2.2 mm), its radius is 3.3 mm.

However, it was found that if all of the bundle’s fibers are lit simultaneously, the task of determining the subsequent location of the emitting fiber, based on the intensity levels at each fiber captured by the webcam at the opposite end of the bundle, becomes extremely difficult. For this purpose, it was decided that the diameter of the modal field should only cover half of the POF bundle, which corresponds to the bundle’s radius value.

The achieved value for optimal distance between fibers was of, approximately, 3 mm.

To allow better stability of the accelerometer in its operating mode, the sensor was fixed to a rectangular wooden heavy base (dimensions: 20 cm width × 25 cm depth × 2 cm height) through a hole at the bottom of the plastic structure and joined by a metal screw and nut.

Fig. 4 shows the assembly of the support structure of the optical accelerometer on the wooden base.

Fig. 4. Mounted structure for the initial version of the accelerometer.
In order to capture the light intensity level coupled to each of the seven fibers of the sensor’s bundle, we placed at its opposite end a webcam (*Growing 300K Turtle*) using a 320x240 pixel video resolution at a sampling rate of 25 Hz, powered by a Universal Serial Bus (USB) cable connected to a personal computer.

In order to check the accelerometer’s behavior when it’s exposed to an external movement or induced vibration, we proceeded to do several laboratory tests.

**B. Digital Image Processing Algorithm**

The algorithm implementation began designing a digital image processing algorithm to generate masks to select and identify the areas of interest (sets of pixels) to analyze over the video frames. These areas consist in the cores of the seven fibers that form the receiving/emitting bundle of the accelerometer, since it’s inside them that occur the intensity variations of the light signal transmitted by the transmitting fiber.

A random frame was extracted from the test video in order to serve as a reference figure for the positioning of the bundle’s seven fibers throughout the video, and stored it in Joint Photographic Experts Group (JPEG) image format for posterior use.

Using MATLAB and with the help of "imellipse" and "createMask" functions, we generated a mask with circumferences positioned over the regions of the respective bundle’s fiber cores. The generated mask can be observed in Figure 5.

![Figure 5](image)

**Fig. 5. Core position mask identifying each fiber of the POF bundle for a given frame of the test video.**

Using this mask eliminates any background lighting or other lighting sources that were surrounding the optical accelerometer.

Having set the location of the regions of interest in the reference frame, we created an object with the "VideoReader" function for opening and reading the test video in the MATLAB Script. After recognizing the video file, a structure was created in MATLAB for the information storage of all the frames contained in the video. MATLAB interprets each frame as a matrix whose dimensions are the same resolution used in the test video in which each array element contains the information of the values of the color code Red-Green-Blue (RGB) of its associated pixel.

Afterwards, the RGB frames previously stored in a frame structure were converted to grayscale. This way, it became possible to apply the function "regionprops" to the frames stored in grayscale in order to calculate the average intensity value by analyzing the parameter "MeanIntensity" of the regions bounded by the mask set in the reference frame.

Calculated the average intensity values of all constituent pixels of each masked region over the frames, we set up an array for each of the seven fibers in order to store the intensity level values of the respective fiber cores until the end of the test video. In order to facilitate the task of finding the intensity values of any fiber throughout the video that satisfy certain criteria, we created an intensity matrix formed by the intensity values of the bundle’s fibers stored in the seven arrays.

As the fiber cores which are not transmitting any portion of the light emitted by the LED possess counter-intuitive very low intensity values, (but greater than zero), we compensated this error induced by ambient light by finding the minimum intensity value in the respective intensity matrix, and subtracting that same value to each of the fiber’s arrays. After the compensation of ambient light, we saved the corrected intensity values in a new matrix. In order to verify the distribution of light coupled to the POF bundle by the emitting fiber, we created a graph (Fig. 6) with the evolution of the intensity levels of each of the seven fibers along the duration of the test video.

![Figure 6](image)

**Fig. 6. Behavior of each fiber’s intensity levels along the duration of the test video.**

As it can be seen, the variation of the light intensity levels for each of the seven fibers presents a behavior similar to a quantized signal as the intensity of the light signal is subdivided into 255 intensity intervals. Furthermore, the fact that the sampling frequency is 25 Hz also contributes to the quantization of the digital signal in the registered interval.

Registered the intensity variations along the test video, we advanced to the task of obtaining the emitting fiber’s position in Cartesian coordinates (x, y) in each frame. The best found solution to determine the emitting fiber’s position was through a two-dimensional geometric manipulation, relating the intensity levels of each fiber to each frame of the video, starting from the equation of the light propagation losses due to lateral misalignments of the fibers. This operation consists in drawing geometric circles centered on the actual position of each of the
bundle’s fibers, whose radius varies inversely proportional to the intensity of the same fiber in a given frame.

After we set the distances and coordinates of each fiber based on the physical dimensions of the POF bundle, we shifted to the transformation of the equation of the light signal propagation losses produced by lateral misalignments between fibers in order to generate the seven circles in each frame for geometric analysis.

To calculate the power, we used the following expression:

\[ P_i = A_i \times e^{- \left( \frac{R_i}{\omega_0} \right)^2} \]  

solving in order to \( R_i \), we obtain:

\[ R_i = \sqrt{- \ln \left( \frac{P_i}{A_i} \right) \times \omega_0} \]  

where \( R_i \) is the value of the radius of the circle generated for the fiber \( i \) of the accelerometer’s POF bundle, \( P_i \) is the light intensity value of fiber \( i \) in a given frame and \( A_i \) the absolute maximum intensity value registered over every frame by any one of the seven fibers.

Then, we set up a loop so that the algorithm would cycle through all the light intensity values registered during the video, and draw the circles for each of the bundle’s 7 fibers. Although at this stage we have already found a solution to limit the region where the emitting fiber could be found in any frame, it still remains to find a way to make MATLAB identify the area that is intended to be selected as the region of interest for analysis (the two-dimensional space where all the circles overlap).

The best found solution was to use the statistical method of Monte Carlo. This method consists in generating a very high number of random points across the region in each frame, from the center point (0,0) to a distance equal to the radius of the largest circle generated. Using the "randn" function and taking advantage of the computing power of the MATLAB software, we generated a hundred thousand random points distributed along the frame.

After this operation, we verified which of the randomly generated points would be contained within the circle of larger radius, verifying if the distance that each point was from the origin, was smaller or equal to the radius of that same circle, using a direct comparison with the expression that defines a circumference. Having found all the points in the plane that were contained only within the largest circle, we repeated the same operation, but now in respect to the next circle with smaller radius, repeating the same procedure until it reaches the smallest circle generated in the frame. The remaining points after the application of all geometric conditions, define in this way the area of relevance. By geometric analysis, we conclude that the position of the emitting fiber is located at the midpoint of the region highlighted by the remaining points. To identify the point that corresponded to the geometric center of this region, we calculated the midpoint using the "mean" function of MATLAB. An example for a random frame is shown in figure 7.

Once the emitting fiber’s position is found in a given frame, we can easily obtain the (x,y) coordinates that define the respective point. In order to obtain the displacement of the emitting fiber in the Cartesian coordinate system (x,y) in an isolated form for each variable, we associated each set of points to its corresponding variable.

Having obtained the displacement points of the emitting fiber along the video’s duration, the respective velocity was calculated for each axis, in millimeters per second, through the derivation of the displacement values in order to time, which is expressed in seconds. After achieving the velocity values presented by the emitting fiber in the two-dimensional plane of the POF bundle, we applied a second derivative to the velocity values in order to time, and reached the acceleration values for each variable, expressed in millimeters per second squared.

As the acceleration values presented by different types of accelerometers on the market are typically expressed in gravity units (G), we converted the previous acceleration values into this more conventional type of units (1G = 9.80665 m / s²).

After the operation testing of the accelerometer, initial version, an optimized version was implemented, in order to provide advanced features and the registration of external accelerations in orientations beyond the horizontal.

C. Accelerometer Prototype with a 19 POF Bundle

A clear goal to improve the initial version of the accelerometer was increasing the sensor’s accuracy and range. In order to enable the capture of the emitting fiber’s movement with larger oscillations, we studied the possibility of increasing the number of fibers that compose the accelerometer’s sensing POF bundle. The first step was to examine and estimate the optimal number of fibers to insert, and where to, in the bundle in order to increase the sensor’s accuracy, keeping the hexagonal shape that minimizes the spacing between fibers. It
was determined that the optimum number that follows to the 7 POF used in the bundle of the initial version of the accelerometer was 19. The increase in size of the POF bundle is shown in Figure 8.

As we can see, the new POF bundle allows the coverage of a wider area when compared to the first bundle, with the advantage of having an extra ring of fibers in all directions.

In order to allow for a greater portability of the optical accelerometer, eliminating the need to use a DC power source, a fairly small simple electronic circuit to power up the LED emitter with a battery was implemented.

Intending to build the support structure for the accelerometer prototype, its dimensions and form were designed and constructed with the necessary adjustments to fit the elements that compose the respective sensor.

To provide a more robust and easily configurable structure, a modular type based construction was chosen and adopted, consisting of three distinct parts.

After designing the three parts, presented in Fig. 9, using the "Cubify Invent" software of 3D Systems, they were printed on the 3D printer used on the previous version.

Taking into account the new configuration of the accelerometer, a new webcam model (Microsoft Lifecam Cinema HD Webcam) with an appropriate shape for the assembly in the new structure was used.

After mounting the respective components in the accelerometer’s prototype support structure, some minor necessary parameters were adjusted on the algorithm, in order to adapt it to the operation of the new version of the sensor.

IV. RESULTS AND DISCUSSION

A. Laboratory tests of the Initial Version of the Accelerometer

Using the webcam, several videos with about eleven seconds of duration were recorded, where we manually shifted the position of the emitting fiber in random directions contained in the catch plan of the 7 POF bundle.

With the algorithm designed for initial version of the sensor, we read the test video parameters and generated the results for the movements registered by the accelerometer, which are shown in Figures 10, 11 and 12.

By analyzing the displacement in X and Y, it is observed that the signals possess a noticeable quantization over time. This is due to the limitation of the number of samples that is imposed by the sampling rate. The intervals at which the velocity reaches negative values for X and Y are a result of the displacement of the emitting fiber in the negative axis of the bundle’s plane.
B. Laboratory tests of the Accelerometer Prototype

We held another video with the same configuration parameters for the operating test of the accelerometer prototype with the bundle of 19 POF. The results are demonstrated in Figures 13, 14 and 15.

![Fig. 13. Displacement in X (top) and Y (bottom) registered in millimeters by the accelerometer prototype.](image)

![Fig. 14. Velocity in X (top) and Y (bottom) registered in millimeters per second by the accelerometer prototype.](image)

![Fig. 15. Acceleration in X (top) and Y (bottom) registered in G by the accelerometer prototype.](image)

The displacement registered for each axis present a slight quantization of values due to the limited number of samples per second (25) imposed by the used webcam. There are velocity values registered in both axes with variations contained in a range of 50 millimeters per second and accelerations of around 0.1 G.

C. Pendulum test with Periodic Damped Oscillations

In order to analyze the performance of the accelerometer prototype when exposed to periodic damped oscillations, we ran a laboratory test in a pendulum configuration. The sensor’s structure was fixed to a solid plastic base with a small support for the LED feed circuit, fixing it with plastic cable ties.

To properly register the pendulum oscillations, we chose an inertial mass of 80 g to fixate to the emitting fiber, without deviating too much outside of the reach of the 19 POF bundle.

Using a thin nylon cable, the accelerometer’s structure was hung to the ceiling with a vertical extent of approximately 1 meter. The result of the assembly of the accelerometer prototype in a pendulum configuration is shown in Figure 16.

![Fig. 16. Pendulum test configuration used with the accelerometer prototype.](image)

The assembly, was moved from its resting position, in the perpendicular direction to the ceiling, up to forming an angle of 20°, and then released. The oscillations were acquired during 34 seconds.

The test video was processed with the MATLAB algorithm providing the results presented in Figs. 17, 18 and 19.

![Fig. 17. Displacement in X (top) and Y (bottom) registered in millimeters from the pendulum test with the accelerometer prototype.](image)
In the $X$ variable there is signal variation which presents an oscillatory periodic behavior typical of a sinusoidal function, as it was expected from the pendulum oscillations. A more careful analysis shows that the oscillatory motion has a frequency of approximately two seconds, relatively to the $X$ axis. Due to the curvature shown in the POF segment, it was found that it wasn’t perfectly aligned with the bundle’s central fiber, lying deflected about a millimeter away from the center of the referential. As to the $Y$ variable, it is observed an initial displacement from its resting position, stabilizing rapidly after a few seconds.

As to the values registered for the velocity and acceleration, it’s possible to see in both a greater variation in the opening seconds of the video, when the pendulum is released and the oscillatory motion starts. The oscillations begin roughly after three seconds of the experience and not at the beginning, due to a small initial delay of releasing the pendulum when the recording of the test video had already been started.

Contrary to what was expected, the registered acceleration does not present a sinusoidal variation over time, caused by the influence of noise. This result requires an analysis and signal processing to clarify the data resulted from numerical derivatives, which lies outside of the scope of this thesis.

V. CONCLUSIONS

We demonstrated the feasibility of obtaining acceleration values from the basic principle of operation presented by this type of optical accelerometers, combining the power of digital image processing, with the geometric manipulation based on changes in the position of a given light source registered along a given period of time.

This type of accelerometer presents a very simple operating principle compared with the solutions presented by other types of optical sensors available on the market. This solution combines the advantages of optical sensors with the low cost of its interrogation mode.

It was found that the cutting quality at the end of the fibers oriented to the webcam lens deserves a more careful approach, since this aspect directly influences the intensity values interpreted by the digital image processing algorithm.

With 3D printing it’s possible to achieve, faster and with lower cost, a wide range of alternative configurations for the support structure of the accelerometer, allowing a detailed level of customization.

After the pendulum test, there was an appropriate registry of the periodic oscillations of the accelerometer with an inertial mass fixed to the emitting fiber, having been verified that the sensor is able to measure freeform accelerations in addition to manually induced movements.

As proposals for future work, several changes may be adopted either in the sensor and the algorithm, to improve the accuracy, such as: a possible reduction of the accelerometer dimensions, using other camera models and/or further adjusting the support structure of the sensor;

Evaluating the possibility of including in the algorithm the longitudinal and angular losses in the light transmission between fibers generating different radius circles that may increase the accuracy;

Trying alternative geometric shapes to circles for locating the emitting fiber along the frames, such as the use of triangles (principle of triangulation);

And try other configurations and framerates for the test videos and evaluate the changes caused in the acceleration results.

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