Polymer Optical Fibre Sensor for Measuring Breathing Rate of Lying Person

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Abstract— **A physiological sensor enabling measurement of one of the vital signs (breathing rate) of a person without direct contact with the person is presented. Compared to current vital signs measuring devices we present a much simpler and less time consuming method of measuring vital signs with the potential for applications in hospitals and homes. A practical prototype sensor, based on polymer optical fibre (POF) sensor instrumentation was fabricated using Toray specific grade fibre exhibiting an increase in 30 % bending losses from the standard (FX 1000) commercial fibre. A 640 nm light-emitting diode was used to illuminate the fibre, with its sensitivity to bending increased by cutting transversal grooves along the fibre and then by applying plastic rods along the fibre to increase bending loss. Although both methods increased the bending loss of the fibre, grooving reduced POF durability and integrity, whereas use of the plastic rods enhanced bending losses without damaging the fibre. Signals from respiration as well as postural movements of a person lying on the POF sensor allow measurements to be taken in an unobtrusive manner. Bending losses attenuating light transmission through the fibre were related to displacement of POF during respiration (expansion and contraction of the chest cavity displace the surface in contact with the upper torso – in this case the meandering arrangement of the fibre sensor located on a TREDAIRE substrate). Bending losses were converted to voltage signals and captured by National Instruments hardware together with LabVIEW software. The sensor was found to be competent in evaluating respiration with a resolution of 100 µV and a sensitivity of 2.3 % change in light transmission for each breathing cycle of the person under study.**

Keywords- ***POF sensor; physiological sensor; noncontact; respiration rate; grooving; unobtrusive; passive; vital signs***

I. Introduction

Ageing of society in recent years has led to an increased interest in identifying solutions that reduce the risks associated with developing chronic conditions and disability. Hypertension and diabetes for example are manageable chronic conditions with opportunity for disease prevention within the community as well as disease management within health care services [1]. Hence, there is large potential for use of technology in intervening at earlier stages in life to prevent economic (cost of long term care) and human costs. This has led to research into unobtrusive and efficient techniques to measure the vital signs of patients and in so doing preventing deterioration of a patient's condition. Vital signs include temperature, pulse, respiration (collectively called TPR), and blood pressure (BP). Monitoring these vital signs indicate a person's health status, and a sensor capable of such functioning without physically limiting and disturbing people under measurement is essential for the elderly to remain active and independent for as long as possible. It is a priority to take such steps to improve the quality of life of elderly people in an ageing society where many seniors would prefer to avoid moving to institutions or nursing homes and would rather age in their own homes.

In [2], a review of automated physiological and behavior monitoring systems capable of functioning without disturbing the individual's activities of daily living is presented. Such systems have been expanded, based on a concept of providing sequential clinical examinations. They are though, obtrusive and limit the individual's movements. A passive sensor that continuously monitors a person lying in bed such as the Emfit bed sensor [3] minimises these limits and disturbances providing greater comfort for the user. However, motion artefacts and false alarms need to be addressed with the technology [4]. Passive monitoring devices simplify the method in which physiological parameters (heart rate and breathing rate) can be tracked without the person under measurement having to self-locate or maintain the device. The physiological condition of elderly people, who often wait until they are at a later stage of ill health before seeking medical attention, can be observed with intelligent passive devices [5]- [7] in their homes with the aim of mobility assistance and unobtrusive disease prevention to avoid hospitalisation and costs. A study by [8] showed a decrease of 74 percent in the cost of caring for people in assisted living using passive monitoring devices, as well as, urinary tract infection rate reducing to almost zero.

Continuous passive monitors in health and elderly care enable nurses to observe changes in vital signs via a computer-based interface that prioritises cases subject to real-time condition readings rather than having to wait for routine observations to be made. Such identification of changes in vital signs at an earlier stage avoids the requirement for lengthier hospital stay with the potential of human and cost savings.

This paper presents a technique to passively measure vital signs using sensor technology in which a looped polymer optical fibre (POF) sensor is placed under a person. Being inexpensive and easy to apply (requiring no user interaction such as having to attach fibre to body) offers a unique alternative to current vital signs monitoring apparatus [9] [10] which require the hospital patient to be connected to a device (such as the pulse oximeter) through a series of wires to various body parts. This substitute does not then limit a person's movements and independence. The POF sensor is aimed to be a solution to meeting the needs of healthcare and society, by developing the sensor focused towards a user centred design approach, rather than based on a technology push. Thus the sensor aims to measure the vital signs of a person, in a form that reduces the effort and time required by health care staff to attach obtrusive, complicated devices to a person.

The main aim for this study was to measure one of the vital signs (respiration rate) of a person and to identify from the vital signs, a person's movement while lying on the mattress. By using physical modification to sensing points along the optical fibre to detect mechanical parameters with differing time periods (0.2 - 0.5 Hz for breathing and 1 - 2 Hz for heart rate), it is possible to examine the difference in the transmitted intensity of a light-emitting diode light source passed through a fibre as a function of pressure and displacement. A change in pressure on the POF sensor results in a change in light intensity output from the fibre due to bending losses. These bends applied to the fibre from pressure exertion are not at a single point along the fibre but rather at various areas specific to the body in contact with the fibre. This then results in displacement of the overall fibre set-up when affected by the body in contact.

Acquiring the respiration rate of a person using the proposed POF sensor provides an essential baseline observation in an unobtrusive manner. A change in the breathing rate as subtle as 3 breaths per minute to 5 breaths per minute is a significant initial indicator of respiratory distress and potential hypoxaemia [22]. As well as being one of the most profound indicators of critical illness [23], this data can be used to identify and avoid early stages of illnesses such as acidosis [24].

II. PLASTIC OPTICAL FIBRE SENSORS

Polymer Optic Fibres (POFs) are receiving a lot of interest due to their new found applications in sensing devices, ultra-high-speed LANs, optical computing and even clothing that illuminates for safety or purely fashion [12]. POFs have been implemented as a wireless and wearable design [13] intended to quantitatively assess the human gait, permitting knee sagittal motion monitoring over an extended distance and recently, [14] put forward a method to establish concrete water concentration when undergoing its curing process. The sensing principal was centered on the scattering of the optical signal in grooves inserted in the POFs. Such applications of POFs in low cost designs (costs of tools, assembly and technical training) with ease of use (increased power of semiconductor light sources at reduced costs) make them attractive for use as sensors.

We propose a POF sensor in this study in which the particular sensing principle relies on the bending sensitivity due to displacement of the POF. When the light transmitted within an optical fibre is affected by a particular physical parameter of the environment; for this study the expansion and contraction of the thorax (causing displacement of the resulting body surface in contact with the fibre, leading to deformation due to inspiration and expiration) and mechanical perturbations caused by the heart beat, it changes the optical properties of the light passing through the fibre. This is due to macrobending [15] and enables the fibre to be used as a sensor of the parameter.

Fibre-optic sensors have specific advantages over conventional sensors, allowing medical use; resistant to corrosion [16] thus the sensors can be sterilised without problems, and as optical fibres are passive, biocompatible, being unaffected by body fluids and immune to electromagnetic interference [17]; the risks of patient electrocution and data errors are removed (electrical isolation - no earth loop and interference problems) [18] hence providing scope for medical applications.

For this study, a polymer optical fibre is considered rather than the more traditional glass optical fibre (GOF) due to its superior mechanical flexibility with high elastic strain limits (GOFs have a low elastic limit and are brittle [19]) as well being lower costing [20], rugged, biocompatible, intrinsically safe, inert to body fluids such as blood and urine and are skin safe. They have increased sensitivity for strain sensing applications (+14 %) than Glass fibres [21]. Handling and enhancing performance of POF sensors is easier (GOFs require training and care) [12] using simple and inexpensive equipment and techniques; the POF to be used has a large diameter and can be sensitised by cutting grooves with a scalpel.

III. SELECTION OF POF

Various fibres from Toray and Mitsubishi, were evaluated for use in this study. The final selection of fibre for the sensor was based on the principle of bending sensitivity, i.e. optimising the fibre bending losses when deformed by the expansion and contraction of the chest cavity. This required analysis of two of the essential parameters that determine bending sensitivity of fibres; the diameter and numerical aperture (NA). The fibres were subjected to bends, summarised in Fig. 1 and the losses were recorded in terms of percentage power loss characterising the response of POF to bending into by circles of radius 10 – 20 mm radius.

The numerical aperture is dependent on the difference, Δ, in refractive index of the core/cladding material as shown in Equation (1). The fibre acceptance angle increases with Δ, enabling more efficient light collection at the fibre end. As well as optimising light launch into the fibre, a higher NA reduces the losses associated with fibre bending, since most of the light rays are guided through the fibre. Hence it was predicted that a lower NA fibre would exhibit greater bending sensitivity to a change in angle for the same radius of curvature. A large NA fibre would be less sensitive than that of a lower NA where bending results in a radius that is too small for light to be retained in the core.

$$N_A = \sin\theta_{max} = n_{core}.\sqrt{2\Delta} \qquad (1)$$

where $\Delta = \frac{{n_{core}}^2 - {n_{cladding}}^2}{2.{n_{core}}^2}$ and θ_{max} = acceptance angle

Fig. 1 shows losses of 1 mm fibres resulting from bends in a standard FX grade Toray fibre, a Mitsubishi POF and a low NA-POF (PFU FB1000). The low NA-POF exhibits considerably larger losses (17 % at 15 mm bend, 30 % at 10 mm bend) compared to the standard NA-POF and the Mitsubishi

POF (commercially available). The two fibres of same NA (0.5) exhibit almost identical power losses over the same range of bend radii. A difference of 30% in power loss at a bend radius of 10 mm was observed with the PFU grade fibre compared to the standard FX grade Toray fibre. The fibres that were evaluated in Fig. 1 were all of 1 mm diameter which enabled the relation to the conclusion drawn from [25], "the larger the NA, the narrower the permissible bending radii may be in relation to the fibre diameter" since a smaller bend radius is required for the same bending loss to be achieved with a higher NA grade of fibre.

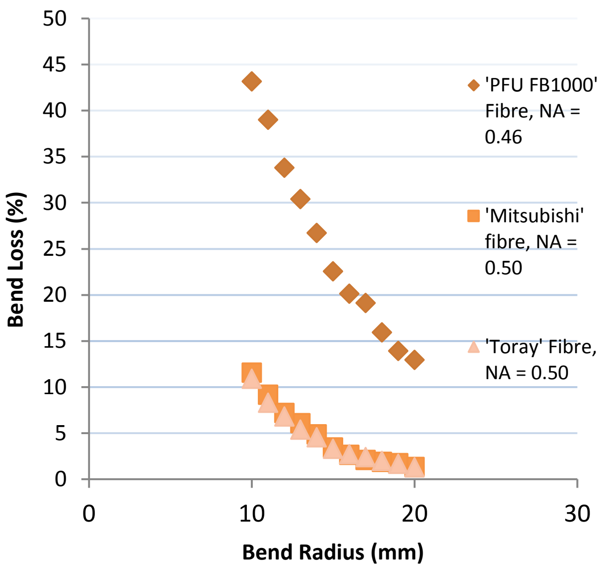

Figure 1: Comparing Bending Loss of 3 Different Types of 1 mm Fibre

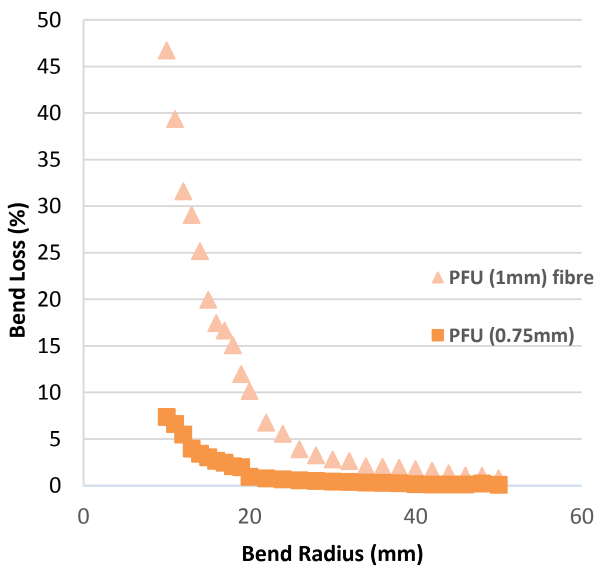

Figure 2: Comparing Bending Loss of 1 & 0.75 mm PFU Fibre, NA =0.46

The PFU FB1000 fibre with lower NA was selected and its bending sensitivity further evaluated with respect to diameter. The 1 mm diameter fibre was compared with a 0.75 mm diameter fibre under the same bending conditions. From Fig. 2 it can be seen that the larger diameter fibre exhibited higher bending losses (almost 40 % at a bending radius of 10 mm in comparison to the smaller diameter fibre). However, this is only true for the range of 25 – 10 mm radius bends, since above 25 mm the difference in losses are not so significant (less than 5 % change which gradually reduces to below 2 % after 34 mm). It appears that an equilibrium mode distribution (no longer a significant change in light loss with respect to bend radius) reduces the losses above a 25 mm bend radius. For application to measurement of breathing rate this equilibrium mode is irrelevant as the bends produced from body movement are out of this upper range of radius values (the bending radii caused by the human thorax deforming the fibre are below 20 mm).

IV. Preparation of POF Sensor

To enhance the sensitivity of POFs to deformation, various methods of applying small perturbations (external bending) to the fibre to modulate light transmission with respect to bending radius have been used. In [20], the development of a fibre optic strain gauge using radial grooves in a POF to increase its bending sensitivity was demonstrated and in [26] tooth-like transversal grains, longitudinal surface grains, and random grain surfaces were prepared on the fibre using milling and grinding techniques to sensitise the specific length of grained fibre.

One of the most efficient and cost effective methods of enhancing sensitivity with respect to bend loss is to cut grooves of a specified depth (0.1 mm being the typical upper limit of groove depth and 0.5 mm the extreme upper limit in a fibre of diameter 1 mm) and period along the fibre [27]. Bending the fibre will open the grooves if they are facing the bending direction (positive bending) resulting in transmitted light being attenuated. The opposite is true for negative bending which closes the groove and as a result increases transmitted power (Fig.3).

Grooves were cut into the fibre using a blade at a depth of 0.30 ± 0.01 mm in the transverse direction at a period of (15 ± 1 mm) along the fibre. As demonstrated by [20] [27] sensitivity is thus related to the opening or closing of the grooves which causes bending losses of the light transmitted through the fibre. Attenuation of transmitted light indicates deformation from the initial unbent shape of the fibre. This enhances the detection of mechanical parameters such as pressure and displacement caused by a person lying down on the fibre, together with the mechanical perturbations generated by the expansion and contraction of the chest cavity during respiration. In this way bending of the optical fibre is detected due to the changes in pressure and displacement on the fibre by the human body.

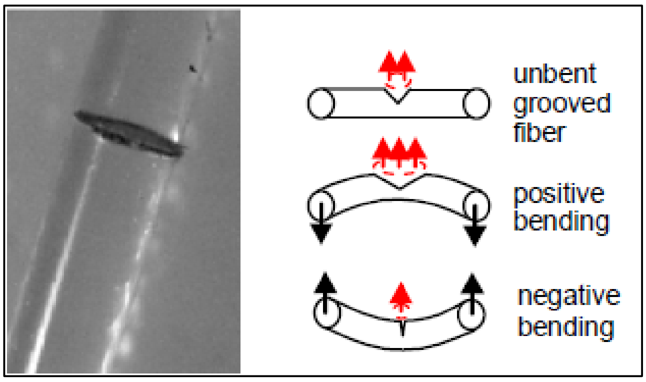

Figure 3: Positive and Negative Bending [27]

Figure 4: Illuminated Fibre highlighting Periodic Grooves

An increase of 61 % in bending losses was observed for a 1.5 m grooved fibre, illustrated in Fig. 4, compared to a nonsensitised fibre when a force of 81.75 N was applied to the fibre. This force represented the force applied to the sensor when positioned under the torso of a human body during respiration. However, applying grooves to the fibre also had a disadvantage since it made the fibre more brittle and prone to breaking. This was largely due to the reduction in integrity when grooves were cut into the fibre as well as the requirement for a substrate to support the fibre. A bending fibre has to be supported by a substrate that allows the fibre to deform and return to its original position. After evaluating several substrates (carpet, expanded polyethylene mesh, TurfProtecta Mesh and high density conductive foam) for use with the fibre sensor (on top of which the fibre was to be positioned), the TREDAIRE Vibrant Carpet was selected as its deformation properties were ideal for the support it provided to the fibre. The selected substrate, provided support to the fibre in relation to the pressures and displacement the fibre would have to sustain when positioned under a person.

A separate technique to increase sensitivity without grooving is illustrated in Fig. 5 where plastic rods were placed alternately below and above the fibre. Sensitivity is defined here as percentage light loss per kg of load added to the set-up with plastic rods; calculated as 0.66 % kg^{-1}. In terms of voltage and stress the sensitivity was calculated as 32.05 mV N^{-1}. The optimum period was determined to be 3 cm along the fibre with a length of 3 cm for each rod. Each point of the fibre in contact with a plastic rod experiences an increase in modulation compared with the situation without the plastic rod, resulting in increased light losses for that fibre section which increases the accumulated bending losses throughout the fibre. The losses obtained are illustrated in Fig. 6.

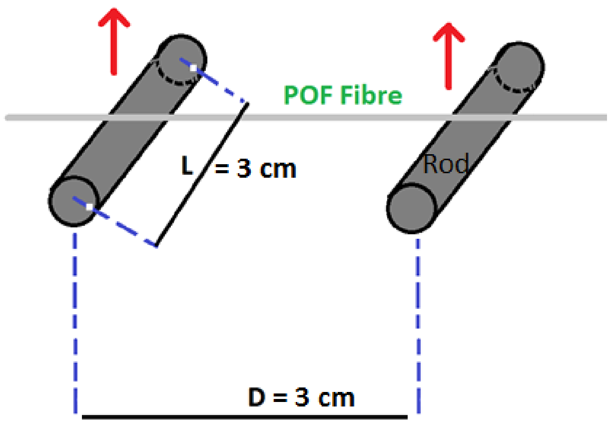

Figure 5: Plastic Rods to Enhance Sensitivity of Fibre

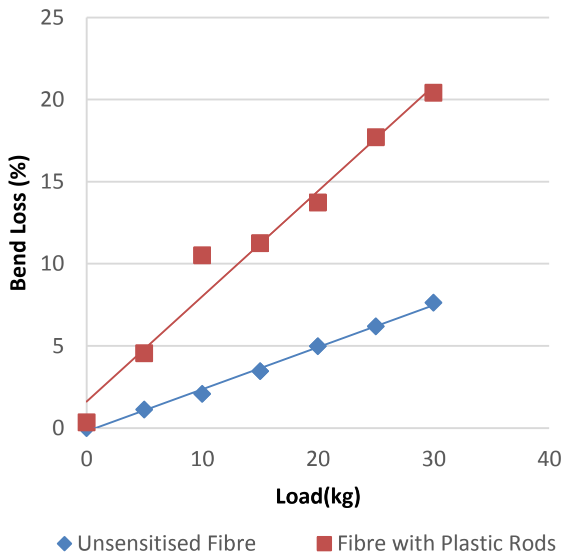

Figure 6: Bending Loss of Fibre with Plastic Rods

V. Results and Discussion

The POF with plastic rods, was tested by unhindered, resting respiration of a person lying on top of the POF sensor. The sensor was positioned under the small of the back region of the person. Light was transmitted through the fibre using an AVAGO SFH 756V LED and detected using an INFINEON SFH 250V photodiode at the other end of the fibre. The output signals obtained were fed to National Instruments hardware; an NI 9219 4 Channel Isolated, 24-bit, ±60 V, 100 S/s Universal AI Module which fed into the cDAQ-9188, CompactDAQ chassis (8 Slot ENET). This chassis was then connected to a PC and LabVIEW software was used for data analysis. The data obtained indicated the voltage signals related to the displacement of the fibre during unhindered respiration of the person and are illustrated in Fig. 7. Deeper breaths were then taken which are displayed in Fig. 8 as an increase in light intensity values (1.36% compared to 0.28 % for normal breathing), caused by an increase in the expansion and contraction of the chest cavity resulting in further displacement to the fibre with smaller bend radius (increased bending).

The POF sensor shows strong potential for use in a practical environment to monitor the respiration rate of a person. It demonstrates the differences in normal and deeper breathing (higher intensity, lower frequency) which can be used to monitor the status of a person who is struggling for breath. Respiratory effort (depth of inspiration and use of accessory muscles) can be related to thoracic expansion by the user. An abnormal respiratory rate is a paramount predictor of an approaching adverse health event such as a cardiac arrest [29]; therefore detection of, breathing rate and pattern, enables the POF sensor system to alert users to avoid deterioration of a person's condition.

The POF sensor demonstrated successful monitoring of the respiration rate of a person simulating a laboured situation with a faster breathing rate represented by an increase in the frequency of cycles per unit time. This identification allows the rate to be further analysed (by clinicians monitoring a person) and classified as eupnoea, tachypnoea, bradypnoea or hypopnea [30], enabling diagnosis of the cause of a faster or slower breathing rate with the specific individual under study.

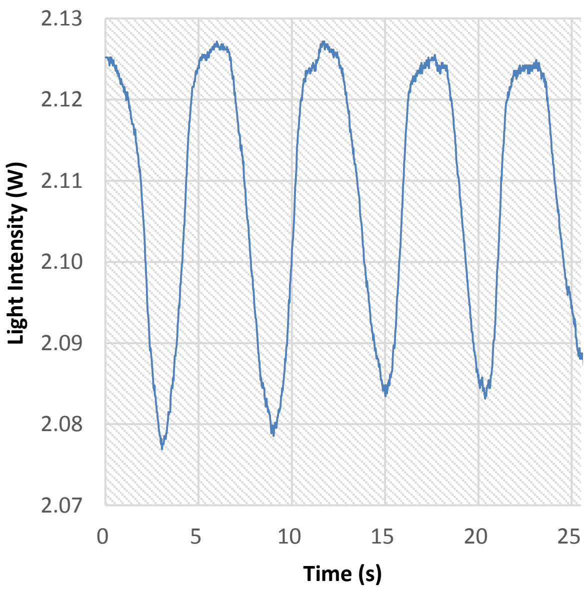

Figure 7: Unhindered Respiration Data using POF Sensor

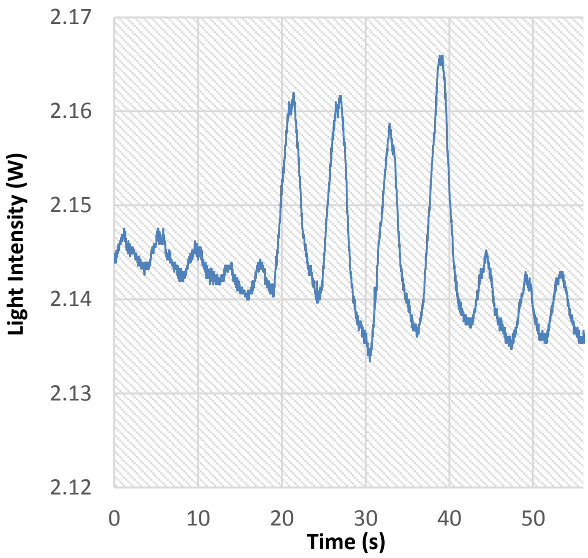

Figure 8: Faster and Deeper Breathing Data using POF Sensor

VI. CONCLUSION

In summary, we report on a POF sensor developed to detect the breathing rate of a person. It was demonstrated to measure the respiration rate of a person and it is desired to extract the heart beat from the same data with further analysis and filtering. Experiments were carried out to select the optimum fibre for this project with respect to sensitivity to bend losses. It was found that the Toray PFU FB1000 grade was the most sensitive to bending. Plastic rods were used to further modulate the fibre by enabling increased bend losses to the same load being applied to the fibre. Such simple enhancements increased sensitivity by 0.66 % kg^{-1}. The sensitivity in terms of voltage and strain was defined as 32.05 mV N^{-1} for the sensor. This sensitivity was proportional to the number of plastic rods (increased by 0.11 % for every plastic rod used). The POF sensor also detects movement of a person with larger light intensity variations (an increase in 15 % when compared with breathing) with each respective movement.

The next phase of this study will analyse the ability of the POF sensor in detecting health changes illustrated in the respiration signal of a person. This will include extracting the signal and testing for variations in frequency and intensity of the respiration signal of a person.

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