A Robust and Low-Cost 2-Dimensional Pressure Sensing System using Polymer Optical Fibre

Henrie van den Boom, Oded Raz, Ton Koonen
Institute for Photonic Integration, Eindhoven Univ. of Technology, Eindhoven, The Netherlands
E-mail: h.p.a.v.d.boom@tue.nl, O.Raz@tue.nl, A.M.J.Koonen@tue.nl

Abstract *A novel system based on a robust grid of standard low-cost Polymer Optical Fibres has been created which efficiently detects varying 2-dimensional pressure profiles at high speed. Unobtrusive body movement detection in bed is demonstrated with 25 profiles/s using an easy to manufacture 16x8 grid.*

Introduction

Polymer or Plastic Optical Fibre (POF) is commonly used for low-speed, short-distance optical data communication[1] and is robust, flexible, and insensitive for Electro-Magnetic Interference (EMI). POF is popular for in-building wiring, as it is cheap and due to its relatively large core and cladding diameter, easy to handle and to couple light into. Being made of a ductile polymer (e.g. PMMA), it is not as brittle as silica fibre, and when stretched it does not break but is elongated. For interconnecting two POFs, low precision connectors may be used, and may even be skipped, i.e. interconnecting by simply cleaving and butt-joining the POFs.

Because of its bending-sensitive properties, augmented by its ductility, POF can also be used for sensing[1-2]. Sensor systems based on detecting POF attenuation variations when pressure or bending is applied have been reported[1-3], and commercial products based on this are available. However, a straightforward 2-Dimensional (2-D) pressure detection system based on only detecting attenuation in POF links is in principle not possible, only with complicated fibre grids and signal processing[4]. Also fibre pressure sensing using Bragg gratings has been studied and reported extensively[2], but is significantly more complicated and expensive. We present a 2-D grid made of unmodified standard POFs where fibres in one direction are connected to light sources and fibres in the perpendicular direction are connected to highly sensitive optical receivers. At each crossing point an amount of optical power can couple from the POFs carrying light to the POFs connected to the receivers, depending on the pressure exerted on the crossing. Hence each fibre crossing of the grid acts as an independent pressure sensor. Previously we have presented technology where fibres had to be modified[5] or precisely aligned with respect to rings[6-7]. We further demonstrate that an accurate pressure profile of a patient lying in bed can be reconstructed and that the system sensitivity is sufficient to detect respiration and heart beat rate based on well-known principles of ballistocardiographic [8].

Principle of Operation

Fig.1 shows the principle of operation. Our system consists of a 2-D POF Grid, an Optoelectronics module and a Data Acquisition and Control module. The 2-D POF Grid is composed of a grid of SI-POFs (step-index POFs) arranged as a matrix of crossings. The so-called transmitting fibres of the POF grid are connected to simple light sources like LEDs and the receiving fibres to photodiode receivers of the Optoelectronics module. The Data Acquisition and Control module controls the LED transmitters and processes the measured data obtained from the photodiode receivers. The optical coupling between the POFs at the crossings is a function of the local pressure, so by detecting the optical power received by the photodiodes, the pressure on a crossing can be measured. Because the optical coupling effect between transmitting and receiving POF fibres is very small, high-sensitivity optical receivers are needed, using transimpedance amplifiers (TIAs) with high gain and a high input impedance. Moreover, as only a very small amount of light power, in general $< 0.01\%$, is coupled out of the transmitting fibre when pressure is exerted on the respective crossing, the light which stays in the transmitting fibre and goes on to the next crossing is hardly reduced. Thus the sensitivity of a crossing is hardly affected by the pressure on other crossings, i.e. the location-dependence of the performance of a crossing is negligible. This makes the system well-scalable to larger 2-D matrices and is experimentally tested with 64 crossings in a row. To achieve a simple and scalable system, a crossing scanning method is

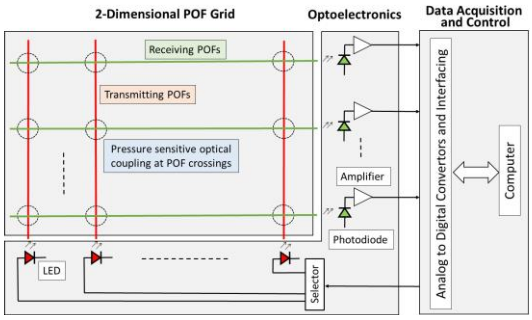

Fig. 1: Block diagram of 2-D pressure sensing system. Vertical columns are scanned one by one.

implemented. The Data Acquisition and Control module in Fig. 1 controls the Selector, which selects only one LED at a time, and the crossings are scanned column by column. Reading simultaneously the photodetector outputs line-by-line, enables the Data Acquisition and Control module to construct the 2-D pressure profiles. This solution is readily scalable because *N* photodetectors and *M* LED sources can detect *N* x *M* sensor points.

POF Crossing

The main novelty in the presented concept is the pressure-sensitive optical coupling mechanism and construction of a crossing where the fibres are left in their original state and are thus kept unmodified. Moreover, the crossing design is very tolerant to alignment errors because small patches of flexible and scattering material at a crossing which increase the sensitivity do not have to be precisely aligned, in contrast with a ring-based solution[6-7]. Using such patches makes the POF grid easy to manufacture at low cost. In Fig. 2, a POF crossing is shown with on both sides a small patch of thin flexible light scattering material, for instance white silicone rubber and a thin rigid material, such as hard PVC. When pressure or weight is applied, the flexible scattering material will press on both sides on both fibres and will smoothly bend the fibres a little bit. Also the physical contact of both fibres with the flexible scattering material will increase. Due to micro-bending[1] occurring where the fibres touch each other and macro-bending[1] because the fibres are smoothly bent, a small amount of light will escape from the transmitting fibre which is proportional to the applied pressure or weight. The escaped light will be scattered in all directions in the (white) flexible scattering material and partially couple into the receiving fibre, again, due to micro bending and macro bending of the fibres. The flexible material makes the sensor grid also very robust. It gives the fibres a smoother bending radius at the crossing when pressure is applied and forces are partly absorbed by the flexible material outside the fibre crossing. Without the flexible material

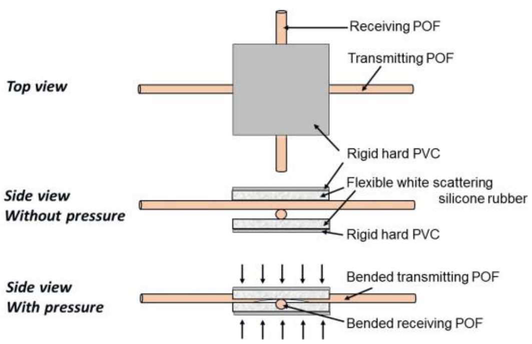

Fig. 2: POF crossing with scattering material on both sides.

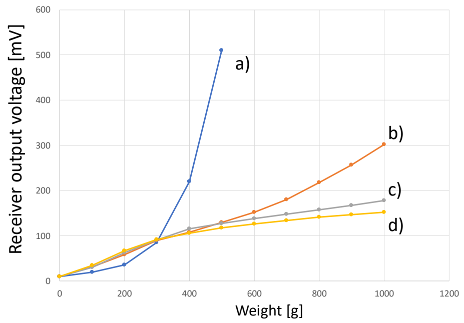

Fig. 3: Receiver output voltage as a function of applied weight for size of patches of flexible material of: a) 5 x 5 mm^2, b) 10 x 10 mm^2, c) 15 x 15 mm^2, d) 20 x 20 mm^2.

and only rigid material, forces are concentrated on the crossing of the fibres which can cause permanent deformation. To make the crossing thinner, instead of using flexible light scattering material on both sides, it can also be used on one side to obtain a thinner mat.

In Fig. 3. static characterisation results of a single POF crossing are given for various sizes of the patches by measuring the output voltage of an optical receiver connected to the receiving fibre as a function of applied weight to the crossing. The cladding diameter of the POFs is 0.5 mm, the sensitivity of the optical receiver 0.4V/nW and the optical power of the white LED coupled in transmitting POF >1mW. Depending on the dimensions of the patches, different sensitivity characteristics can be realised. Using larger patches, logarithmic characteristics are obtained resulting in a wider dynamic range.

Heartbeat, Respiration and Movement Detection for Sleep Monitoring

An application example of this pressure sensing technique is unobtrusive sleep monitoring in a home environment by applying a POF grid underneath the mattress in a bed. Long-term at-home monitoring of sleep-related movements would be an important diagnostic tool in cases of sleep-related breathing disorders such as sleep apnea, which are often body-position dependent.

To demonstrate that this POF sensor technique can be used for long-term unobtrusive sleep monitoring, a low-cost prototype was realized consisting of a grid with 16 transmitting and 8 receiving POFs at a distance between the fibres of 9 cm, so covering an area of about 140 x 70 cm^2. The grid is connected to 16 white light LEDs and 8 optical receivers including 8 Integrate and Dump filters. This type of filtering optimizes the Signal-to-Noise ratio of the signals at the sampling moments of the Analog-to-Digital convertors of the Data Acquisition and control part, see Fig. 1, for which a simple Teensy 3.6 microcontroller board is used. With the 8 x 16 POF grid located underneath the mattress, the motions of a person on the mattress are detected and processed by the microcontroller board. The

Fig. 4: Photo of a running 2-D bed sensor pressure profile detection system, detecting at 25 profiles a second. POF grid is under the mattress.

pressure profiles can be displayed in real-time with a Visual Studio program on a computer connected to the microcontroller with a frame rate of at least 25 profiles/s, or can be stored on an SD card in the Teensy 3.6 microcontroller for off-line examining. Fig. 4 shows a photo of a measured profile of a person lying on his side on a 16 cm thick foam mattress of a running system. The sensitivity of a POF crossing underneath the mattress can be large enough to detect also heartbeat due to body vibrations and respiration of the person lying on the mattress, as is shown in Fig. 5. Here the output signal of the optical receiver is measured in time with an oscilloscope for a period of 10 seconds. Fig. 5b shows that on top of local pressure also the respiration of the person lying on the mattress can be observed. To detect heartbeat the optical receiver output signal is amplified with a second AC coupled amplifier and displayed after low pass filtering in Fig. 5c. For comparison, simultaneously the heartbeat is detected electrically with three electrodes on the body of the person lying on the mattress and displayed in Fig. 5a. As can be seen the heartbeat detected with the POF sensor

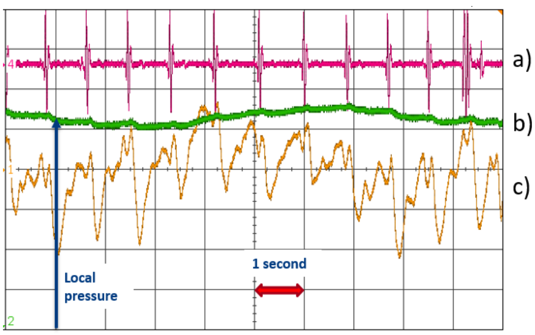

Fig. 5: a) Heartbeat detected with electrodes, b) Local pressure and repiration detected with POF sensor, c) Heartbeat detected with POF sensor.

underneath the mattress clearly matches the electrically detected heartbeat.

Large area 2-D detection

This 2-D POF sensor technique is also suitable for sensing large areas, for example in a Virtual Reality (VR) floor mattress in a gaming room to detect the exact location of the gamers[9], under a carpet or woven into it, or under a PVC floor for for privacy friendly fall detection of (elderly) persons[10-14]. The relatively high weight per cm^2 opens the possibility to scan large areas with many crossings, with many profiles a second. To demonstrate this, a thin flexible mat has been realized with a 64 x 8 POF grid so 512 crossings, covering an area with a length of 5.76m and a width of 0.72m. With this mat, experiments have been carried out under a carpet, PVC and laminate flooring and in all these cases the footsteps of walking persons could clearly be detected with a speed of 25 profiles/s and didn't influenced each other.

Discussion

Next to the applications demonstrated above this easy to manufacture, low-cost and robust 2-D optical pressure sensor principle can be used for many other applications, such as:

- for monitoring precise pressure profiles of persons in bed with limited movement to prevent pressure injury (e.g., decubitus),
- in adaptive mattresses where local pressure is controlled automatically to improve sleep comfort.

Conclusions

A robust, optical EMI insensitive, low-cost 2-Dimensional pressure sensing technique is presented and experimentally verified. The technique uses a simple grid of Polymer or Plastic Optical Fibre (POF) where the fibres are left intact. Each fibre crossing is a pressure sensor and to realize sufficient pressure-dependent optical power coupling while the fibres are not modified, small patches of flexible light scattering material are applied. This makes the POF grid robust and alignment tolerant so easy to manufacture at low cost. Unobtrusive movement detection of a person in bed is demonstrated with a 8 x 16 POF grid underneath a 16 cm thick foam mattress with a rate of 25 pressure profiles a second. Even heartbeat and respiration detection is demonstrated with a POF crossing underneath the mattress. The feasibility for 2-D large area detection is demonstrated with a 64 x 8 grid so 512 sensor points in an area of 5.76 x 0.72 m^2 with a speed of 25 profiles a second and a resolution of 9 cm.

References

[1] Olaf Ziemann, Jürgen Krauser, Peter E. Zamzow, Werner Daum, POF Handbook, 2nd Edition, Springer, 2008.

[2] Ginu Rajan, Optical Fiber Sensors: Advanced Techniques and Applications, CRC Press, 2015.

[3] Markus Rothmaier et al., “Textile Pressure Sensor Made of Flexible Plastic Optical Fibers”, Sensors (Basel). July 2008; 8(7): 4318–4329.

[4] G. Feng, J. Mai, Z. Ban, X. Guo, and G. Wang, “Floor Pressure Imaging for Fall Detection with Fiber-Optic Sensors,” IEEE Pervasive Computing, vol. 15, no. 2, pp. 40–47, apr 2016.

[5] Boom van den, H.P.A., Overeem, S. & Koonen, A.M.J. (2016). (Invited) “Robust two-dimensional pressure sensing mattress based on optical coupling between crossing polymer optical fibres”, 25th International Conference on Plastic Optical Fibres (POF 2016), September 13-15, 2016, Birmingham, United Kingdom.

[6] H.P.A. van den Boom and A.M.J. Koonen, Patent Application PCT/EP2017/054353, Optical waveguide system for 2-dimensional location sensing, February 24, 2017.

[7] Boom van den, H.P.A., Overeem, S. Forni, F. & Koonen, A.M.J. (2017). “Real-Time two-dimensional pressure sensing for patient monitoring based on optical coupling between crossing polymer optical fibres”, 26th International Conference on Plastic Optical Fibres (POF 2017), September 13-15, 2017, Aveiro, Portugal.

[8] Eblen-Zajjur, Antonio, "A Simple Ballistocardiographic System For A Medical Cardiovascular Physiology Course". Advances in Physiology Education. 27 (4): 224–229.

[9] Julia Schwarz and Jason Michael Ray, Patent Application US 2019 / 0302879 A1, Virtual Reality Floor Mat Activity Region, Oct. 3, 2019.

[10] A. Bueno-Cavanillas, F. Padilla-Ruiz, J. J. Jim´enez-Mole´on, C. A.Peinado-Alonso, and R. G´alvez-Vargas, “Risk factors in falls among the elderly according to extrinsic and intrinsic precipitating causes”, European Journal of Epidemiology, vol. 16, no. 9, pp. 849–859, 2000.

[11] A. Yu, W. Wang, Z. Li, X. Liu, Y. Zhang, and J. Zhai, “Large-Scale Smart Carpet for Self-Powered Fall Detection,” Advanced Materials Technologies, p. 1900978, jan 2020. [Online]. Available: https://onlinelibrary.wiley.com/doi/abs/10.1002/admt.201900978

[12] P. S. Sase and S. H. Bhandari, “Human Fall Detection using DepthVideos”, 5th International Conference on Signal Processing and Integrated Networks, SPIN 2018. Institute of Electrical and Electronics Engineers Inc., Sept. 2018, pp. 546–549.

[13] V. Vaidehi, K. Ganapathy, K. Mohan, A. Aldrin, and K. Nirmal, “Videobased automatic fall detection in indoor environment”, International Conference on Recent Trends in Information Technology, ICRTIT 2011, 2011, pp. 1016–1020.

[14] K. M. Shahiduzzaman, X. Hei, C. Guo, and W. Cheng, “Enhancing Fall Detection for Elderly with Smart Helmet in a Cloud-Network-Edge Architecture”, 2019 IEEE International Conference on Consumer Electronics - Taiwan, ICCE-TW 2019, pp. 1–2, 2019.