Photonic Guided-Path Tomography Sensor for Deformation in a Non-planar Surface

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Abstract. We introduce theoretically and demonstrate experimentally the performance of a Guided-Path Tomography sensor head and a complete system for imaging of physical parameters on non-planar and possibly flexible surfaces. Novel in our approach is to employ waveguiding sensor elements, strategically arranged on the imaged surface, to allow tomography measurements and the inverse problem solution. In the reported particular implementation we image deformation over ~1sq.m., which is achieved by sensitizing the sensor elements to bending. The problem of severely limited number of measurements is addressed by an original method for sinogram recovery, followed by the application of well established methods for solving the hard-field tomography inverse problem. We show that the sensor is capable of distinguishing objects of different mass and shape of footprint. It also calculates the coordinates of the centre of mass of the imaged objects, which facilitates integration with control systems.

1. Introduction

GPT was originally introduced[1] and successfully demonstrated for imaging of temperature[2]. The new Photonic GPT (PGPT) is based on the controlled change in the waveguiding properties of plastic optical fibers (POF), sensitized to external influence (mechanical, chemical, etc.) and the imaged parameter is reconstructed from simple light intensity measurements at the periphery of the surface, with low cost optoelectronic components. This allows the application in a variety of imaging and control scenarios, ranging from healthcare to structural and ambient monitoring.

Consider a thin flexible transducer of length L, transmitting light intensity \( \phi \), depending on deformation D: \( \phi = \phi(D) \). The light transmitted through the transducer is given by the Beer–Lambert law:

\[
\phi(l) = \phi_0 e^{-a l} \quad (1)
\]

Where \( \phi_0 \) is the light input into the transducer, \( a \) is the attenuation coefficient and \( l \) is the distance along the transducer. For small values of \( a \), equation (1) becomes a linear function,

\[
\phi(l) \approx \phi_0 a l \quad (2)
\]

If \( a \) is small and varies in space because of the transducer’s sensitivity to deformation \( a = a(D(x,y,z)) \), the transmitted light intensity is given by the path integral

\[
\phi(l) = \phi_0 \int_a(D(x,y,z))dl \quad (3)
\]
A number of such flexible transducers can be placed in the surface of interest, which is not necessarily planar, that is illustrated in Fig. 1a for ten transducers. If individual paths $L_i$ are equidistant straight lines and are grouped in parallel, crossing each other without interaction between the transducers, the measured overall transmitted intensities $\phi_i$ are samples of the Radon transformed spatial distribution of attenuation.

\[ \phi_i = \phi_0 \sum_{j=1}^{n_i} a_{ij} \lambda \]  

(4)

where $\phi_i$ is the intensity from chain $i$, $n_i$ is the number of elements in that chain and $a_{ij}$ are the attenuation coefficients. The measured values of $\phi'_i$ can be also expressed as

\[ \phi'_i = \phi_0 a_i n_i \lambda \]  

(5)

where

\[ a_i = \frac{1}{n_i} \sum_{j=1}^{n_i} a_{ij} \]  

(6)

is the attenuation coefficient averaged over all discrete sensor elements along the chain.

In this work, sensitization was achieved by cutting transversal grooves into the POF to introduce losses that are sensitive to bending (see Fig.3). In this particular way of sensitization, (4) can be interpreted as the measured intensity being the result of losses at $n_i$ discrete points. In the absence of bending, these losses are identical for identical grooves and the transmitted intensity is obeying the Beer-Lambert law, as also proven experimentally. The bending losses come as a small deviation from this initial condition and can be measured as the difference between the initial and actuated condition. Indeed, with calibration to the initial condition, the imaging task can be performed only on the difference signal between any two conditions. This has been proven by the observation that identical bending at any position along a 75 grooves transducer results in identical changes in transmission.

Fig. 1: a) Component of the sensor which can assume the shape of a non-planar surface. This example contains only two 90° projections for clarity; this number is extremely low and usually is not sufficient for a reasonable quality of reconstruction. b) Irregular pixel grid $\Gamma$, projecting onto a regular 2-D pixel grid $G$. 

Non-planar surface will be characterized by an irregular pixel grid $\Gamma$ which projects into a regular planar reconstruction grid $G(x,y)$, as illustrated in Fig.1b. During the projection operation the sensitivity matrix for the data inversion will have to be re-calibrated to yield the in-plane sensitivity matrix taking into account the geometrical details.

Therefore, if the geometry of the surface is known then data inversion can be performed by a suitable method of planar reconstruction. Since $\phi = \phi(D)$ is a monotonic function it can be recalculated as a deformation map with spatial resolution in the order of $1/N$.

Discrete transducers can be considered as a chain of transducer elements connected by POF sections which are not sensitized. A generalisation of this would be discrete optical attenuation sensors coupled to a number of waveguide sections. Assuming that each discrete transducer element of length $\lambda$ introduces attenuation determined by the deformation induced losses, the raysum, which is the analogue of a path integral in the continuous case, is given by

\[ \sum_{j=1}^{n_i} a_{ij} \lambda \]  

is the attenuation coefficient averaged over all discrete sensor elements along the chain.
2. Results

For imaging of deformation, the sensor head is integrated with a deformable foam mat. The sensitization is along the middle 0.8m of the 3m long POF elements. Imaging is achieved with only 32 such elements, each coupled to a red LED, arranged in parallel groups of 8 at four equidistant angles, 0, 45, 90 and 135° (Fig. 3).

Fig. 3: Sketch of the PGPT sensor head. The red triangles on the left denote the individual LEDs for each fibre element. On the receive side, the elements are bundled and fed into a single photodetector

Each individual POF sensor yields a path integral of the light attenuation along the fibre, due to cumulative waveguiding losses. The measured dataset consists of 32 transmitted intensities, demultiplexed from a single photodiode. Fig. 4 shows as a flow chart the concept of the image reconstruction approach for the PGPT.
Fig. 4: Flow chart of the image reconstruction approach for PGPT. The shaded area labelled “This work” shows the modifications to the conventional hard-field reconstruction

As the collected dataset is a severely under-sampled Radon transform (sinogram) of the deformation map, we apply sinogram recovery by applying sinusoidal Hough transform on the available sinogram samples [3]. The highest peaks in Hough space identify the most significant traces, corresponding to the individual objects on the mat. Further, their center of mass is extracted directly, or full reconstruction is performed on the recovered sinogram by standard filtered backprojection (nearest neighbour interpolation with a Hamming window on a Ram-Lak filter). Maps are obtained of deformation induced by objects of different weight (see Fig.5.i) and footprint, as well as by multiple objects (see Fig. 5.ii). The robustness of the sinogram recovery approach to measurement noise is tested with suitable numerical phantoms, exhibiting sharp and diffuse edges, as well as Gaussian and flat object functions. The application of three different error metrics on the reconstructed images indicate that the nominally small error becomes on the average 1.15 and 2.1 times its original value (in the absence of noise) at signal-to-noise ratios of 30 dB and 20dB respectively.

Fig. 5: i) PGPT of the foam mat deformation from three objects with identical position and circular footprints and with masses a)3.36kg, b)4.28kg, and c)6.63kg. ii) Same for composite objects. The actual position of the objects on the grid is given on the left for each reconstruction

The mechanical integrity of the fibre sensors was tested in a variety of conditions with original equipment designed in-house. Under realistic conditions, with bending radii in the order of 100mm, the sensors showed no performance deterioration even after 250,000 cycles, applied repetitively at 1Hz or faster. This promises the application of the pressure-sensitive mat to variety of cases where monitoring of activity over large areas is required. Sensitization can be achieved with respect to other measurands, such as concentration of chemical species, allowing a wide range of imaging contrasts.

References
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