

# A fibre optic angle sensing tape for applications in robotics and automation.

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## ABSTRACT

A dual-fibre single-plane angle-sensing tape that utilizes optical Fibre Segment Interferometry and Range-Resolved Interferometry (RRI) for angle sensing is presented. The sensing tape facilitates the multiplexing of an array of angle sensors along its length and can be retrofitted into small robots and construction equipment. We demonstrate its application on three non-rotational joints of a small five-axis robot, describing the design, construction, measurement principle, and presenting measurement results. Preliminary data shows that the angles measured by the sensing tape exhibited agreement within a range of  $\pm 0.005^\circ$  with the manufacturer-installed angle encoder of the robot.

**Keywords:** Angle sensing tape, Fiber Segment interferometry.

## 1. INTRODUCTION

The use of small robotics in manufacturing is desirable to allow increased automation. However, such robots typically employ low cost angle encoders that suffer from limited angular resolution, gear backlash and gear wear, which can limit positioning performance [1]. A robust high-resolution alternative that allows measurement of the robot pose, including any link bending, in the form of an optical fibre based angle sensor, could offer a practical and cost-effective solution. In this paper, an optical fibre based angle sensor, exploiting Fibre Segment Interferometry (FSI) [2] is reported. FSI is an emerging fibre optic strain sensing technology, offering high resolution ( $n\epsilon/\sqrt{\text{Hz}}$  measurements at bandwidths of 10s of kHz. In previous work, characterising the vibration mode shapes of a helicopter rotor blade, we have shown that the differential measurements of the strain in two optical fibres containing fibre segment interferometers and mounted either side of the neutral axis of a flexible support structure can offer angular resolutions of order  $10^{-6}$  rads/ $\sqrt{\text{Hz}}$  [3], with the sensitivity determined by the interferometer length and the distance of the fibre from the neutral axis. Here, the concept, measurement principle, design and construction of an angle sensing tape are described, and results for an installation measuring angle changes on three joints on a low-cost robot arm are presented. Such a single-axis, fixed-plane, fibre optic-based sensing tape could be retrofitted to industrial robot arms and even be used in harsh environments, for example, for the automation of construction equipment such as excavators, providing enhanced and reliable angle feedback, while a full fibre optic shape sensor could be used where traditional rotary encoders would not be easily applied, such as in snake-like continuum robots [4].

## 2. CONCEPT AND MEASUREMENT PRINCIPLE

The angle-sensing tape concept, shown in Figure 1, consists of a flexible metal substrate with optical fibres mounted on the top and bottom surfaces. By measuring the differential strain between fibre segments located on either side of this metal substrate, the angle between the two ends of the segments in the plane of the fibre-pair can be determined, assuming a fixed lateral separation of the fibres [5], with the arc angle,  $\Delta\theta$ , given by [6]:

$$\Delta\theta = \frac{\epsilon_{diff} l}{\delta} \quad (1)$$

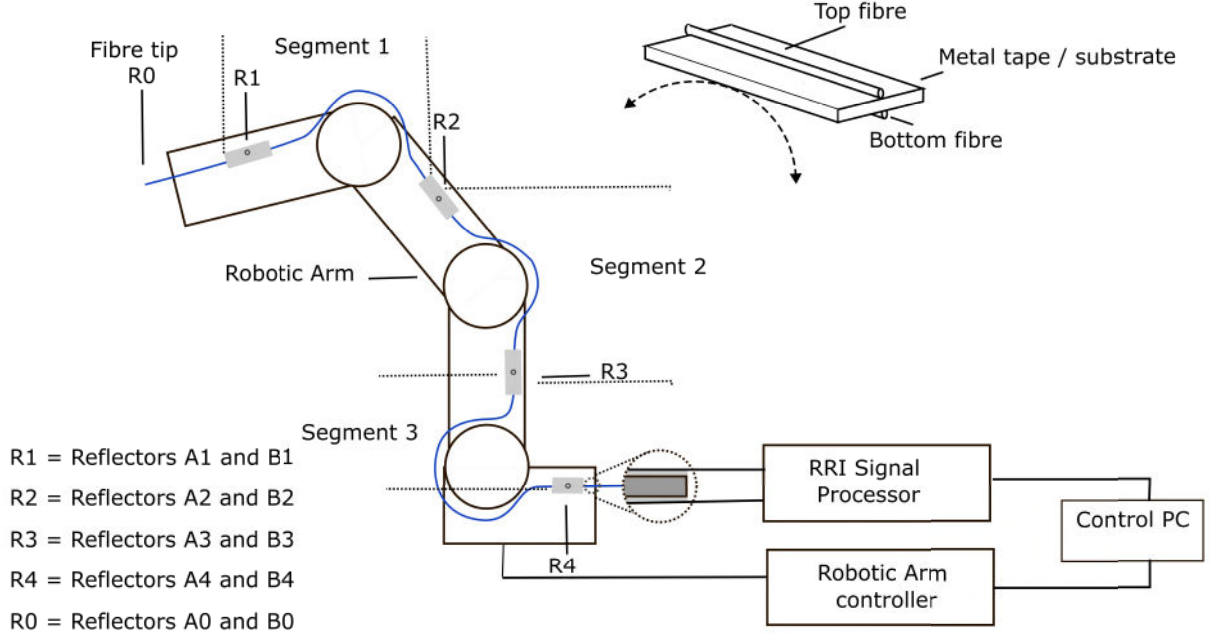


Figure 1. Schematic of the concept for a dual-fibre angle-sensing tape applied to a robotic arm. Top right shows the tape construction, with fibres mounted either side of a metal tape/substrate. The tape is mounted to the robot arm and fixed either side of the joints to be measured. The points  $R_1$ ,  $R_2$ ,  $R$  and  $R_4$  represent the locations of the reflectors that form the segment interferometers. The reflectors in the “top” (A1 to A4) and “bottom” (B1 to B4) fibres are arranged to be co-located along the length of the tape, with the tape in the region of the reflectors housed rigidly in a 3D printed structure.

where  $\epsilon_{diff}$  is the differential strain between fibre pair cores,  $l$  is the path length, and  $\delta$  is the fixed lateral separation between the top and bottom fibres. The use of a metal substrate ensures a fixed lateral separation of the fibres and provides resistance to out-of-plane twisting of the fibre pair, needed to ensure measurement fidelity [5]. To allow an array of angle sensors to be multiplexed along a length of the tape, the fibres can be divided into segments, co-located on either side of the tape at positions  $R_1$ ,  $R_2$ ,  $R$  and  $R_4$ . The reflectors are formed using weakly reflecting ( $< 0.01\%$ ) optical fibre Bragg gratings, each of which forms an interferometer with the fibre-tip reference (R0). Interrogation of the phases of the multiple interferometers, needed to determine the differential segment strains, and hence angles, is performed using the principles of Range-Resolved Interferometry (RRI) [7]. The change in the angle for a segment of the tape can then be found in terms of the measured differential phase between two corresponding segments in the top and bottom fibres using:

$$\Delta\theta = \frac{(\Delta\phi\lambda_0)}{\delta 4\pi n_g k} \quad (2)$$

where  $\Delta\phi$  is the differential phase change between the top and bottom fibre segments,  $\lambda_0$  is the free space wavelength of the laser used during the measurement,  $n_g$  is fiber core group index. The value of  $k$ , the fibre strain sensitivity, is 0.79[8].

### 3. CONSTRUCTION AND MOUNTING OF THE TAPE

The tape took the form of a steel packing tape, 13 mm wide by 380  $\mu\text{m}$  thick. To form the segment interferometer array, short ( $\sim 250 \mu\text{m}$  long), low reflectivity (0.1%) fibre Bragg gratings (FBGs) were fabricated in two lengths of single mode optical fibre (SMF-28) using the point by point technique with a femtosecond laser. The length of the FBG was selected to provide a reflection peak of full-width-half-maximum 9 nm, ensuring that there would

be a reflection at the interrogation laser's wavelength irrespective of Bragg wavelength shifts induced by typical temperature and strains that would be experienced during use of the angle sensing tape. The locations of the reflectors in the two optical fibres (A and B), are illustrated in Fig. 2. The separations of the reflectors were selected such the interferometers of interest had distinct path lengths that could be resolved by the RRI based interrogator, and were such that parasitic interferometers formed through multiple reflections did not have path lengths that overlapped with the interferometers of interest, which would otherwise introduce non-linearities to the angle measurement.

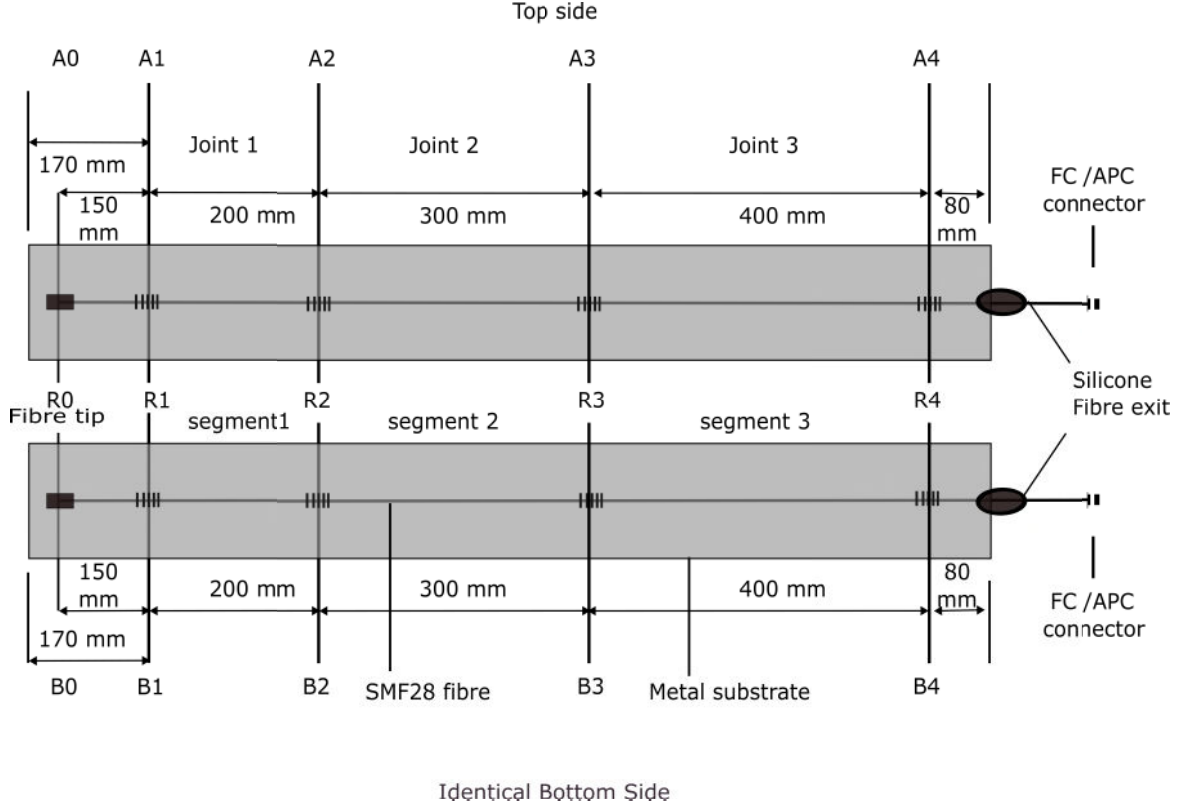


Figure 2. Schematic of the FSI reflector array; Here R0 is the fibre tip and R1, R2, R3 and R4 are FBG reflector locations corresponding to the fixed points on the robot arm. A and B refer to the specific locations of the reflectors fabricated in the optical fibres bonded to top and the bottom surfaces of the tape

The SMF-28 optical fibres containing the FSI reflector arrays were attached along the centre line of the tape using cyanoacrylate adhesive, one on the top surface, the other on the bottom surface. The cleaved fibre ends, which acted as the reference reflectors for the segment interferometers formed in the two fibres, were protected by 3d printed end caps. The proximal end of the fiber was protected at the point where it left the metal tape using silicone sealant, and was terminated with an FC/APC connector, via which it was connected to an FSI interrogation unit [7]. The completed angle sensing tape was attached to the robotic arm as shown in Figure 3, with the tape secured at fixed points between joints using 3d printed clamps, deployed such that reflectors were located at the centre of each clamp. The rotation of a robot joint causes a change in the relative angle between the two ends of the tape segment bounded by the reflectors. For example, joint 1 is monitored by relative changes in the phases of the interferometers formed between the reflectors located in the two fibres at positions R1 and R2 along the tape, from which the angle can be calculated using equation 2.

#### 4. EXPERIMENTAL SETUP AND RESULTS

The constructed measurement tape was used to monitor changes in the angles of three joints of the 5-axis robot arm shown in Figure 3. A python script was used to control the robot joint and synchronise the recording of data

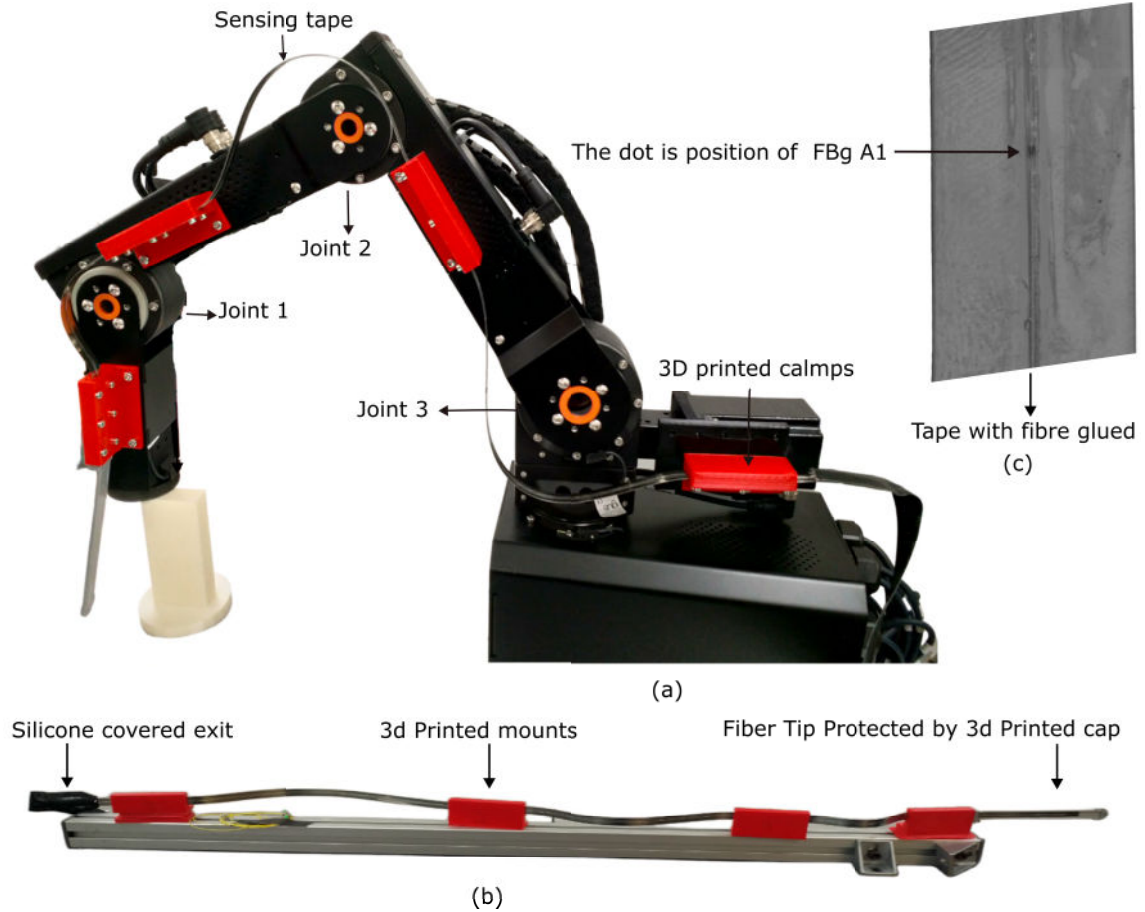


Figure 3. Photograph of the measurement tape installed on the robot arm. (a) Robot (b) Sensing tape (c) Detailed view of sensing tape

from the FSI interrogator with that from the robot's rotary encoders. In the experiment described here, joint 3 was moved while the other two joints remained at rest. Joint 3 was moved from  $0^\circ$  to  $60^\circ$ , followed by a pause for 10 seconds to allow data to be recorded with the robot stationary. The angle of the joint was then returned to its starting value ( $0^\circ$ ). This was repeated for 10 cycles, with the time series of the acquired data shown in Fig. 4. Figure 4 (a) shows good agreement with the expected motion of the robot joints. Figure 4 (b) shows an enlarged view around the  $60^\circ$  position, where it can be seen that the offset between the measured and expected joint angle is  $\pm 0.005^\circ$ . As the robot joint employs stepper motors, it is not clear whether this discrepancy is due to the measurement system or due to the actual robot positioning uncertainty. Future work will investigate the accuracy of the sensing tape.

The rapid increase and then decrease of the rotation angle measured at the end of the stationary phase, shown in Figure 4 (b), may be indicative of backlash in the stepper motor. This demonstrates the high sensitivity of the sensing tape, as the movement of  $0.03^\circ$  is clearly resolved. The movement was not resolved by the robot's built-in encoders. A lower limit on the resolution of the angle sensing tape measurements can be estimated from the noise present when the joint is stationary, suggesting a resolution of approximately  $0.005^\circ$ . Similar results were found when analysing the measurements for the other 2 joints. Figure 4 (c) shows the measurements obtained from the sensing tape for joints 1 and 2 during the time when joint 3 was being moved. The apparent movement of the joints that were meant to be stationary is not believed to be cross-talk, rather it is thought to be a real movement arising from a change in the moment acting on the joints, and the response of the servo to bring the joints back to their set position. This is the subject of further investigation.

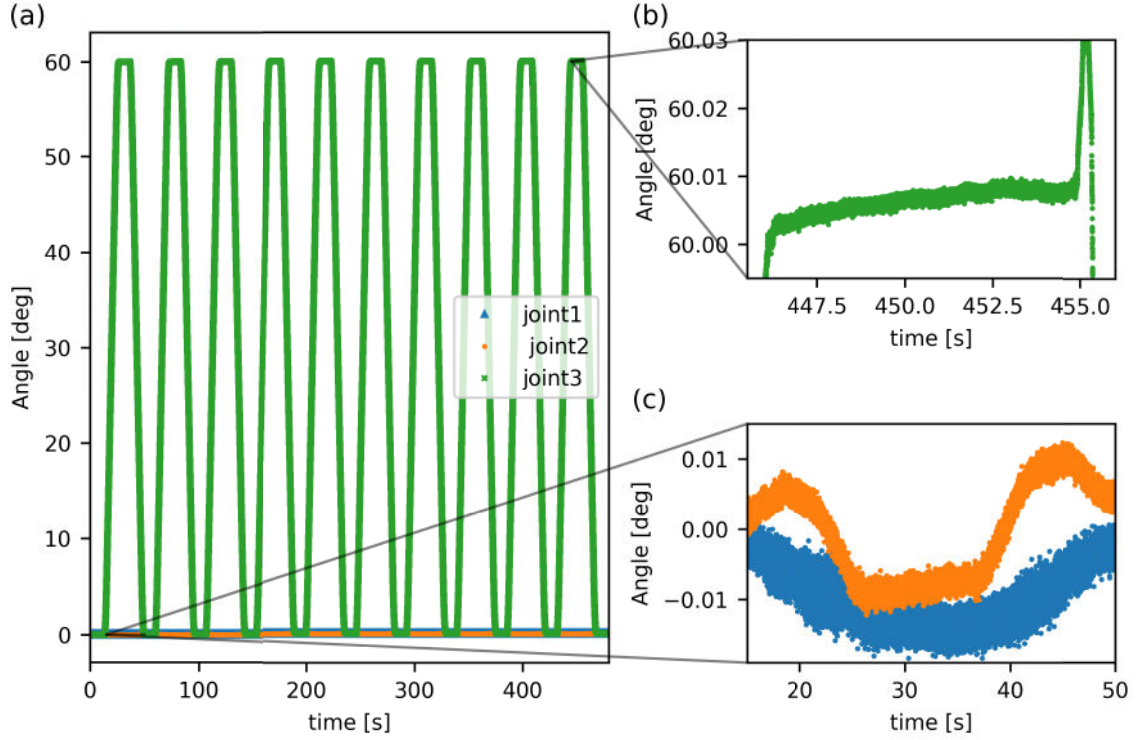


Figure 4. Robot joint angles measured using the sensing tape when joint 3 was rotated repeatedly between  $0^\circ$  to  $60^\circ$ , with a pause of 10 seconds

## 5. CONCLUSION

A fibre optic based angle sensing tape, which allows the multiplexed measurement of multiple robot joint angles has been described. Exploiting the high resolution fibre segment interferometry technique, the data obtained from the sensing tape agreed to within a range of  $\pm 0.005^\circ$  with the measurements obtained from the in-built robot encoders. However it is currently unclear whether this is really a measurement bias or a limitation of the robots angular control. The measurement precision/resolution of the tape was estimated from the noise on the stationary joints to be around  $0.005^\circ$ , however it is believed that the data may have been influenced by vibrations from the robotic arm. This achievable accuracy and precision will be investigated in future work using a high resolution reference angular measurement system.

## 6. ACKNOWLEDGMENTS

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