

Shape Sensing of Miniature Snake-Like Robots Using Optical Fibers

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Abstract—Snake like continuum robots are increasingly used for minimally invasive surgery. Most robotic devices of this sort that have been reported to date are controlled in an open loop manner. Using shape sensing to provide closed loop feedback would allow for more accurate control of the robot's position and, hence, more precise surgery. Fiber Bragg Gratings, magnetic sensors and optical reflectance sensors have all been reported for this purpose but are often limited by their cost, size, stiffness or complexity of fabrication. To address this issue, we designed, manufactured and tested a prototype two-link robot with a built-in fiber-optic shape sensor that can deliver and control the position of a CO₂-laser fiber for soft tissue ablation. The shape sensing is based on optical reflectance, and the device (which has a 4 mm outer diameter) is fabricated using 3D printing. Here we present proof-of-concept results demonstrating successful shape sensing — i.e. measurement of the angular displacement of the upper link of the robot relative to the lower link — in real time with a mean measurement error of only 0.7°.

I. INTRODUCTION

Minimally Invasive Surgery (MIS) is a widely adopted technique due to the many potential advantages it holds for patients. These include reductions in both healing times and the lengths of time for which patients are hospitalized. A number of approaches have been reported for MIS, with one of the most advanced involving the use of a snake-like robot as a single port surgery instrument [1], [2], [3]. The snake-like robot is inserted through a natural orifice and is directed towards a chosen surgical site. Small instruments are then deployed at the head of the robot to perform minimally invasive surgical tasks (e.g. cutting, suturing, etc.). These instruments need to have a small diameter of below 3-4 mm such that they can be inserted through working channels or biopsy ports within the snake-like robot. In addition, ideal instruments should be inexpensive and disposable to allow for sterile operation. For these reasons, the instruments themselves need to be kept as simple as possible, with complex components such as motors being transferred to the proximal end.

Multiple different designs are published to design small instruments. The targeted design focused is tendon-driven based on the design published by Shang [1]. It consists of rigid links connected by alternating hinges. This allows to position the end effectors in four dimensions. Figure 1

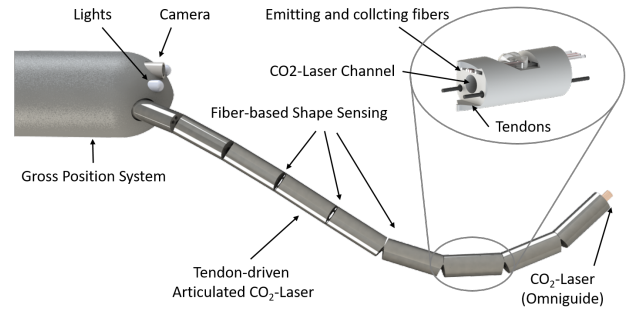


Fig. 1. A gross positioning system equipped with a shape sensing, tendon driven robot. The robot uses optical fibers to measure the angle of each joint and a CO₂-laser fiber is delivered through the central working channel.

depicts the intended use of our system. The instruments are controlled by changing the tension in the tendons to match the desired position of the master interface being used by the practitioner. This is achieved by calculating the motor values with inverse kinematics. The resulting position is only well defined within a certain range, due to tendon stretching, backlash and other inaccuracies. Shape sensing can be used to validate and correct the position of the end-effector in a closed loop manner. In the case of fiber delivered devices, shape sensing and closed loop control are particularly important as excessive bending can cause damage to the CO₂-laser-fiber.

Most robotic instruments for MIS that have been reported to date are controlled in an open loop format with no feedback information available. Notable exceptions include Fiber Bragg Gratings (FBGs) for shape sensing [2], [4], [5], optical reflectance sensors for shape or force measurements [6], magnetic displacement sensors [7], and electromagnetic (EM) tracking systems [8], [9]. Zhang et al. [10] also suggested the use of inertial sensors for shape sensing, and a more complete review of shape sensing technologies applied to snake-like robots can be found in reference [3]. While FBGs are capable of providing precise shape sensing in three dimensions, expensive spectrally resolved detectors are usually required. Furthermore, if commercially available devices are not suitable for a given task then fabrication of the FBG sensors can be complex and challenging. Magnetic shape/displacement sensors and EM tracking systems can also offer high precision measurements, however, the embodiments reported to date either incorporate stiff cables into the robot or require the use of external magnets for readout.

All of these have obvious drawbacks for MIS. Fiber-optic

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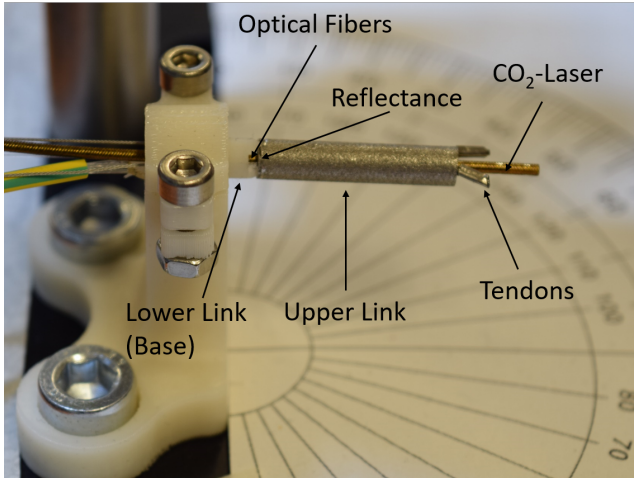


Fig. 2. The proof-of-concept test scenario: Two links connected with a hinge actuated by two tendons. Optical Fibers at the end of the lower link and a reflective surface on the upper link.

reflectance measurements can be deployed in a variety of formats using small, low cost components (e.g. unmodified fibers, laser diodes or light emitting diodes, and phototransistors or other single channel detectors) and relatively simple fabrication procedures. Ideally, shape sensors used for robotic MIS need to be small enough to be integrated into the instruments of a snake-like robot without increasing the tool size or reducing the flexibility. Thus, they are well suited for use in small scale snake-like robots [2].

In this article we present a two-link proof-of-concept snake-like robot with a 4 mm outer diameter and with integrated optical shape sensing based on reflectance measurements (illustrated in Figure 1).

II. METHOD

A. The Prototype Test Setup

In this paper, a single joint prototype is used to assess the sensing capability of the proposed concept, as shown in Figure 2. The design is based on the design published by Shang in [1] which is used as starting point for the development of the instruments for the new snake-like robot. The two links of the joint contain a central hole to allow delivery of the CO₂-laser fiber and two smaller holes at the edge of the robot through which motor-driven tendons are used to provide motion control. We tested a range of different theoretically valid joint designs and selected the one with the best light response. The joint design is described in Section II-D and the iterative design process is discussed in more detail in [11]. The upper link was printed in metal with the base polished to produce a flat and highly reflective surface. The lower link was printed in ABS plastic to allow precise fabrication of channels for the shape sensing optical fibers. This lower link was clamped in place (using a 3D printed mount) on an optical breadboard. Five optical fibers were secured in the lower link of the robot to measure the bending angle of the two-link joint by collecting light

reflected from the polished surface of the upper link (the light was delivered by the central optical fiber — see Section II-B). Custom control software was used to control the robot with two motor controllers (Maxon EPOS Module 36/2, Maxon Motor AG, Sachseln, Switzerland), which steered two brushless EC motors (Maxon EC13, Maxon Motor AG, Sachseln, Switzerland). The motors were used to drive the robot by altering the tension in the two tendons. To test the shape/angle sensing we programmed a continuous motion, which drove the robot from right to left and back again over the entire range of the joint. This motion was observed using a C920 HD webcam (Logitech, Switzerland) mounted directly above the robot joint (see Figure 2 and Section II-F). The light intensity collected by each optical fiber was recorded by phototransistors as the robot moved and these intensity values were correlated to the bending angle using a multi-layered perceptron (MLP) machine learning algorithm in order to demonstrate shape sensing.

B. Optical Setup

In order to provide shape sensing — i.e. measurement of the bend angle of the robot joint — we incorporated five optical fibers into the lower link of the joint. These fibers were manually positioned using a 10x stereo microscope and were fixed in place using glue (see inset of Figure 3). The base of the upper, metallic link of the joint was polished (see Section II-E) such that it was highly reflective at visible wavelengths. The fibers were aligned in a horizontal plane perpendicular to the joint's rotation axis. The central fiber was then used to deliver light from a supercontinuum laser (Fianium WL-SC-400-4, NKT Photonics A/S, Birkerød, Denmark) while the outer fibers collected the light reflected back from the upper link of the robot joint. As the bend angle was adjusted, the amount of light coupled into each of the four collection fibers changed, and this effect provided the underlying basis for the shape sensing.

To read out the shape sensing signal from the optical fibers, we built a compact optical system that acted to couple light into the delivery fiber and to direct the collected light onto phototransistors for detection. The layout of this system is shown in Figure 3. The output from the supercontinuum laser was collimated and focused into the delivery multimode optical fiber (MMF1) using a pair of lenses. A variable neutral density (ND) filter was placed in the beam path in order to permit control of the optical power without affecting the spectral features of the beam, and a 50/50 beamsplitter directed half of the input light onto a phototransistor to allow measurement of the laser power. This input measurement was included to allow us to correct for variations in the laser power. The proximal end of the delivery fiber was mounted in a 3-axis alignment stage such that the coupling into the fiber could be optimized. The proximal ends of the four collection fibers (MMF2-5) were mounted in front of phototransistors for detection. Prior to laser alignment and positioning of the fibers in the robot joint, each of the optical fibers were cleaved at both ends using a manual cleaving tool (Swift CI-02 Cleaver, Opticus) to ensure that the fiber end faces were

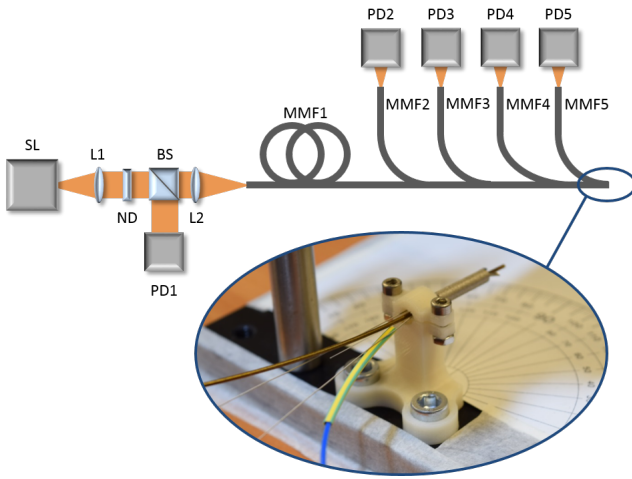


Fig. 3. Optical setup used to address the shape sensor in the base of the single-joint robot. Inset is a photograph of the robot showing the sensing optical fibers, tendons and CO₂-laser fiber entering at the base of the device. Abbreviations: SL — supercontinuum laser; L — lens; ND — neutral density filter; BS — 50/50 beam splitter; PD — phototransistor; MMF — multimode optical fiber.

flat and provided optimal coupling and transmission.

Multimode optical fibers with core diameters of 200 μm and total diameters (core + cladding) of 225 μm (FP200URT, Thorlabs, Inc.) were chosen for use in the robot joint. These fibers had a high numerical aperture (NA) of 0.5. The NA defines the divergence (and collection) angle (θ) of the light emitted from (and collected by) the fibers as

$$\theta = \arcsin(NA/n) \quad (1)$$

where n is the refractive index of the surrounding medium ($n \approx 1$ in this case, as the surrounding medium was air). Thus, for the fibers used in these experiments, $\theta \approx 30^\circ$.

Considering this divergence/collection angle, the lower link of the robot joint was designed with a cutaway at which the fibers were fixed, such that they sat approximately 1.42 mm from the polished surface of the upper link. The three central fibers were positioned directly adjacent to one another (i.e. with the cores separated only by the fiber claddings) in a single cylindrical hole in the center of the base link. The outer two fibers were secured a further 1 mm from the central fiber in two additional cylindrical holes (see Figure 4). This configuration ensured that sufficient light was collected by the optical fibers to provide shape sensing over a 35° range of bend angles. Importantly, this range was larger than the maximum bend angle of the CO₂-laser fiber, meaning that shape sensing was achieved over the complete extent of the robot's motion.

C. Sensor and Micro-Controller

We measured the data from the phototransistors while the robot moved through a series of bend angles. We used two different sensors (phototransistors) for light detection: two Everlight Sidelooker Phototransistors (PT928-6B-F) and two Kingbright Ambient Light Photo Sensors (KPS-3227SP1C).

We tested if one type of these sensors would receive more light. But we figured out that this is not the case. These sensors react to light by opening and allowing a current to flow. The analog-to-digital converter (ADC) of a PSOC micro-controller was used to measure an output voltage for each phototransistor on the pins between V_{ssa} ($= 0V$) and V_{dda} ($= 5V$). The phototransistor current was transformed into a voltage using a resistor, which specified the dynamic range of the sensor. We used 33 k Ω resistors, as the light intensity at the phototransistors was relatively low, particularly for the two outer collection fibers. We adjusted and optimized this resistance in order to obtain the highest possible signal while maintaining safe phototransistor current values.

The PSOC micro-controller was chosen to control and read out the sensors due to its range of embedded components, such as the ADC_SAR, multiplexer and RS485. The ADC was used to convert the analog signal into a 12 bit digital signal. After analog-to-digital conversion we used the RS485 to send the measured data to a PC, where it was processed and recorded.

D. Joint Design

We tested a variety of options for fixing the fibers including individual or shared channels, straight or angled channels, different channel widths, and different channel locations. We began by using a link published in [1] with no central cutaway and with fibers placed on both sides. However, the reflected light was not efficiently collected by the detection fibers. We discuss the development of the joint in detail in [11].

After optimizing, the fiber channels allowed for accurate positioning of the fibers. The design of the final link that was used to collect the data presented below is shown in Figure 4. This figure shows the important features of the design including the optical fibers used for shape sensing, the tendons used for angle control, the central hole for delivery of the CO₂-laser fiber, the joint hinge, and the window used to secure the sensing fibers. A cutaway was manufactured so that the fibers were positioned on a flat surface at a known distance from the upper reflective surface which is flat for efficient polishing. As is typical in fiber-optic sensors, the alignment of the fibers was crucial, and small changes in the fiber positions had large effects on the light collection efficiency. We also incorporated a window into the design, which was used to fix the fibers in place in a simple and effective manner using a glue gun. Finally we tested several cutaway heights with the final cutaway being 1.42 mm. In this arrangement, we observed good signal on all four phototransistors.

E. Manufacturing

The two links of the robot were fabricated using additive manufacturing technologies. Two separate 3D printers were used. The base joint (Figure 4) that carries the CO₂-laser fiber and holds the sensing fibers was printed in ABS plastic using an Ultra 3SP HD printer (EnvisionTEC, MI, USA). This printer uses the 'scan, spin and selectively photocure'

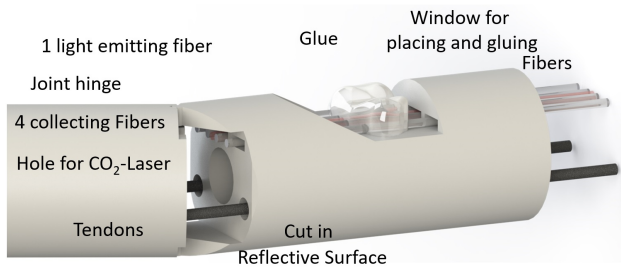


Fig. 4. The final design of the lower link of the robot, in which the shape sensing optical fibers were fixed. The other important features of the link are also indicated

technology (3SP), which operates a laser to cure a liquid material in a similar manner to stereolithography. This printer has a voxel resolution of $50\ \mu\text{m}$ and a large build plate. As such, it allowed printing of large parts with features small enough to precisely hold the five $225\ \mu\text{m}$ diameter sensing fibers in a parallel alignment. Many different shapes and sizes of guiding hole were investigated before a satisfying result was obtained (see Figure 4 and Section II-D). ABS plastic was chosen rather than metal as it is softer and, hence, protected the fibers from being scratched during assembly. The upper link of the robot with a reflective base was printed in stainless steel using an Mlab metal 3D printer (Concept-laser, Lichtenfels, Germany). This printer uses the selective laser melting (SLM) technology that operates a laser to melt material layer by layer. The base of the printed link was then polished manually to ensure a smooth and reflective surface to efficiently reflect the light from the delivery fiber back to the collection fibers. During the prototyping phase, the reflection profile of the laser light appeared to be extremely sensitive to the small surface asperities caused by the 3D printing process. To address this issue a polishing tool was manufactured to ensure that a smooth, flat surface could be reliably produced.

F. Shape Sensing Evaluation

In order to evaluate the shape sensing capability of the prototype robot, we built a test rig in which the base link of the joint containing the optical fibers was fixed directly below a webcam (Logitech HD Pro Webcam C920). The webcam was mounted above the joint and recorded the angular displacement as the joint was periodically rotated over the entire range of its motion. An angular measurement chart (i.e. a protractor) was positioned below the robot joint (see inset of Figure 3) such that the angle of the joint could be measured manually for any given image frame after the collection of a dataset. The webcam video was recorded alongside the phototransistor intensity values such that the angular displacement could be correlated to the corresponding phototransistor intensities. Correlated intensity and angle data points of this sort were then used as separate training and test datasets for a MLP machine learning algorithm (see following section) that was used to convert the optical signals into angle measurements.

G. Multi-Layered Perceptron Based Angle Prediction

To calculate the angle using the values from the phototransistor sensors we need a function $f(S_t) = a_t$, where S_t is the set of intensity values from the phototransistors at time t and a_t is the corresponding angle. This function is five dimensional and thus not simple to determine. For that reason, we used a machine learning technique called multi-layered perceptron (MLP) to ascertain the function $f(S_t)$. MLPs are a subcategory of artificial neural networks and are specialized on function approximation. The MLP takes a dataset of input values with their corresponding output values also provided, and uses back-propagation of errors to iteratively adapt a weighted sum over all input values until an optimized mapping onto the output values is determined — i.e. until the error in $f(S_t) = a_t$ has been minimized. Once this training process is complete, the optimized function $f(S_t)$ can be used to calculate an unknown angle, a_t , for a given set of input intensities, S_t .

To apply the MLP to our system, we collected training and test datasets with the previously introduced setup. The sensor values were read by the micro-controller and recorded on the PC, and the webcam was used to record the exact position of the joint (see Section II-F). An incremental number was displayed in both the data log and the webcam video such that each frame could be associated with the corresponding sensor values. Training data points were extracted manually from the video frames (see Section II-F) and correlated to the related sensor values. The training set consisted of 52 data points recorded at two second intervals. This dataset can be seen in Figure 5 where the red dots represent the manually measured angles. We first used all four sensors and then reduced the number of sensors to three.

The optimized function output by the MLP training regime had three input nodes — one for each sensor — and one output node, which represented the angle. In addition, five hidden nodes were required to obtain a satisfactory angle prediction. After collection of the training set and calculation of $f(S_t)$, we tested the optimized MLP function on a series of 74 test data points. The results of these test are presented in Figures 6 and 7.

III. RESULTS AND EVALUATION

A. Shape Sensing Proof-of-Concept

In the optimum joint design we used four out of five optical fibers for the shape sensing measurements, one to deliver illumination and three to collect the reflected light and deliver it to the phototransistors. The raw signals recorded by the four phototransistors in this arrangement are shown in Figure 5. The data is plotted as a function of time as the robot joint was rotated through two cycles of 35° (i.e. 17.5° either side of the central zero position).

In addition to the phototransistor intensity values, the manually measured bend angle is also plotted on this graph, with the values displayed on the secondary y-axis on the right hand side. Thus, Figure 5 demonstrates how the phototransistor intensity values vary as a function of angle. It

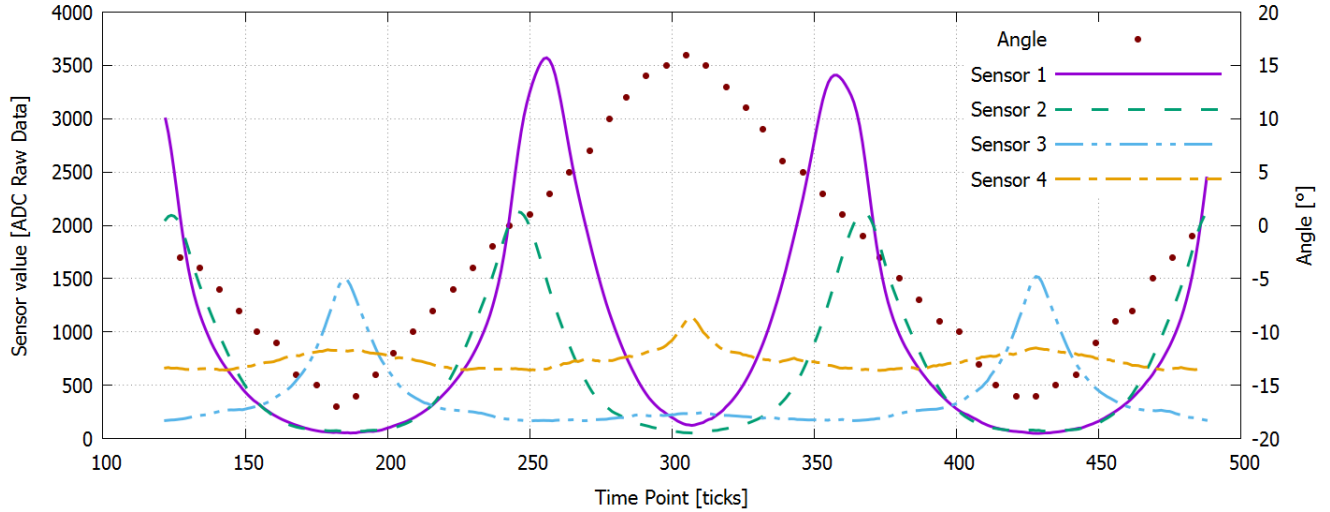


Fig. 5. Phototransistor intensity values and corresponding manually measured angles plotted as functions of time as the robot was rotated through its entire range of motion. Note that the intensities recorded by sensor 4 have been multiplied by a factor of five to account for the low signal levels recorded by this transistor. This explains the high background level observed with this sensor.

is clear from the graph that the observed signals respond to changes in angle in a repeatable and predictable manner, suggesting that they can be used to provide a readout of the angle. Sensors 1 and 2 correspond to the fibers directly adjacent to the central emitting fiber. These detect peak signal levels for angles close to the central point (0°), which occurs at time points 243 and 360. The signals from both sensors 1 and 2 decrease to zero beyond angles of approximately -10° and $+13^\circ$ (which correspond to turning left and right respectively). Thus, this implies that these two fibers alone could provide shape sensing within this range.

The 4th and 5th fibers (sensors 3 and 4) were placed further from the central emitting fiber (one on either side) and, hence, acted to increase the dynamic range of the angle measurements. While training the MLP we found out that using sensors 1-3 was enough to determine the angle without loosing precision. As such, the third fiber is enough to increased the range of sensing from approximately

$-10^\circ < \theta < +13^\circ$ to approximately $-17^\circ < \theta < +17^\circ$. The measurement range could be increased further simply by incorporating more fibers (at wider positions) into the robot joint or by using fiber arrangements with wider collection angles (e.g. higher NA fibers or fibers with distal lenses).

Similarly, the sensor setup used in the joint could be simplified if smaller angle sensing ranges were required. For example, as discussed above, sensors 1 and 2 alone could be used to provide sensing over the range -10° to $+13^\circ$. A single detection fiber could also offer sensing over a similar range, however, this would not provide direct measurements of the direction of the turn — i.e. there would be uncertainty between, for example, -10° and $+10^\circ$. Nonetheless, this could be mitigated by using the motor control values to ascertain the direction of motion and then using the phototransistor value to calculate the magnitude of the angle.

Overall, Figure 5 demonstrates that the fiber arrangement used in the prototype robot joint was suitable for shape sensing. The signals detected varied predictably with angle over a range of approximately 35° . In order to convert these variations into direct measurements of the robot bend angle we used a machine learning approach, and this is discussed in the following section. The result can be seen in Figure 7. We reached a absolute mean error of 0.71° . The angle was in the limit of 1.5° for 90 per cent of the time and in 2° for 98 per cent.

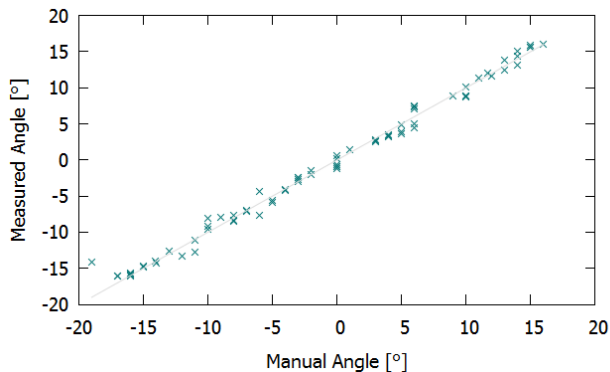


Fig. 6. Plot of the angle measured using the optical sensor and the MLP algorithm as a function of the manually measured (ground truth) angle. The graph shows a linear $y = x$ relationship indicating excellent agreement between the values from the optical sensor and the ground truth.

B. Multi-Layered Perceptron Results

As discussed above, it is evident that the intensities recorded by the phototransistors were strongly affected by the angle between the lower and upper links of the robot joint. In addition, the changes observed appeared repeatable and predictable (Figure 5). The trained MLP was tested on a series of 74 randomly chosen data points (recorded after the training set) and the calculated angles were plotted

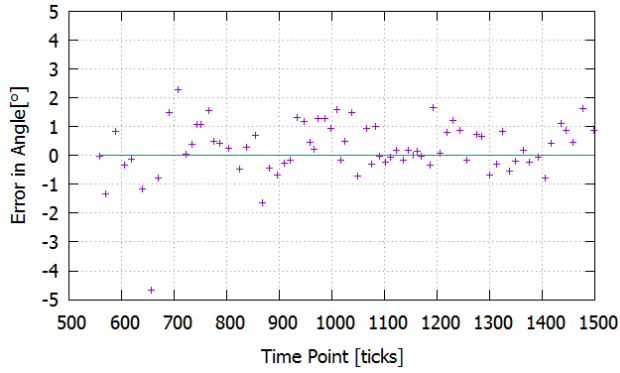


Fig. 7. Error in the optically measured angle for the same data points shown on Figure 6 but using only three sensors.

as a function of the manually measured angles. As shown in Figures 6 and 7, the angles calculated by the MLP were in excellent agreement with the manually measured values. We calculated the average error in the optical angle measurement (i.e. the mean difference between the MLP values and the manual values) as 0.7° . Furthermore, once the training was complete, optical angle measurements could be performed in under 0.5 s. The time taken to output an angle measurement was limited by the low frequency at which the micro-controller was operated in these proof-of-concept experiments and, hence, this could easily be improved in the future. Despite the slow operation of the micro-controller, the results nonetheless indicated that that our system was capable of real-time shape sensing with an update rate of approximately 2 Hz.

IV. CONCLUSIONS

In this article we have presented a prototype, single joint robot. This prototype contains an integrated optical shape sensor — using four multimode optical fibers (out of five) — to provide measurements of the bend angle between the two links of the joint. This angle measurement can be extended to shape sensing of an instrument consisting of rigid links connected with alternating hinges. We have demonstrated proof-of-principle results illustrating that this approach can provide accurate, real-time shape sensing over a 35° bending range (i.e. over the entire bending range of the robot joint used in this study) with an average error of approximately 0.7° . We have further shown that a reduction of the fibers should be feasible, since we got a similar mean error of 0.71° training a neural network with only the first three fibers.

Integrating shape sensing (using this approach or others) into snake-like robots will provide improved control during surgery and, hence, will offer clear advantages in the field of MIS. As such, our future work will focus on extending the proof-of-concept device presented here to a multi-joint system with shape sensing incorporated into all joints. Since this is a demonstration of the principle based on the assumption of a controlled environment, some restrictions are still to overcome:

- To establish shape sensing in an entire robot four fibers per joint are a lot. Space and stiffness issues might appear. Combining the small fibers to a single fiber bundle will overcome the size restriction and reduce the stiffness.
- The influence of the environment on a sheath covered instrument (water condensation, smoke, etc.) has to be investigated.
- The update rate of the sensor is not extensively explored and can certainly be increased. This is necessary to enable closed loop control.

Such a device would allow for dexterous, closed loop control of an articulated CO_2 -laser fiber, with feedback provided in three dimensions by the optical sensors. Importantly, feedback of this sort could be used to ensure that the bend angles of individual joints remain within safe zones in which the CO_2 -laser fiber, the robot itself, and the surrounding tissue are all protected from damage caused by excessive bending.

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