Towards a flexible polarimetric camera-on-tip miniature endoscope for 3x3 Mueller matrix measurements of biological tissue

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1. INTRODUCTION

The interrogation of polarisation state of light is a developing technique in biomedical imaging. As polarised light interacts with structural changes in tissue, it has seen use in differentiation between (pre)cancerous and non-cancerous tissue, for example.[1] In biomedical imaging rapid diagnostics using minimally invasive techniques is desirable. Endoscopy is already very prevalent in medicine and therefore miniaturisation of polarimetry systems onto endoscopic platforms is a natural development. Flexibility of such a device allows navigation to more complicated parts of the body. All polarimetric systems consist of a polarisation state generator (PSG) and a polarisation state analyser (PSA) which need to be integrated into such a system.

A rigid endoscope capable of imaging a full 4x4 Mueller matrix has been developed by Qi et al.[2] This endoscope achieves the polarisation state generation a rigid rotating sheath. Partial polarimetric endoscopy which captures a 3x3 Mueller matrix has also been demonstrated and is easier to achieve since it does not require quarter wave plates in the generator or analyser. Clancy et al and Qi et al both demonstrate a rigid polarimetric endoscopy using a stereo endoscope and a standard rigid endoscopy, respectively.[3,4] Integration of polarisation state analyser and generator into the tip has been demonstrated using complex mechanical designs.[5] However questions have been raised regarding the electromagnetic compatibility of such a system due to the presence of motors in the tip.[6] Forward et al present a flexible 3x3 fibre based probe that uses diced polarisers orientated at the horizontal, vertical, and -45 degree positions to generate and acquire the necessary polarisation states.[7]

This work presents an imaging probe designed to enable *in-vivo* polarimetry measurements using a micro camera on the tip as a sensor. A 3x3 Mueller matrix image of crossed linear polarisers, captured using a micro camera is demonstrated. This device demonstrates the potential of micro camera sensors in providing 2-dimensional polarimetry data in a flexible endoscopic system. For a device to be used in a clinical setting it needs to be capable of providing data rapidly when it is needed, as well as being navigable to the target location. A fibre optically illuminated endoscope with micro-camera sensor allows for rapid switching of illumination fibres using backend illumination systems as well as rapid acquisition of data. Optical fibres enable the probe to be rigid or flexible depending on application, and the camera at the tip ensures consistent image quality regardless of application area. An idealised system and its potential future of polarimetry in translational biophotonic devices is also discussed.

2. DESIGN

The design in Figure 1 utilises diced polarisers mounted in front of six illumination fibres that act as the PSG. These fibres are concentrically arranged around a central camera with opposite pairs of fibres illuminating with the same polariser orientation to provide an even illumination over the field-of-view of the camera. The camera sits fixed within core component (indicated grey). The inner sheath (indicated in cyan) is allowed to rotate freely

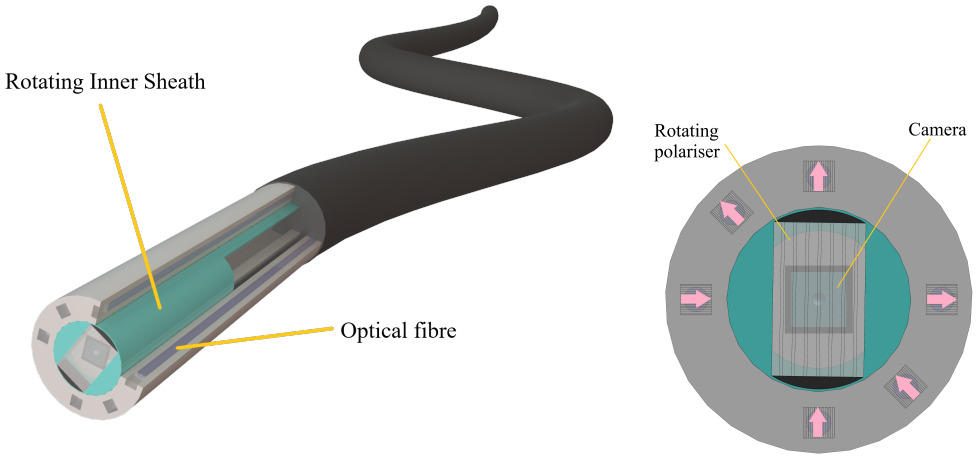

Figure 1. Probe design with sectioned view of the outer sheathing (L) and close up view of the distal end (R). The outer shell is part of a core component (indicated grey) which also connects to the camera housing in the center. The inner sheath (indicated cyan) is allowed to rotate freely within a limited range of motion inside this core component. In the close up view the polariser orientations are indicated using the pink arrows, the camera can be seen in the centre with the PSA polariser mounted in front of it on the inner sheath.

between angles of 0 and 90 degrees within this core component. This inner sheath includes a mount for a larger polariser that sits in front of the camera.

The probe tip is designed to be is 7 mm in length, and 5 mm in diameter, with mechanical validation to follow. In theory the length of this distal end is variable and must at minimum support the length of the camera and more importantly secure attachment to the rotating inner sheath. Rotation will be achieved using a stepper motor, integrated proximally with a torque coil to transfer rotation along the length of the device. The initial design however, includes a rigid rotation mount to more accurately control the rotation at the distal end.

3. METHODS

Linear glass polarisers (Edmund Optics 12-649) are diced using a mechanical dicing saw to the required dimensions and mounted in front of the fibres. The polarisers are orientated at 0, 45, and 90 degrees with respect to the zero axis of the probe as shown in Figure 1. All components are integrated into a 3D printed components and secured using UV cure epoxy (Norland NOA68). A monochrome AMS NanEYE image sensor, with 90 degree field-of-view (FOV) and F2.7, is used as the sensor. Six illumination fibres 400 μm with numerical aperture of 0.5 are arranged concentrically around the micro-camera, ensuring that the FOV of the camera is illuminated sufficiently. Two illumination fibres are active for each polarisation state generated to ensure an even illumination over the FOV of the camera for each image captured.

Figure 2 shows a microscope image of the assembled tip of the system with a 5 mm diameter. The large central polariser is allowed to rotate freely around the camera by rotating the back of the innner sheath. Optical fibres are mounted behind the polarisers. Tolerances will be tightened in future iterations of the design.

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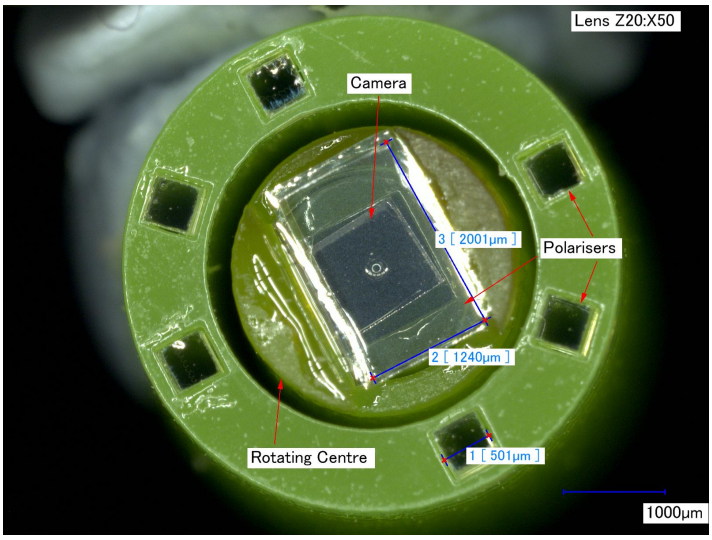

Figure 2. Image of the 3D printed holder with integrated polarisers concentric around the camera, and the rotating centre piece with larger linear polariser.

4. RESULTS

Figure 3 shows results captured using a micro camera with rotating polarisers. To the best of the authors' knowledge these are the first Mueller matrix images captured using a micro camera.

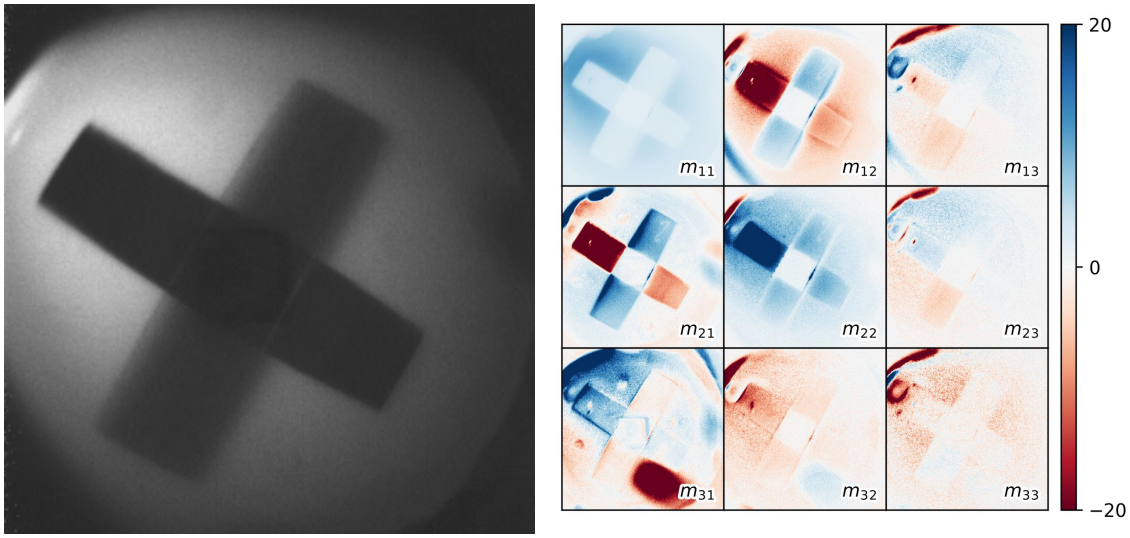

Figure 3. Image of crossed plastic polarisers on a white tissue phantom acquired using AMS NanEYE camera, PSG set to 90 degrees and PSA set to 0 degrees (L) and 3x3 Mueller matrix images of the same region (R). Analysis code used.[8]

5. DISCUSSION AND CONCLUSION

A design for a miniaturised camera on the tip endoscope with 3x3 polarimetric capability is presented. With Figure 3 demonstrating the ability to resolve a polarimetric measurement using a micro-camera. Another proposed design uses a MEMS device to rotate the polarisation optic in front of the camera.

A monochrome image sensor allows for the full utilisation of the pixels per measurement run, and since polarimetry is usually performed at a single wavelength at a time makes the most sense for the device. Illumination

fibres are preferred over LEDs in illumination as they provide flexibility in the delivered illumination as well as remove concerns of heating effects and electrical safety in the body. Fibre illumination also allows for potential extension of the system to the broadband system using multiple illumination wavelengths. Illumination with fibre bundles can allow for greater numerical aperture to improve the illumination if overlap is problematic in the final probe.

An idealised device would use a polarised camera sensor (such as the Sony IMX250MZR) in the micro camera format. However currently a sensor like this is not commercially available. The disadvantage of such a sensor in the small footprint would be the pixel utilisation, with only a quarter of the pixels available for each image. An alternative is a polarisation rotator in the micro format mounted in front of the camera and electrically controlled. With the inclusion of variable retarders of sufficiently small footprint mounted in front of two of the illumination fibres and in front of the camera, a 4x4 mueller matrix imaging system would be theoretically possible at this scale.

In conclusion we have demonstrated acquisition of a 3x3 Mueller matrix using a micro camera system, as well as the integration of such a system into a small footprint endoscope tip.

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REFERENCES

[1] Singh, M. D., Ghosh, N., and Vitkin, I. A., [*Mueller Matrix Polarimetry in Biomedicine: Enabling Technology, Biomedical Applications, and Future Prospects*], 61–103, Springer International Publishing, Cham (2023).

[2] Qi, J. and Elson, D. S., "A high definition mueller polarimetric endoscope for tissue characterisation," *Scientific reports* **6**(1), 1–11 (2016).

[3] Clancy, N. T., Arya, S., Qi, J., Stoyanov, D., Hanna, G. B., and Elson, D. S., "Polarised stereo endoscope and narrowband detection for minimal access surgery," *Biomedical optics express* **5**(12), 4108–4117 (2014).

[4] Qi, J., Ye, M., Singh, M., Clancy, N. T., and Elson, D. S., "Narrow band 3× 3 mueller polarimetric endoscopy," *Biomedical optics express* **4**(11), 2433–2449 (2013).

[5] Huang, Z., Fu, Y., Li, Z., and Wu, J., "A portable 3× 3 mueller matrix polarimeter prototype for cancer detection ex vivo," in [*Proceedings of the 3rd International Conference on Biomedical Signal and Image Processing*], 92–97 (2018).

[6] Qi, J. and Elson, D. S., [*Polarimetric Endoscopy*], 179–204, Springer International Publishing, Cham (2023).

[7] Forward, S., Gribble, A., Alali, S., Lindenmaier, A. A., and Vitkin, I. A., "Flexible polarimetric probe for 3× 3 mueller matrix measurements of biological tissue," *Scientific Reports* **7**(1), 1–12 (2017).

[8] Ryota, M., "Polanalyser v1.2.0." https://github.com/elerac/polanalyser (2022).