An Integrated Systems Design Framework for Computational Polarimetry

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Abstract

In this study, we propose and implement an integrated systems design framework for computational polarimetry. This framework leverages knowledge of the optical elements to aid in the design of the polarimetry instrumentation and the enhancement of the measurements. This framework incorporates the use of spatial detector arrays, and models the non-ideal performance of the optical components, providing error bounds that can decrease the cost of the system depending on the accuracy needed. Noise modelling is incorporated, as well, in the measurement formation models. The framework is demonstrated in the design of a computational polarimetry system for a glucose concentration estimation.

1 Introduction

Polarimetry is a common tool for observing unique molecular properties, as well as their bulk structural characteristics. Used in combination with spectroscopy, more information can be utilised and the difference between objects in multiply scattering media and their molecules therein can be accentuated[1]. Polarimetry is a useful technique that is restricted to the lab due to the need for complex optical arrangements for accurate measurements, resulting in costly devices. In an attempt to reduce the complexity of such systems, computational polarimetry methods involving clever combinations of polarising and analysing components have been placed together to mimic more advanced methods of polarisation state capture [2, 3]. However, while less complex that traditional polarimetry systems, current computational polarimetry is more limiting in accuracy as they are often based on ideal theoretical performance. In this study, we propose an integrated systems design framework for computational polarimetry. leveraging spatial detector arrays.

2 Methodology

The proposed integrated systems design framework for computational polarimetry can be summarized as follows. First, the elements used in the optical element train are modelled based on their modulation of the observable polarisation state. The observable polarisation state is parametrised using Stokes parameters and the modulation of these parameters is modeled using Mueller matrices. These matrices can model the behaviour of elements that attenuate the orthogonal states of light (polarisers), rotate the polarisation vector (rotators) or change the relative orthogonal phase (retarders). With the use of Mueller matrices, the non-ideal behaviour can also be modelled and used as an error bound in any application.

For polarisers, the non-ideal characteristic is imperfect diattenuation of orthogonal states. Thus, the non-ideal diattenuation is characterised by extinction ratios and polarisation efficiencies.

For rotators and retarders, their performance is not quantified used singular values due to their varying performance relative to wavelength. Rotators and retarders change the polarisation of light by exploiting the birefringent nature of materials, described by their ordinary and extraordinary refractive indices. Unfortunately, the dispersion from these materials can cause error when using light sources with a spectral bandwidth. The incurred error results in unexpected rotations, as well as additional relative phase changes. In addition, there can be losses from the reflection at the interfaces [4]. The error in the relative phase retardance can be modelled using the Mueller matrix by adding an error term for the expected variance relative to the bandwidth of the light source, as well as including the non-ideal diattenuation from the absorption at the interface if non-reflection coating was not used.

Next, we model the noise characteristics of the system and choose an appropriate computational enhancement method that leverages the spatial detector array. Under low SNR conditions, a Poisson-Gaussian noise model should be considered, while high SNR conditions allow for just a Gaussian noise model. Should low SNR measurements be considered, the appropriate pixel model cannot be enhanced using conventional means, like those proposed by Haider *et al.* [5].

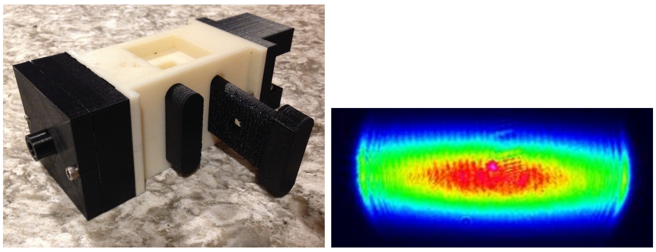

Fig. 1: Glucose measurement system (a); Spatially modulated laser spot (b)

Finally, a structural design is produced based on analysis that reduces error that can occur from oblique transmission and satisfies the spatial alignment needs of the application and computational enhancement method, simultaneously. One method for error reduction is ensuring that the polarising elements are normal to one another. This reduces the polarising and absorbing nature of oblique transmission modelled by the Fresnel equations and also reduces the error caused by elements with limiting angles of incidence [4]. Unfortunately, there is no procedure for optical alignment beyond check-correct-check-again. To remedy this issue, optical housings are proposed that ensure that the optical components are aligned and perpendicular to the optical axis.

3 Results and Discussion

We demonstrate the efficacy of the proposed integrated systems design framework by employing it in the design of a computational polarimetry system for glucose concentration estimation using single state measurements. The optical elements in the designed system consists of two parallel linear polarisers placed vertical and the detector measures the vertical polarisation state. The performance of the polarisers were modeled using Mueller matrices and the confidence intervals in the estimation of the glucose concentration was determined. The noise model was characterized based on the optical setup and the detector and a parametric estimation framework [5] was chosen based on the expected high SNR. Finally, a housing was produced based on the analysis that holds a cuvette, two linear polarisers, a laser (Thorlabs CP635S), a spatial detector array (Point Grey GS3-U3-236M-C) and an ND filter. All these components had to be assembled as normal as possible to the optical path to reduce the potential of error from oblique transmissions. The designed glucose measurement system, along with the detected spatially modulated laser spot, is shown in Fig. 1. By using this design framework, we were able to design a highly compact system with significantly reduced alignment errors that enables the use of cheaper polarising elements while still maintaining high performance. This system illustrates the potential of the proposed design framework for designing high-performance, low-cost computational polarimetry systems.

References

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