Electronic Control of Polarimeter Motors

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The purpose of this report is to detail the introduction and motivation to developing a closed loop control structure for the Advanced Sensing Laboratory (ASL) polarimeter, the process that was undertaken and the results that were observed. The objective of this project was to design and test a controller capable of meeting current deficiencies in the open loop control structure within the ALS polarimeter. The proposed solution is a four-slave configuration operating with a positional observer. Simulation of this system demonstrated mean drift of 0.0012 radian per sample over extended periods. This report outlines each stage of controller design and presents the effects the proposed solution will have on polarimeter performance, specifically the effects on the modulated optical channel structures.

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I. Introduction and Project Motivation

Over the past four decades significant advancements in the process of imaging polarimetry have enabled development in remote sensing applications, industrial monitoring and microscopy [1]. Imaging polarimetry presents a means of filling a knowledge gap in current imaging methods through the ability to manipulate optical phenomena in a way that exceeds previous hyperspectral methods. For example polarimetric imaging was recently used to provide accurate contrast between healthy and cancerous colon cells allowing for more accurate diagnosis where traditional multispectral imaging methods have failed [2].

Polarimetry involves the observation, measurement and analysis of the polarization of transverse waves. Mapping the vector qualities of an optical scene facilitates the user in gaining an appreciation of surface features, shape shadowing and roughness [1]. Polarization of light occurs through the degrees of freedom presented by Maxwell’s equations. As electromagnetic waves interact and propagate from an object the properties of the light can be formalised mathematically through the four element Stokes vector 1. This vector identifies the means in which the wave propagates which is fundamentally traced to the object from which it propagates. This analysis creates the link between the physical scene and the light from which it
propagates.

\[
\mathbf{S} = \begin{bmatrix}
S_0 \\
S_1 \\
S_2 \\
S_3
\end{bmatrix} = \begin{bmatrix}
I_x + I_y \\
I_x - I_y \\
I_{45} - I_{-45} \\
I_R - I_L
\end{bmatrix}
\] (1)

Within the stokes vector \(S_0\) represents the intensity of the total irradiance of the wave, \(S_1\) represents the linear horizontal and vertical polarization state of the wave, \(S_2\) represents the presence linear polarisation at \(\pm 45^\circ\) to the plane of propagation and finally \(S_3\) represents the circular polarisation state of the wave. Whilst \(S_0\) is easily observed and measured, the remaining elements of the Stokes vector are not due to limitations of optical sensing materials. At optical frequencies, the value of the instantaneous value of the fluctuating wave cannot be observed. Therefore to build the total mathematical understanding of a polarised wave, manipulation of the optical irradiance measurement is required. The role of the polarimeter is to make these states observable through the transfer of a series of polarisers and retarders. Mathematically this is represented through the Mueller Matrix 2. Polarimeters may be passive or active depending on whether the polarisation state of the source of the light is controlled. Within both of the these types of instruments a series of retarders and polarisers manipulate the polarisation state of the wave in a manner capable of constructing the Mueller Matrix. As a result full mathematical understanding of the time-averaged measurement over each individual pixel is made and the objective of polarimetry is achieved.

\[
\begin{bmatrix}
A_{00} & A_{01} & A_{02} & A_{03} \\
A_{10} & A_{11} & A_{12} & A_{13} \\
A_{20} & A_{21} & A_{22} & A_{23} \\
A_{30} & A_{31} & A_{32} & A_{33}
\end{bmatrix}
\begin{bmatrix}
S_0 \\
S_1 \\
S_2 \\
S_3
\end{bmatrix} = 
\begin{bmatrix}
I_0 \\
I_1 \\
I_2 \\
I_3
\end{bmatrix}
\] (2)

Prior to this project a gap was identified in the ability to maintain adequate synchronisation between the fours motors with reference to position and speed. The existing configuration operated in an open-loop configuration at a frequency of 16Hz or lower. The configuration included a polariser and two retarders linked in series with a micro-grid array of polarisers. Both of the retarders were composed of two rotating optical elements. The motors used in this setup were IntelliDrive ACR-55UT Ultra-precision rotary devices driven through a Copley Control interface. Positional accuracy was quantified through a magnetic encoder of 540,000 quadrature counts. The incorporation of Controllable Area Network (CAN) interface provides a highly suitable physical layer implementation for industrial interfaces as it facilitates the the transmission and reception of high data volumes through a standardised means [3]. Limitations in control were presented through saturation of the CAN buses within the existing configuration due to bandwidth constraints. As a result a more effective means of synchronising motor position and speed was identified as a performance requirement. The objective of this project was to demonstrate the suitability and design a controller capable of maintaining effective rotation of the retarders and polarisers used in the ASL polarimeter. The design requirements included system stability over a 30 minute test period with drift that did not lower the signal to noise ratio (SNR) of the optical channels below 50%. This involved the analysis of the problem from an optical viewpoint and a solution achieved through control engineering. Finally the project quantified the effects of motor performance on optical channel structure.

II. Method

To successfully link the optical and control components of this project, the approach undertaken aimed at gaining motivation and context for the need of controlled rotation, developing an understanding of the system plant, controlling a single motor and incorporating this design into a full system and finally linking the outputs of the control structure to the mathematical optical principles.

A. Characterisation of Optical Channel Structure

The first component of this project involved the analysis of motor wander on optical channel performance. This process was undertaken to define the requirements of the motor controller and link them to optical channel performance. Azzam first introduced the concept Fourier domain channels in 1978 [4]. He proposed a method of attaining a spectral understanding through the Fourier transform of data captured through a
dual rotating-retarder configuration. This work established the foundations used to facilitate the capture of individual Mueller matrix entries.

To commence this project, optical channel structure models were developed to include temporal parameters for motor wander at each of the four rotating elements of the ASL polarimeter. This was achieved through including a uniformly distributed vector to each motor position capture. A series of tests were then completed, altering the magnitude of this drift, to gain an appreciation of the effects drift had on optical channel measurements.

B. Characterisation of the ACR-55UT Ultra-Precision Motor

The first stage of controller design involved characterisation of the ACR-55UT motor which was the system plant. The objective of this project component was to develop a transfer function for the system. The first approach included numeric modelling of the motor using conventional brushless DC motor understanding. Similar to most DC motors, the ACR-55UT relies upon the interaction of reactive components and AC power to generate torque. At each of the 16 poles a simple model of a DC motor was generated to predict the effects of applying an input signal to the device using specifications provided by the manufacturer. The results from these simulations provided an indication of the response of the plant to a variety of input signals.

Frequency response methods were next attempted to derive the plant’s transfer function in a more reliable manner accounting for inconsistency between simulated and actual performance. To achieve this a series of sinusoidal current inputs were applied to the motor at 1A and then 3A across all possible frequencies. Due to limitations on motor inputs only two full decades of measurements were possible. The results were then analysed to derive a transfer function for the plant.

C. Control Structure Design

Following plant characterisation the process of controller design was commenced. The purpose of this project element was to design a valid control structure and to test for the necessity of an observer within the system. This progressed from testing simple compensation methods through to modified PID designs. For each iteration of experimentation Simulink was used to model controller performance in two configurations:

1. The first configuration contained a master-slave configuration whereby the reference ramp input was an input to only one motor. The output of this ‘master’ motor was then used as the reference input the other three motors in parallel. The relative angular velocity of each motor was normalised to that of motor 3 operating at 16Hz. The incorporation of the gain blocks compensated for the relative motion of each of the other motors in the ASL configuration. Furthermore the use of Gaussian noise with a mean magnitude of twice the manufacturers quoted precision was incorporated for any system imperfections. This system configuration is depicted in Figure 1.

2. The second configuration was a four slave configuration whereby each of the four motors were placed in parallel to a common ramp input. The incorporation of gain and noise sources was used in the same manner as the master-slave configuration. This configuration is represented in Figure 2.

For each of these configurations the effects of altering input signal amplitude was varied to provide evidence for the recommended system operating current. Next the observer frequency was varied between 1kHz and 15kHz to test for the validity of a positional observer within the system. High data rates associated with the positional data packets of the four motors over the CAN bus presented saturation at sample rates above 1kHz. To compensate for this saturation, a proposed solution was identified to incorporate a system observer comprised of a BeagleBone Black to monitor motor position. This solution was investigated by incorporating a sampling frequency of 15kHz into the simulated configuration.

During all experiments the position of each rotating element was referenced to the position of motor 3. This was to account for the triggering mechanism used in the physical ASL system to capture each optical sample. Due to the ability for the encoder to monitor absolute and relative position, the starting positions were irrelevant assuming the trigger mechanism was calibrated for motor 3.
D. Modelling Effects of Drift on Optical Channels

Following the simulation of the proposed system configuration the positional outputs of the model were mapped to the resulting optical channel structure. The objective of this component of the project was to identify the qualitative and quantitative effects of the control system on the optical channel structure of the ASL polarimeter. Mueller Calculus was used to mathematically derive the Fourier domain delta channels of a 64 sample measurement set under a variety of conditions. These conditions included:

1. The first optical channel simulation included a 64 sample set of ideal retarder positions. Four positional vectors were calculated in a temporal manner negating noise with the optical elements rotating at the frequencies used during testing.

2. The second simulation incorporated the same four positional vectors however also included Gaussian noise with a mean magnitude of twice the quoted precision of the system motors. This noise was
compounded over the positional vector to simulate the effects of motor wander in an uncontrolled system.

3. The third simulation incorporated a controlled system based upon the results of the proposed system controller simulation. Four ideal positional vectors were used and a Gaussian noise vector was added with a mean magnitude equal to the mean observed positional error during the simulation. The purpose of this simulation was to validate the positional accuracy of the proposed system configuration.

4. Finally a revised trigger algorithm was developed to remove the temporal or count dependency of the current ASL configuration. Rather than sampling at an even rate, or period, commencing at a known position, a spatial trigger algorithm was developed. The final optical channel simulation included the spatial triggering of the simulated positional output vectors from each of the four motors.

The method applied to this component of the project was mathematically reversing the optical interactions experienced by light in the ASL configuration represented by Equation 3. For each of the conditions tested each of the positional vectors were applied to the R matrices in this equation. The development of the spatial trigger algorithm was aimed at removing the time dependency of the sampling mechanism which relied upon certainty of the trigger count or sampling period.

\[ S_{out} = P \cdot R_{\delta_4,t} \cdot R_{\delta_3,t} \cdot M \cdot R_{\delta_2,t} \cdot R_{\delta_1,t} \cdot S_{in} \]  

(3)

III. Results

A. Characterisation of the ACR-55UT Motor

Using conventional frequency response methods the following bode plots were constructed from test observations.

![Bode Plot of Motor input of 1A](ACR-55UTMagnitudeBodePlot.png)

![Bode Plot of Motor input of 3A](ACR-55UTMagnitudeBodePlot.png)

(a) Bode Plot of Motor input of 1A  
(b) Bode Plot of Motor input of 3A

Figure 3: Experimental Frequency Response

Figure 3a represents the observed frequency response at 1A whilst figure 3b represents the observed frequency response at 3A. Numeric calculation of the plants transfer function was attempted using Matlab’s System Identification Toolbox however due to the limited observed bandwidth adequate results were not obtained. To overcome this traditional control methods contained in Ogata [6] were used to match the observed performance to an approximated transfer function.

Both Figure 3a and 3b depict a second order system characterised by the 40dB gain decline. Manufacturer guidance validated this and identified linear performance across current inputs up to 8A. As a result the characteristics common to both plots were generalised however greater weighting was placed upon the attributes of the 1A experiment. This was due to prevalence of the corner frequency and gain spike at 12Hz. The asymptote evident in Figure 3a matched the corner frequency to 11Hz with a \( \zeta \) value of 0.3. The resulting transfer function was approximated as Equation 4.
\[ H(s) = \frac{40}{-2s^2 + 20s} \] 

The transfer function identified was limited heavily by the ability to observe a suitable sample size during the frequency response observations. It is recommended that for a more accurate representation further research should be done focussing solely on accurately identifying the motor as an LTI system. To achieve this a number of possible methods could be used however the purpose of these would be to gain experimental plant response data below 1Hz and above 1kHz. This could be achieved in many ways such as using the Xenus programming language to deliver a large bandwidth chirp signal over the CAN interface. Due to the complexity of the task and time taken to reach this milestone it was determined that the best way to proceed with the project was to use the approximation identified in Equation 4.

B. Controller Performance

Following approximation of the plant various motor configurations were tested in Simulink. It was identified that due to the dominance of the poles within the right-hand 'S' plane, simple compensation methods were not possible discounting an arbitrary solution. Proportional, integral, derivative and combinational methods of controllers were attempted however due to the highly oscillatory nature of the plant these methods could not stabilise the system. Fuzzy Logic was also investigated however due to the lack of complete characterisation the development of Fuzzy Inference was not accurate enough to generate a stable controller. Proportional integral derivative control (PID) in parallel with a first order derivative filter to eliminate oscillations was the most effective means of achieving transient and steady state stability. The use of PID-F control is becoming more common in high-oscillation second order industrial applications and presented a suitable solution to this project. The four slave configuration demonstrated more accurate performance regardless of observer sampling frequency or input signal amplitude as depicted in Figure 4. These effects were more noticeable as the current input magnitude increase and also as the observer frequency increased. Within this figure the mean positional error was calculated as the average of the positional offsets of motors 1,2 and 4 normalised to the position of motor 3.

![Comparison of Motor Positional Error](image)

**Figure 4: Comparison of System Configuration Motor Positional Error**

Following the comparison of the two proposed system configurations the magnitude of the input signal was next investigated. Figure 5 represents the mean positional error of both 1A and 3A input current signals. The same method of calculating the mean offset between the motors was utilised from the previous experiment.
Following the analysis of system configuration the effects of introducing a positional observer were identified. Table 1 represents the average error as a function of observer frequency. The instability caused by sampling the position at only 1kHz stipulates the requirement for a state observer to monitor the position of each motor within this structure. The effects of saturation caused by the amount of data being transported by the CAN bus in the current configuration limits the sampling rate to 1kHz. Therefore it was identified that the BeagleBone Black microprocessor would be a suitable means of overcoming the sampling limitations of the current system.

C. Effects on Optical Channel Structure

Following simulation of the complete control system the positional output vectors were mapped to optical channel structure using the Mueller calculus described previously. Figure 6 reveals the ideal optical channel structure of the ASL polarimeter when no noise is present and each positional sample vector is ideal. Within each of the optical channel figures, observations of the magnitude of the modulated channel structures were taken along 3 planes of the 3 dimensional frequency domain. Figure 7 represents the optical channel structure resulting from uncontrolled motor wander. The effects of drift on the modulation of these channels is evident through the destruction of required channels and the generation of erroneous channels at unwanted frequencies.

Table 1: Average Positional Error over a 3 Second test period

<table>
<thead>
<tr>
<th>Input Current (A)</th>
<th>Observer Sampling Frequency (kHz)</th>
<th>Average Positional Error (radians)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>1</td>
<td>Unstable Past 0.8 seconds</td>
</tr>
<tr>
<td>1</td>
<td>15</td>
<td>0.0013</td>
</tr>
<tr>
<td>3</td>
<td>1</td>
<td>Unstable Past 0.82 seconds</td>
</tr>
<tr>
<td>3</td>
<td>15</td>
<td>0.0012</td>
</tr>
</tbody>
</table>

Figure 5: Comparison of System Input Amplitude Motor Positional Error
Figure 6: Ideal Optical Channel Structure in Frequency Domain

Figure 7: Uncontrolled Optical Channel Structure in Frequency Domain

Figure 8 represents the optical channel structure resulting from adding a positional error vector to the ideal positional vectors of each retarder at a magnitude equivalent to the system simulation results. The strong similarity between Figure 8 and Figure 6 indicates the suitability of the proposed control system as the desired channels are maintained and the unwanted frequency components remain excluded. Figure 9 represents the optical channel structure of the controlled system utilising the revised trigger algorithm. The destruction of the ideal channels and introduction of unwanted frequency components represent the current shortfalls in this implementation. When implemented correctly however it is anticipated that the resulting channel structure will be equal to that of Figure 8 however this implementation will carry many practical advantages.
IV. Discussion

The objective of this project was to design a control structure for the ASL polarimeter in order to allow extended test times for imaging purposes. This project has successfully designed and validated the suitability for a PID-F controller to satisfy these requirements as part of a larger four-slave system, and has quantified the effects of this system on optical channel structure. The proposed control structure achieved mean drift of 0.0012 radians over extended test periods. This project however experienced a number of setbacks and scope-drift during the characterisation of the system plant.

Critical to any control engineering process is adequate knowledge of system plant and how it responds to a variety of inputs. If accurately understood and represented, the system can be precisely monitored and controlled for a variety of purposes. Within this project understanding and implementation of the system plant presented a range of challenges to achieve the required precision of control. As a result of a nested control loop identified in the motors used in this project, the scope expanded and only two complete decades of data were able to be assessed to derive a transfer function. Whilst best attempts were made to accurately represent the plant’s transfer function, it is still only an approximation and any implementation of this
structure would have to be criticised against actual performance. The engineering process applied to the project however remains valid and if the plant was to be more accurately characterised, the control principles would remain the same. With this considered, this provides value to the project despite the fact physical implementation was not achieved.

Following the simulation of various system configurations, the recommended solution was applied to Mueller calculus to gain an appreciation of the effects of the controller on optical channel structure. The design requirements of the project were to develop a control system capable of maintaining a signal to noise ratio greater than 50% over a 30 minute test period. The ability to exceed this requirement using the control structure in conjunction with the existing trigger mechanism would potentially allow for sampling to occur over longer periods or at higher angular frequencies bringing potential benefits to the imaging process. Furthermore the refinement of the spatial trigger mechanism would remove any time limitation placed on the test period and allowing the test to potentially be paused or run at variable frequencies. This would provide potential versatility to the polarimeter’s applications.

V. Conclusion

The purpose of this project was to develop a controller capable of facilitating extended test periods of the ASL polarimeter through eliminating motor wander. This project has investigated the performance of a variety of system configurations and has provided a solution to meet all design requirements. Furthermore this project has quantified the effects of this solution on the modulated optical channel structures with a variety of measurement trigger algorithms. Limitations and complexities accounted during the characterisation of the system plant resulted in solution being limited to simulation. Further work in refining these approximations, and implementing the solution will allow for this solution to be applied to the ALS polarimeter.

Acknowledgements

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References

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