Letter

Mark Johnson*

Polarimetric 360° absolute rotary encoder

https://doi.org/10.1515/aot-2021-0056
Received November 19, 2021; accepted February 14, 2022;
published online March 7, 2022

Abstract: Encoders of angle based on rotating polarizers suffer from 180° ambiguity due to their inherent twofold rotational symmetry. This restricts their applications in motor and machine controls. We show that the ambiguity can be resolved through a geometrical mapping from a plane to a conical surface. Seen from the local surface normal, one full rotation of the cone gives one half rotation of the polarizer axis. With appropriate transmission or reflective optics and multiphase detection, we build high resolution, moderate accuracy, absolute-angle encoders without 180° ambiguity. Polymer birefringent retarders can be used similarly.

Keywords: ambiguity; polarization; rotary encoders.

1 Introduction

The variation in light intensity transmitted through two polarizers as a function of angle θ has long been an attractive basis for absolute angle encoders [1] (Figure 1), potentially at a very low cost. The nominal $\cos^2\theta$ intensity variation allows straightforward angle evaluation using at least two differently polarized detectors. Mobile phones and LCD TVs have made available polymer sheet polarizers in large sizes for large-angle encoders. The “centerless” polarizer allows illumination close to the axis of rotation and hence also very small encoders.

However, one full rotation of the movable polarizer gives two cycles of high- and low-light intensity. The twofold rotational symmetry inherent in all polarizers therefore leads to 180° ambiguity in the evaluated angle. Unless the ambiguity is resolved, for example, using an additional 2-bit encoder in an optical, Hall effect or other technology, the polarimetric encoder is only useful over a 180° range.

***Corresponding author: Mark Johnson**, Carlisle, UK,
E-mail: markj113@yahoo.com

This article describes the preliminary demonstration of an alternative configuration of sheet polarizer, utilizing a change of space from 2D to 3D. We describe encoder configurations for 240° and 360° ranges, offer fabrication methods, give results for a 360° lab demonstrator, and last, compare this approach with other rotary encoder technologies.

2 Change of space

To remove this 180° ambiguity, we consider mapping from a planar space to a 3D conical space, which allows the use of only half a polarizer rotation. A circular annulus is cut from the sheet polarizer and then accurately bisected (Figure 2). Joining the ends of the semicircle gives a truncated cone with a full apex angle of 60°. The polarization axis makes only one half turn per full rotation of the cone, as shown along the local surface normal, and hence one cosine cycle of transmitted intensity; the ambiguity is resolved. Note that the split into two semicircles can be made at any angle with respect to the polarizing axis. Opposite points on the annulus always have the same axis direction. Not only does this change of space resolve ambiguity, but it also allows very flexible mapping of the full dynamic range of the polarimetric encoder onto physical rotations from 180° to 360°.

Rotary actuators such as radio-control “servos” sometimes operate over ranges of ±90° to ±125°. In this case, we can cut the polarizer segment somewhat larger than a semicircle, and then wrap it into a truncated cone with the apex angle between 60° and 180°, fitting the encoder’s full-scale range of one optical intensity cycle to any physical rotation from 180° to 360°. This, of course, eases the joining problems. Figure 3 shows a 270° segment of polarizer wrapped onto a truncated cone of apex angle 97.2°. This maps the 180° unambiguous range onto a 240° physical rotation.

3 Fabrication

A motorized plate-glass platen and a scalpel blade mounted on an XYZ-stage were used to cut annuli with various

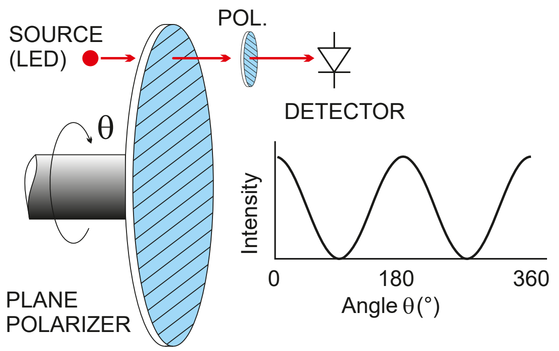

Figure 1: Polarimetric angle determination is 180°-ambiguous due to the two bright/dark cosine cycles per full rotation.

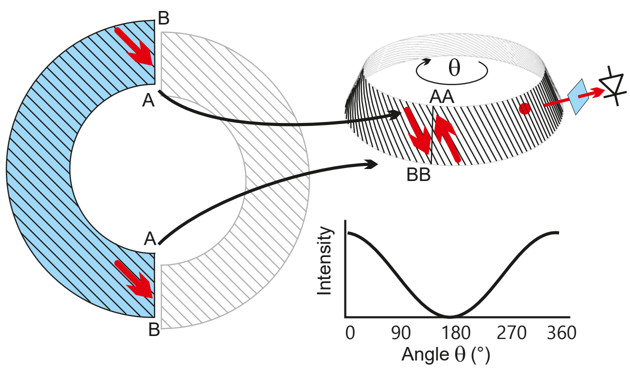

Figure 2: A semicircular annulus of polarizer wrapped into a 60° cone, showing only a single cosine intensity cycle per full rotation.

diameters from 50 to 150 mm. Several techniques for wrapping the annuli into free-standing truncated cones were tested. A butt joint supported with a 2 mm-wide 140 µm-thick transparent PVC glued overlay worked well. Alternatively, cutting 181° segments instead of exact semicircles allowed a glued overlap joint with a good performance. The overlapped areas share the same polarization axis. The cyanoacrylate adhesives made strong joints with minimal contamination.

All bonding techniques risk deformations to the conical geometry as they are either too stiff or too flexible, which give small errors in the evaluated angle. Hence, bonding the polarizer to a transparent or reflecting 60° support cone is expected to improve the performance. As long as all plastic materials are traversed by unpolarized light, their birefringence plays little role. Wrapping and bonding is eased if the height of the truncated cone is minimized; 3 mm or less typically suffices.

4 Evaluation

The optical system used consists of a surface-mount 525 nm LED and three Si-pin photodiodes (Hamamatsu S8729). Each photodiode had a piece of linear polarizer glued to it; these were arranged by eye at 0°/120°/240° (Figure 4). Transimpedance amplifiers using rail-to-rail operational amplifiers, a 16-bit analog/digital converter, and microprocessor completed the data-acquisition system. The same microprocessor controlled a 200-step stepper motor with a microstepping driver.

One full turn of the motor and polarizer cone produced one offset cosine intensity cycle as expected, with each channel A, B, and C separated by approximately 120°. Small changes in sensitivity were corrected with one-time

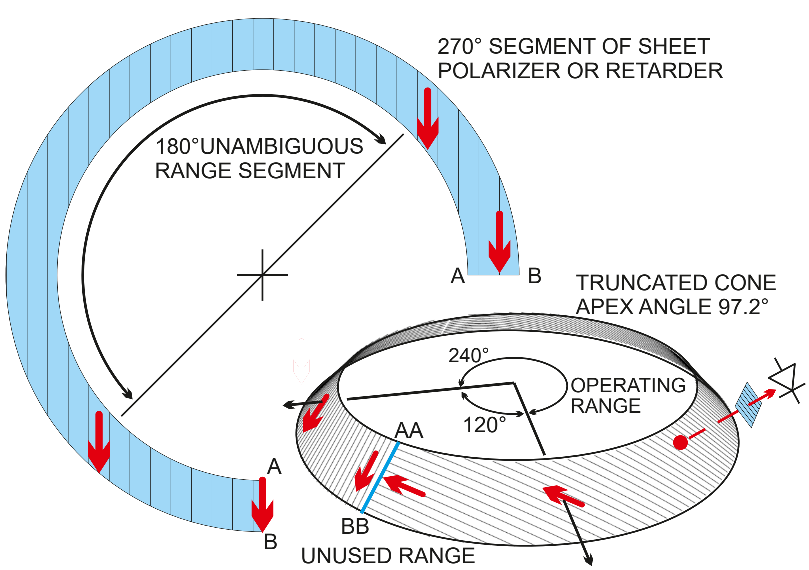

Figure 3: Limited rotation encoder for a servo actuator. A 270° polarizer segment is joined end to end, giving an unambiguous range of 240°. The red arrows depict how the polarization axis rotates.

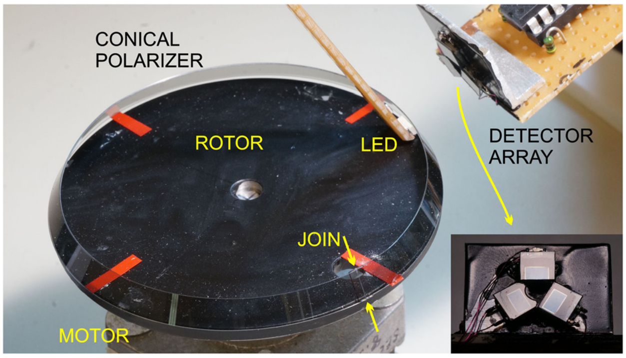

Figure 4: Assembly used to characterize the polarization encoders, showing a 60 mm diameter, 60° apex conical polarizer and the detector array. The inset show the array's three photodiodes with their polarizers.

software scale-factors. Quadrature signals I and Q were generated from $I = -\frac{1}{2}A + B - \frac{1}{2}C$ and $Q = -0.866A + 0.866C$, and then the angle was calculated using the C language arctangent function atan2(Q, I) in floating-point arithmetic.

Figure 5 shows the evaluated angle for one full rotation of the motor. The inset plot shows the linearity error, approximately ±1.4°. This is achieved without any calibration, apart from equalizing the three peak intensities. Most errors arise from the deviation from circularity of the unmounted polarizer cone and from detection polarizer orientation errors. With digital correction for these errors, as is common with magnetic sin–cos encoders [2], we expect the errors to be reduced significantly. Errors at the join come from differential intensity variations as it sweeps past the three, spatially separated photodiodes. The additional absorption of the overlapped, glued join is suppressed by IQ processing. A superior detector would be composed of many

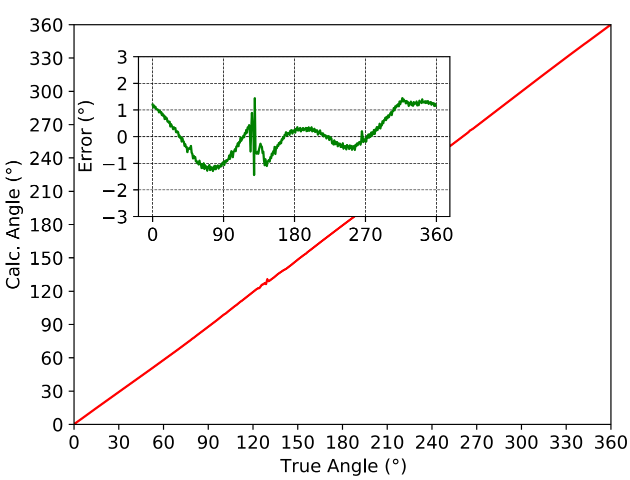

Figure 5: Unambiguous, absolute determination of angle using the conical polarizer. The inset shows the deviation from linearity.

interspersed photodiodes with 0°/120°/240° (or 0°/±45°/90°) polarizers fabricated as a monolithic OptoASIC [3]. Similar devices have been manufactured by Advico [4].

A two-phase system with sine and cosine outputs and arctan(sin/cos) evaluation is often used in interferometric phase measurement, moiré encoders, and magnetic encoders, but three-phase systems better handle the inevitable common-mode intensity changes [5].

5 Discussion

Many configuration variations are possible. The conical geometry works equally in a two-pass reflection mode using a mirrored or diffusely reflecting conical substrate, although optical absorption in the polarizer is increased. The conical geometry is also not restricted to linear polarizers. We have fabricated cones from polymer linear retarders. With polarized source and detectors, equivalent unambiguous encoders can be made. The conical geometry may also have uses for other 180° symmetric planar structures such as diffraction gratings and even printed lines for video angle evaluation.

However, few gains come for free. By remapping our sheet onto a cone, we have generated an axis of rotation, and so can no longer measure with tiny beams on the shaft axis. The simplicity of a plane, centerless sheet encoder has been sacrificed. Small encoders will require very thin and flexible polarizers, or heat treatment, as one of the cone's principal curvatures becomes large near its apex. Some very thin microgrid polarizers are available [6], but at much higher cost. Applications exist for encoders for very large diameter hollow shafts or where optical-fiber connected, electrically passive encoders are mandated.

How does this approach compete with alternative technologies? Hall-effect magnetic encoders [7] share the polarizer's noncontact operation and high resolution but can be sensitive to external magnetic fields. They show several degrees of errors for anything but perfect magnets and perfect alignment, comparable to the 1.4° accuracy of our laboratory demonstrator. Low-cost potentiometer encoders typically exhibit 1–2% linearity error (7° angle). Some potentiometers perform better but are no longer low-cost. They also have friction, wear, and dead-bands as high as 35°. Optical absolute encoders have high accuracy, with the disadvantage of the high cost of precision manufacture and alignment.

We have shown that a mapping from the plane to a conical surface brings new capabilities to polarimetric encoders. Notwithstanding the disadvantages, by sidestepping the primary ambiguity problem, we have made possible a low-cost, noncontact, moderate accuracy, 360° absolute rotary encoder.

Author contributions: The author has accepted responsibility for the entire content of this submitted manuscript and approved submission.
Research funding: None declared.
Conflict of interest statement: The author declares no conflicts of interest regarding this article.

References

[1] N. Albion, R. F. Asmar, R. W. Huggins, et al., "Optical angle sensor using polarization techniques," US Patent number 5,424,535, 1995.
[2] Infineon Technologies AG, GMR-Based Angular Sensor. Infineon TLE5009 datasheet. Available at: https://www.infineon.com/dgdl/Infineon-TLE5009_EXXXX-DataSheet-v01_01-EN.pdf?fileId=5546d46276fb756a01771b1fec2f3a7f.
[3] X. Zhao, X. Lu, A. Abubakar, et al., "Novel micro-polarizer array patterns for CMOS polarization image sensors," in *Conference: 2016 5th International Conf. on Electronic Devices, Systems and Applications (ICEDSA)*, Al Khaimah, United Arab Emirates, IEEE.
[4] advico microelectronics, POLDI – The Optical Micro-Angle-Sensor. Available at: https://advico.de/index.php/26-home/slider/19-slide-poldi.
[5] K. Creath and J. Schmit. Phase-measurement interferometry. Available at: http://www.u.arizona.edu/~kcreath/pdf/pubs/2005_KC_JS_EMO_PMI.pdf.
[6] Artifex Engineering GmbH & Co.KG, Emden. WG1100 wire-grid polarizing beamsplitter.
[7] RLS merilna tehnika d.o.o., Hall sensor RLS AM4096. Available at: https://www.rls.si/eng/fileuploader/download/download/?d=1&file=custom%2Fupload %2FAM4096D02_08.pdf.