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Adaptive Accuracy Enhancement for Simultaneously-Firing Optical Position Sensor

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Summary:

An algorithm for adaptive accuracy enhancement of lateral position sensing based on quadrature spatio-temporal modulation is presented and its application in a prototype micropower optical position sensor with simultaneously-firing infrared emitters is reported. Substantial (4x) improvement in position accuracy over basic detection method has been observed using automated test stand where partial incapacity in one of the emitter channels has been simulated.

Keywords: position sensor, spatio-temporal, quadrature modulation, accuracy enhancement

Introduction

A micropower active optical position sensor measuring one-dimensional displacements lateral to optical axis over decimeter-wide gaps was recently presented [1]. Quadrature spatio-temporal modulation involving four simultaneously-firing infrared emitters and diffuse reference primer has been utilized in order to reduce ON-time for signal processing circuitry, allowing up-to two years of continual battery operation. However, variations in geometry of emitters due to manufacturing process as well as degradation of primer due industrial conditions and aging may result in worsening readout accuracy. To address both issues, an adaptive algorithm for determination of irregular gains in signal path involving emitters, primer and acquisition circuitry has been proposed and implemented in firmware of the prototype device.

Spatio-Temporal Modulation

Implemented position sensing based on spatio-temporal modulation involves four infrared emitters equipped with collimating lenses that illuminate primer pattern in four distinct spots with mutual spatial phase shift of 90°. At the same time, emitters are in regular intervals supplied with current bursts of constant frequency, but again of mutual temporal phase shifts of 90°. Incident infrared light is then modulated and reflected in dependence to the relative position of the recurring pattern printed on a diffuse strip. As a result of the spatial modulation, temporal phase shift to the overall reflected light is induced, revealing lateral displacement of the primer within one spatial period. Overall signal received in set of infrared detectors is amplified, converted and synchronously detected in digital domain, resulting in a complex value with phase angle directly proportional to the lateral displacement of the primer.

Algorithm for Irregular Gains

Because of irregularities in emitter circuitry and collimator geometries, as well as due aging and field conditions, detected in-phase and quadrature components can face irregular distortion observed as affine (shift and scale) transformation on complex plane. To account for it, a model for spatio-temporal modulation and subsequent synchronous demodulation process with distinct channel gains is introduced as

$$D = \frac{1}{T}\int_{T}\sum_{n} G_n I(\rho_n) I(\gamma_n) e^{-i\omega t}\, dt \,, \quad (1)$$

where D is detector output, $G_n > 0$ is arbitrary (presumably known) gain for *n*-th channel and $I(\varphi)$ is biased cosine function representing both spatial and temporal intensity modulation, governed by spatial and temporal modulation phases $\rho_n = 2\pi l / L + n\pi / 2$ and $\gamma_n = \omega t - n\pi / 2$. In case of uniform gains, spatial phase for given lateral displacement l can be found simply as argument of the complex detector output. However, for uneven and possibly time-variant gains, detected phase need to be corrected by inverted transformation in form

$$\begin{aligned} D_{COR} = {} & \frac{\mathrm{Re}(8D) - G_0 + G_2}{G_0 + G_2} + \\ & + i\,\frac{\mathrm{Im}(8D) + G_1 - G_3}{G_1 + G_3} \end{aligned} \,. \quad (2)$$

Measured lateral position can be then evaluated by re-integrating changes in the phase of the corrected detector output using

$$\Delta l = \frac{L}{2\pi}\,\Delta\arg\left(D_{COR}\right) \qquad (3)$$

Adaptive Determination of Gains

For estimation of unknown channel gains, Fourier analysis of detector output at basic spatial frequencies is utilized. Components for integer spatial frequencies $k \in \langle -1,1 \rangle$ can be found as integrals

$$C_k = \frac{1}{L}\int_L D e^{-ik2\pi l/L}\,dl \qquad (4)$$

provided numerically for one or multiple spatial periods. This of course implies that primer is in relative movement in respect to sensor for at least one length L. By solving eq. (4) for unknown gains, we get

$$G_n = 4\,\mathrm{Re}\left(i^{2n}C_{-1} + i^{n}C_0 + C_1\right), \qquad (5)$$

applied in next cycle for gains in eq. (2). The process leads consecutively to enhancement of position accuracy and adaptation of gains for changing field conditions.

Testing and Results

To provide assessment of the algorithm, an automated test stand with configurable sensing gap distances, linear drive and precision position measurement has been readied (Fig. 1).

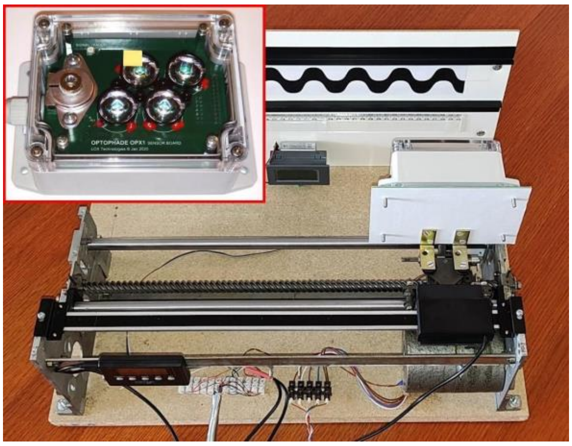

Fig 1. Automated test stand. Inset image: Front side of tested optical sensor with simulated incapacity.

Results for position error and performance of gain adaptation algorithm obtained for 125mm sensing gap can be seen in Fig. 2 and Fig. 3. Initially, as gains are set to equal value of 100, standard position error of 0.8-1mm is indicated. Later, with sufficient amount of detector data integrated, adaptation of gains started resulting in gradual enhancement in position accuracy to less than 0.2mm.

In next phase, we used a 1cm^2 paper strip for partially blocking of one of the infrared emitters. Subsequent surge in position error to approx. 10x of the settled value could be observed, however, as channel gains adapted, measurement error dropped again to almost previous level. Similar behavior could be observed after strip removal.

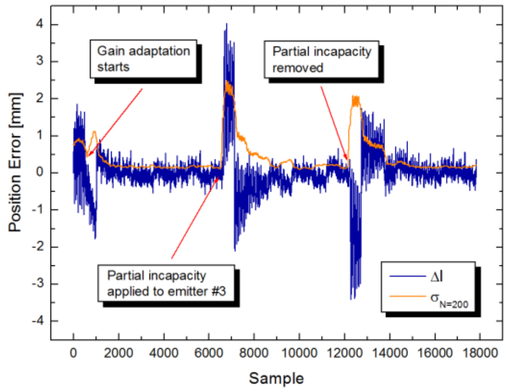

Fig. 2. Position error (blue) and standard deviation (orange) evaluated from preceding 200 samples.

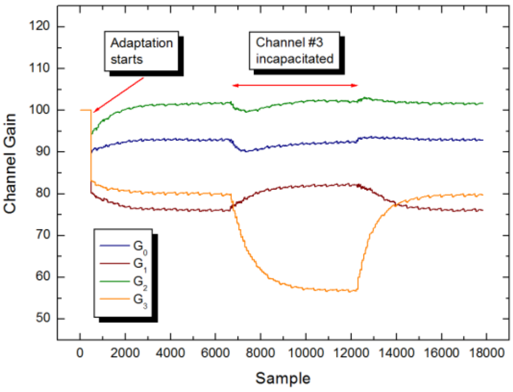

Fig. 3. Adaptation of channel gains with indication of initial and channel incapacity conditions.

Conclusion

Proposed modification to detection algorithm for active optical position sensor has been found effective in determination of both hardware-related as well as environmentally-induced irregularities in signal chain, enhancing accuracy of position sensing down to 0.2mm at >100mm sensing gap distances.

References

[1] E. Burian, "Micropower Active Optical Position Sensor for Decimeter-Range Sensing Gaps," *2023 IEEE SENSORS*, Vienna, Austria, 2023, pp. 1-3, doi: 10.1109/SENSORS56945.2023.10324868