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High Precision Control of Galvanometer Scanner

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Abstract

A high precision controller using two synchronization photodiodes or phototransistors is used to compensate the errors introduced by the position sensor of the galvanometer and its electronic driving circuit. Errors of gain, offset, and phase of a periodic waveform are easily compensated using this technique. This paper will describe the approach used. A comparison with the conventional method of reading the signal directly from the position sensor will also be made. Experimental results will be presented.

Introduction

Low inertia galvanometers and resonant scanners are often used in complex high precision scientific instruments and industrial equipments. They provide a simple and effective way of obtaining high precision deflection system in a relatively small package. They also provide ease of use and versatility in the associated control mechanism.

Galvanometric scanners can produce a steady-state deflection of a light beam as well as sinusoidal and nonsinusoidal wave forms such as sawtooth, triangular, and randomly defined excitation. Several applications require this programmability to achieve a high degree of versatility associated with the measurement process. A second type, resonant scanners, can operate at only one frequency or its harmonics. They are of interest because much higher scanning angles can be obtained at higher frequencies. They take advantage of the resonant amplitude magnification of the mechanical structure to obtain this gain in speed and deflection angle.

The moving iron galvanometer scanner has been used intensively in many applications because of its ruggedness, versatility, and ease of installation and use. In triangulation-based three-dimensional vision systems, a galvanometer can be efficiently employed to scan a laser beam on an object in order to measure the distance of this object from the sensor. Figure 1 shows a conventional geometry which can be used to measure the shape of an object. The two coordinates X and Z are easily computed by triangulation. In such an application, accurate measurement of the scan angle is very important (see Figure 1). Small variations in the deflection angle will produce significant errors in both X and Z coordinates. Special geometry can be used to reduce the error and to increase the precision of the distance measurement [1]; however, errors following the tangential axis X still need correction.

To increase the speed of the measurement and to cover the whole object, the laser beam is often scanned periodically and continuously over the object. In fast acquisition set-ups, point-to-point-based methods are eliminated because of the time involved to stabilize the deflector. Also, as we will see, other types of errors are introduced.

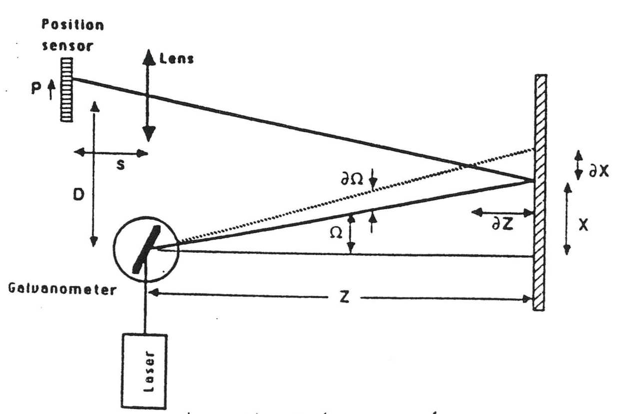


Figure 1:

Optical triangulation: errors introduced by an inaccuracy in the scan angle.

Position sensors are usually incorporated into these devices, especially in the case of galvanometer scanners, to obtain a direct measurement of the scan angle and to increase the speed of the device by proper feedback compensation. However, even if a good resolution is obtained, absolute precision is limited by the nonlinearity of the position sensor and by temperature drifts. If constant, the nonuniformities can be compensated using look-up tables. However, temperature drifts will affect both offset or null position and gain of the transducer and, subsequently, the absolute position of the scan angle. The method used to read this position signal will also affect the accuracy of the measurement. Nonconstant group delay in the different stages of the system will introduce distortion in the response to a nonsinusoidal excitation which can vary with time and temperature changes.

Precision of Galvanometer Scanner

A good overview of the characteristics and performances of low inertia galvanometer scanner has been given by Brosens [2] and Montagu [5]. They described most of the errors which can affect the precision of the scan. These errors are

- wobble, defined as the standard deviation from average scan angle, measured in the direction perpendicular to scan and produced by a rotation of the mirror on an axis parallel to the plane of the mirror and orthogonal to that normal rotation
- jitter, which is defined as the deviation from average scan angle, measured in the scan direction and due to inherent random perturbations
- mirror induced errors such as mirror mounting, dynamic deformations, erosion of the mirror surface, thermal deformations
- repeatability errors which can result from several causes: transducer noise, bearing noise, hysteresis
- position transducers errors, accuracy, linearity, resolution, noise, temperature stability, reference stability (null position), gain stability
- associated driving electronic errors such as drifts of the electronic components, electrical noise

Table 1 and 2 show typical errors which are obtained using commercially available galvanometer scanners. These specifications correspond, respectively, to the galvanometer models G120D and G325D from General Scanning Inc. which are used in our auto-synchronized laser-based 3-D vision systems. As seen in the Tables, wobble and jitter errors are relatively small. Jitter is especially interesting; it gives us an idea of the precision we can theoretically obtain following the scan axis.

The position transducer is however more complex to analyze. If we assumed that, for the same mechanical or physical scan, the nonlinearity is relatively constant with temperature changes and therefore can be calibrated, the only important error which will affect the position sensor will be introduced principally by changes in temperature. Even with the pseudo temperature compensation produced by a thermal blanket placed on the galvanometer body (model DT), a change of only

		% excursion	fraction
Excursion	0.698 rad	100	1/1
Wobble	< 50 µrad	< 0.007	< 1/13960
Jitter	< 100 µrad	< 0.014	< 1/6980
Position Sensor			
Linearity	±0.3 % p-p	±0.3	± 1/333
Zero drift / °C	300 µrad	0.043	1/2327
Model DT	30 µrad	0.0043	1/23267
Gain drift / °C	0.15 %	0.15	1/667
Model DT	0.015 %	0.015	1/6667

Table 1: Specifications Galvanometer Type I

		% excursion	fraction
Excursion	0.873 rad	100	1/1
Wobble	< 25 µrad	< 0.003	< 1/34920
Jitter	< 50 µrad	< 0.006	< 1/17240
Position Sensor			
Linearity	±0.3 % p-p	±0.3	± 1/333
Zero drift / °C	300 µrad	0.034	1/2941
Model DT	30 µrad	0.0034	1/29412
Gain drift / °C	0.15 %	0.15	1/667
Model DT	0.015 %	0.015	1/6667

Table 2: Specifications Galvanometer Type II

5° C will limit the absolute precision of the position reading to approximately 10^{-3} of the peak-to-peak displacement (Tables 1 and 2). Accurate control of the ambient temperature surrounding the system will be required. However, in practice such controlled environment is expensive and not always feasible, especially in industrial applications.

Conventional Method of Measuring the Angle using the Galvanometer Position Sensor

Figure 2 represents the conventional and most widely used method of interfacing galvanometers with the system controller or host processor. This configuration includes a digital to analog converter which provides the excitation to the galvanometer controller and an analog to digital converter which reads the position signal proportional to the deflection angle. The error signal can be used instead of the position, especially when random angles are required. In this latter case, a new displacement will be generated when the error signal is below a predefined threshold at the expense of a limited acquisition speed. In many applications, e.g. depth measurements, periodic waveforms are preferred primarily because of the reduction in the time required to measure the object and in the subsequent processing of the data. Sinusoidal, triangular, and sawtooth excitations are the most commonly used.

Conventional measurement methods as represented in Figure 2 are primary limited by

- the dynamics of the system as a function of the waveform used
- the errors introduced by the anti-aliasing filter and A/D converter
- the sources of noise
- and the other sources of error (drifts, aging, etc.)

Using the Laplace transform s, the transfer function of the galvanometer-controller of Figure 2 can be expressed as

$$\frac{V_{pos}}{V_{exc}} = \frac{KK_e s + KK_i}{Js^3 + (D + KK_f K_d)s^2 + (K_s + KK_f K_e)s + KK_f K_i} \qquad (1)$$

where K_e is the servo gain, K_d the damping or differential gain, K_i the integral gain and K_f the position transducer gain. The galvanometer equation is

$$\frac{\theta}{I} = \frac{K}{K_s + Ds + Js^2}, \qquad (2)$$

where I is the galvanometer drive current, K_s the spring constant of the galvo, D is the damping constant, J the rotor and mirror inertia, θ the shaft rotation, and K the torque constant.

Integral compensation K_i reduces the error to zero for a constant input and produces a constant delay for a ramp input. The servo gain K_e increases the response speed while K_d adjusts the damping of the galvanometer. Approximating $K_i \simeq 0$ in Equation 1 yields a second order system easier to analyse. Even with this approximation, any changes or misadjustments in any of the parameters of Equations 1 or 2 will seriously affect the performance and precision of the scan.

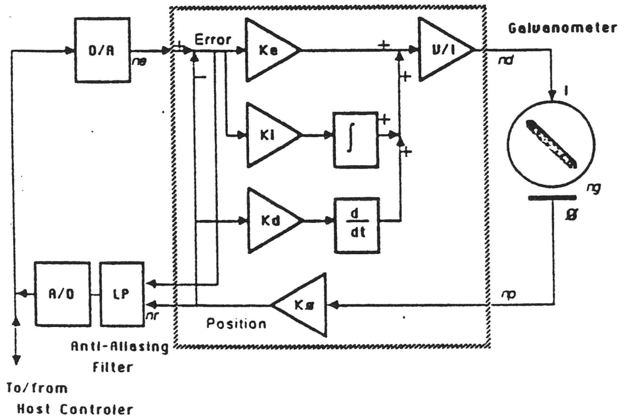


Figure 2:

Conventional method of interfacing galvanometers using D/A and A/D converters.

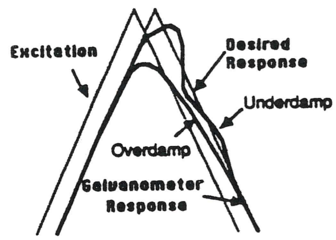


Figure 3:

Response of an underdamped and overdamped galvanometer to a triangular waveform.

Figure 3 presents typical responses of an underdamped and overdamped galvanometer to a triangular waveform, assuming that the natural frequency of the galvanometer is much more than the frequency of the excitation. Tenney [4] computed the time required to stabilize, within a given tolerance, the galvanometer response to a sawtooth excitation. However, because this response is highly affected by adjustment parameters, it is difficult to perfectly predict the effect of any change due to temperature, drifts, etc. For high precision deflection devices this stabilization factor can be prohibitive and therefore a sine wave might be preferred, especially when we consider that any periodic waveform will degenerate into sinewaves for frequencies greater than the cutoff frequency of the deflection device. Also

- the symmetry of the waveform enables measurements in both direction (trace and retrace)
- the number of scans per second can be greater than the cutoff frequency of the scanning device
- galvanometer or resonant scanners can be used independently
- noise and distortion on the scan signal will be almost eliminated if the scan frequency is greater than the bandwidth of the galvanometer
- linearization techniques as described in ref. 2 can be used
- drifts and stability of the system parameters can be compensated using techniques similar to the one describe in this paper. Also adjustments of feedback gains K_e, K_d, K_i, and K_f are not as critical as in the case of the triangular response.

As in any analog system, similar phenomena of distortions and delay will be introduced by the anti-aliasing filter. The previous discussion of the galvanometer response is also valid for the anti-aliasing filter. According to the Nyquist criteria, such a filter is required to reduce the effect of any unwanted signal, such as noise, which corrupts the angle measurements. Filter delays will be introduced in the measurements given by

$$T_{pd} = T_{gd}/2\pi f_f \tag{3}$$

where T_{pd} is the delay, T_{dg} the normalized group delay which is a function of the type and order of the filter, and f_f the frequency cutoff of the filter. The uncertainty in the delay is

$$\left|\frac{\partial T_{pd}}{T_{pd}}\right| = \left|\frac{\partial T_{gd}}{T_{gd}}\right| + \left|\frac{\partial f_f}{f_f}\right| \tag{4}$$

The error in the delay introduced by the filter will be affected by a nonconstant group-delay which is function of the type and order of the filter and by any error on the cutoff frequency [6]. For example, a fourth order Butterworth filter with a cutoff frequency of 1 kHz will introduce a delay of 0.418 ms at 100 Hz and 0.432 ms at 200 Hz. An error of ±5% on the frequency cutoff will give an uncertainty of 36 μs which corresponds to an accuracy of 1/140 on a 200 Hz scan. In the case of a Bessel type filter, constant delay of 0.336 ms will introduce an inaccuracy of 1/300.

These results mean that the bandwidth of the anti-aliasing filter must be very large in order to reduce the error introduced by any changes in the filter frequency cutoff and the type of filter, and consequently the signal-to-noise ratio will be greatly reduced. As shown in Figure 2, noises n_e and n_d produced by the drive circuit are relatively small because of the low frequency response of the galvanometer and the low impedance of the galvanometer coils. However, noise n_p and n_r will have an important influence on the accuracy of the reading, mainly because of the bandwidth of the anti-aliasing filter.

The accuracy of the position reading will also be limited by the accuracy of the A/D converter, drifts, voltage offset, and bias current introduced by the electronic components. In practice, it will be difficult to obtain more than 12 bits of conversion limiting the resolution to 1/4096 of the peak–peak deflection.

Compensation of Gain, Offset and Phase Variations using Synchronization Photodiodes

Probably the most direct approach to measure the absolute position of the laser beam is to use a grating and to monitor the changes in amplitude when the laser beam is scanning this grating [3]. However, such a method is difficult to implement. It requires complex mechanical and optical support. Also, the effect of defocalization of the laser beam on the grating will be important, seriously reducing the amplitude of the modulation.

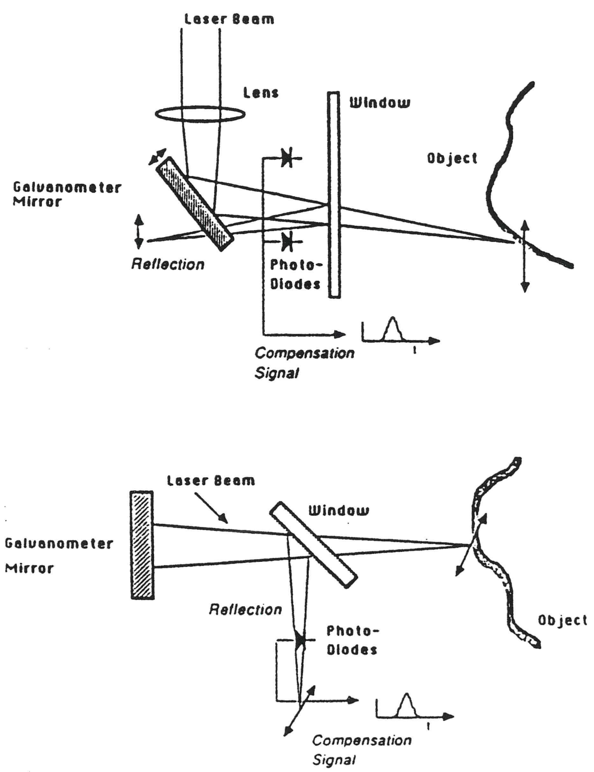
Figures 4 and 5 represent the proposed method of compensating the errors introduced by changes in gain, offset and phase variations in the system. Two photodiodes or phototransistors are positioned in the path of the scanning laser beam as shown in Figure 4. Even if the photodiodes can be located directly in the path of the laser beam, a transparent window is used to reflect a small fraction of the light (3–7%) on the photodetectors. This window is also used to protect and isolate the optical components from the outside world. Figure 5 shows the effects of the drifts on the response of the galvanometer.

Lets assume that t_1, t_2, t_3, and t_4 are the time positions of the electrical pulses of Figure 5. Then

$$T_1 = t_2 - t_1 \tag{5}$$

and

$$T_2 = t_4 - t_3 \tag{6}$$



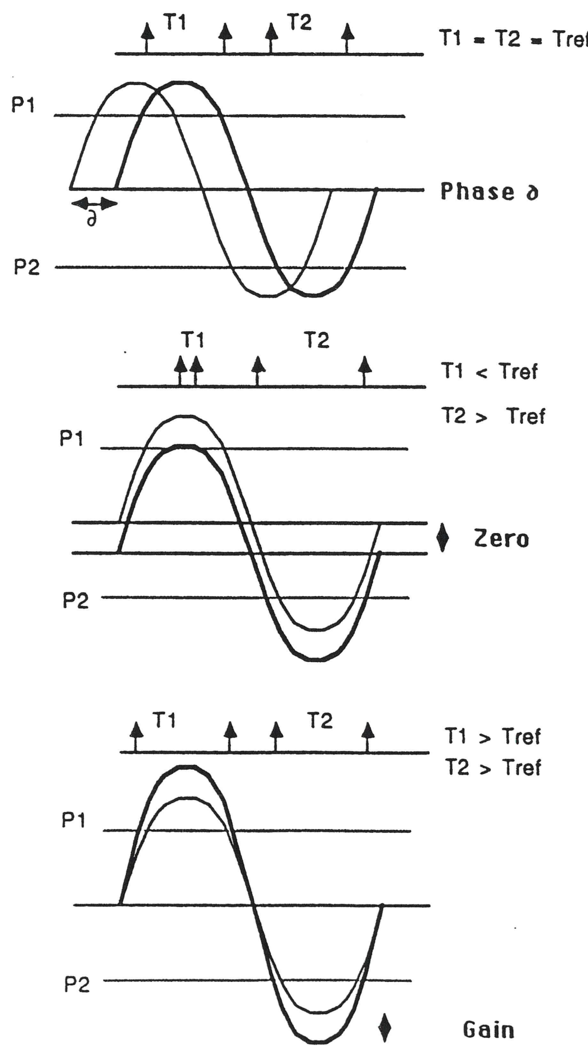


Figure 4:

Practical implementation of the synchronization photodiodes method (top and side views).

Figure 5:

Compensation of gain, offset, and phase errors using the synchronization pulses.

Consider now that T_{ref} is a reference value which corresponds to the *stable* position of the galvanometer such that $T_{ref} = T_1 = T_2$ and $0 < T_{ref} < \pi$. Then the errors of gain, offset, and phase can be approximated by

$$E_{gain} = \frac{T_1 - T_2}{2} \tag{7}$$

$$E_{off} = \frac{T_1 + T_2}{2} - T_{ref} \tag{8}$$

$$E_{\phi} = \frac{t_1 + t_2 + t_3 + t_4}{4} - \pi \tag{9}$$

which should be zero. The equation of the galvo excitation, normalized to $t = [0, 2\pi[$, is

$$\Omega(t) = \beta sin(t - \phi) + \delta \tag{10}$$

where Ω is the deflection angle and

$$\beta_j = \beta_i - k_{gain} E_{gain_i}, \tag{11}$$

$$\delta_j = \delta_i - k_{off} E_{off_i}, \tag{12}$$

$$\phi_j = \phi_i - k_{\phi} E_{\phi_i} \tag{13}$$

are the feedback compensation equations where k_{gain}, k_{off}, and k_{ϕ} are the feedback gain constants used for the error compensation. Assuming now that $P_1 = P_2 = P$ are the normalized positions of the photodiodes on the sinewave, as illustrated in Figure 5, then the total error introduced by this method is

$$\partial\Omega(t) = sin(t - \phi)\partial\beta + \beta cos(t - \phi)\partial t - \beta cos(t - \phi)\partial\phi + \partial\delta \tag{14}$$

where

$$\partial\beta = \frac{\beta}{P}\sqrt{\beta^2 - P^2}\partial t \tag{15}$$

$$\partial\delta = \sqrt{\beta^2 - P^2}\partial t \tag{16}$$

and

$$\partial\phi = \partial t \tag{17}$$

∂t is the accuracy on the positions t_1, t_2, t_3, and t_4 of the photodiodes. Since the errors are independent, minimizing this equation gives $T_{ref} = 0.615$. The relative position of the photodiodes which will give the smallest error is therefore $P = 0.58$. Then

$$|\Delta\Omega| = 0.8\left[|\Delta t_{\beta}| + |\Delta t_{\phi}| + |\Delta t_{\delta}| + |\Delta t|\right] \tag{18}$$

Renormalizing the time interval to $t' \in [0, 1[$ and the amplitude to $\Omega' \in [-\frac{1}{2}, \frac{1}{2}[$ to obtain a direct correlation between the time error and the scan error gives, knowing that $\Delta t \simeq 0$,

$$|\Delta\Omega'| = 2.5 E_{total} = 2.5\left[|E_{gain}| + |E_{off}| + |E_{\phi}|\right] \tag{19}$$

which is the absolute maximum error we can measure with this method for any point on the scan.

The advantages of this technique are interesting.

- The system is simple and inexpensive.
- Absolute compensation of gain and offset as well as the phase of the galvanometer and the associated drive electronics are provided using only two photodiodes or phototransistors.
- The mechanical and optical support required with this method is minimal.
- Using a protective window further improved the compensation system because the photodetectors will not perturb the acquisition path which means that the whole scan is available for the measurements.
- Changes in temperature are perfectly compensated if all the optics are mounted on the same isotropic base. Assuming that the mechanical expansion is the same for all directions (no temperature gradient inside the metallic support), the ratio of the optical distance between the galvanometer and the photo-detectors and the separation between the two photo-detectors will be constant. Only thermal distortions on the mirror or the window will affect this accuracy.
- Cost of the electronics is very low, especially with new single chip microprocessors.
- Effects of the anti-aliasing filter are minimized because of the high signal-to-noise ratio. Even if the pulse is noisy, good detection is possible.
- The effect of defocalization of the spot on the photodetector will only increase the size of the pulse, while in the case of the grating method it will seriously degrade the amplitude of the modulation, especially when the size of the spot is greater than the spacing (2λ) of the grating.

Using techniques as described in ref. 6, peak position can be measured to a fraction of the A/D sample (typically one fifth of a sample). Therefore, the precision of the measurement will be related only to the stability of the galvanometer for low frequencies, as produced by changes in temperature (<< 1 Hz).

However, a limitation of this technique is explained by the Nyquist theorem. Because the compensation is done at each cycle, any noise or unwanted signal between half this correction frequency and the cutoff frequency of the galvanometer will be aliased and will create unstability in the compensation loop. Also, nonlinear distortions are not compensated. We postulated that they are constant for the same mechanical or physical scan and are not related to the transducer response.

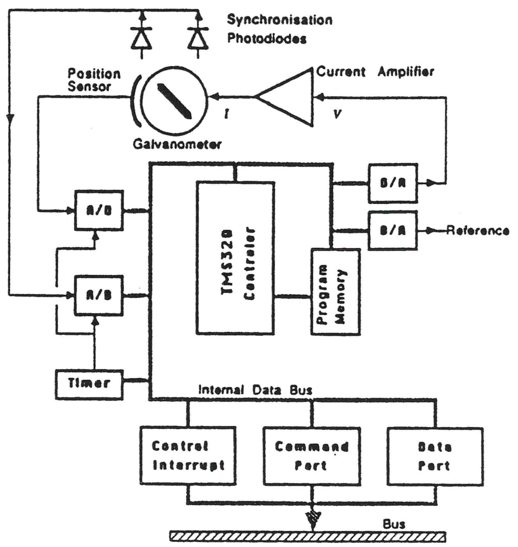


Figure 6:

Realization of the galvanometer controler using the Texas Instruments TMS32010.

Practical Implementation and Experimental Results

A practical implementation of the synchronization controller is shown in Figure 6. Using Texas Instrument single chip TMS32010 series DSP microprocessors, a low cost and versatile system can be developed to control and monitor several processes simultaneously (for example, to monitor other acquisition parameters, to handle the commands from a host system, to control DMA transfer). According to Figure 6 the current pulses from the photodiodes are summed and digitized by an analog-to-digital converter. A second converter is provided to digitize the position signal produced by the galvanometer position sensor in order to have a comparison with the synchronization method. Anti-aliasing Bessel filters, not shown in this figure, were developed to produce an error smaller than one fourth of a sample.

Two digital-to-analog converters are also included. The first one produces the drive signal to the galvanometer while the second converter is used to monitor the different signals from the experiment (e.g., A/D conversion, internal variables such as the error signals, gain). Gain and offset factors are digitally programmed on this second converter, providing a stable and accurate reference signal. Commands and parameters are issued by a host processor based on VME to the TMS320 controler.

The sinusoidal waveform is generated using a sinetable. Linear interpolation between the points reduces the size of the table to 128. Gain, offset, and phase are automatically computed and generated by the TMS32010. Time t is normalized to $[0, 32768[$ which corresponds to a positive 15 bits integer word compatible with the TMS processor.

Figure 7 shows the signals measured using the standard A/D converter method. In this experiment, the D/A sinewave gain, offset, and phase are modified until, respectively, the rms amplitude, the average signal, and the phase (given by the crossing of the average amplitude) is equal to a predefined reference signal. The difference between the measured signal and the reference is computed by the TMS controller and outputted on the reference D/A converter. The A/D error is shown in Figure 7. It should be noted that the system was working in a low electrical noise environment. The quantization error of ± 1 as well as a residual phase error of ± 1 are still clearly shown giving a resolution for the measured sinewave (3200 peak-peak) of $\pm 1/1600$. The optical scan angle was approximately 36°.

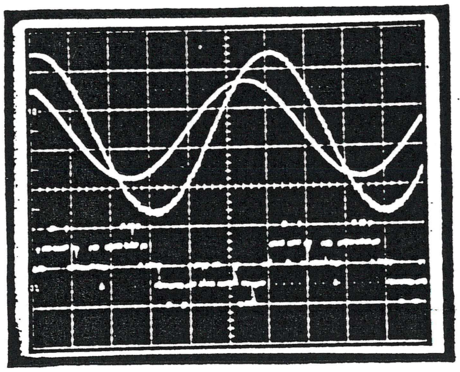


Figure 7:

Quantization error on the angle measurement using the conventional method of the A/D converter for a sine waveform (top trace, excitation and response (3200 quantization levels peak–peak) of the galvanometer; bottom, difference from the expected sinewave).

Figure 8 shows the signals produced by the synchronization photodetectors (top) with relation to the signal produced by the position sensor (center). The bottom of figure 8 represents an expansion of one of the synchronization pulses showing the effect of the defocalization of the laser beam on the photodetector and the need of a sub-sample peak detector [7]. Gain, offset, and phase errors as well as the absolute sum of these three errors are shown in Figure 9, respectively, from top to bottom. The three first traces are signed values while the last one (absolute error) is always positive. Each vertical division represents 2 bits of the 15 bits normalized time value used. A total time error E_{total} (bottom trace) of approximately $\pm 2/32768$ peak–peak is measured. From Equation 18, an absolute peak position error of $\pm 1/6500$ is obtained.

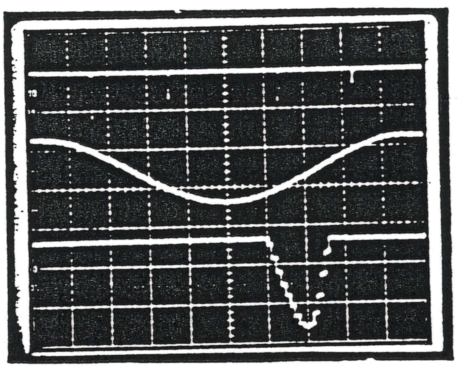


Figure 8:

Signal produced by the synchronization photodiodes for a 8192 point 5 Hz sinewave (bottom trace, expansion of one synchronization pulse).

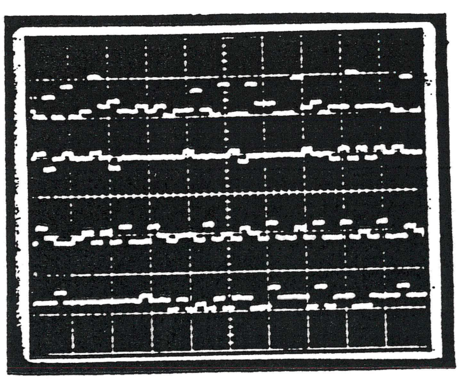


Figure 9:

Errors measured using the synchronisation principle. From top to bottom: E_{gain}, E_{off}, E_{ϕ}, and E_{total}. Each vertical division represents 1/8192 of the total sine period.

Figure 10 gives an interesting result. The total error E_{total} was measured using the synchronization pulses for a change of the temperature of the galvanometer. The compensation feedback constants k_{gain}, k_{off} and k_{ϕ} were set to 0. A change of approximately 15°C was obtained using the galvanometer thermal blanket. The four traces of Figure 10 represent the change in temperature over roughly 3 min (four sequential exposures of the same oscilloscope trace). A total error in time of $\pm 1/256$ gives a maximum absolute position accuracy of only $\pm 1/100$ using the conventional A/D method (Equation 18).

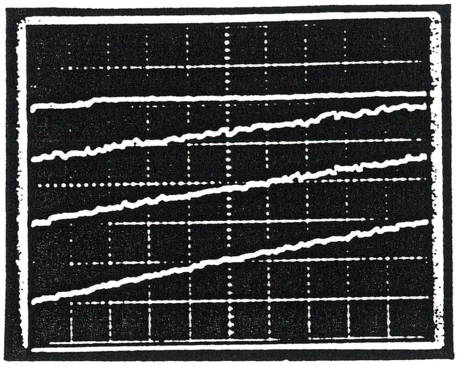


Figure 10:

Total error E_{total} introduced by a change in temperature ($\sim$ 15°C) without compensation ($k_{gain} = k_{off} = k_{\phi} = 0$). Time base=5 s/div, Vertical division = 1/1280 total sine period, Total exposure time $\simeq$ 3 min.

Conclusion

A very simple and inexpensive method has been described to compensate for the errors on the gain and offset of the transducer position sensor of a low inertia galvanometer scanner introduced by a change in temperature. The method also provides an effective way of measuring the phase of the scan without requiring sophisticated and expensive electronic circuits as in conventional A/D converter methods.

An absolute stability greater than ±1/6500 peak is measured for a change of temperature greater than 15°C compared with the ±1/100 obtained with the conventional A/D converter method. In a low noise environment, limited resolution of only ±1/1600 is measured with the A/D method. This limited stability of the galvanometer position sensor with the temperature and the delicate design criteria of the associated electronics confirms the need for an accurate low cost compensation system.

We have not measured the effect of nonlinearity changes of the galvanometer with the temperature. Until now we assumed that these variations were negligible. Other work must also be done on the stability of the galvanometer to improve the precision of the measurements. The use of a resonant scanner must be investigated.

Acknowledgements

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