How precise are opto-interrupters?

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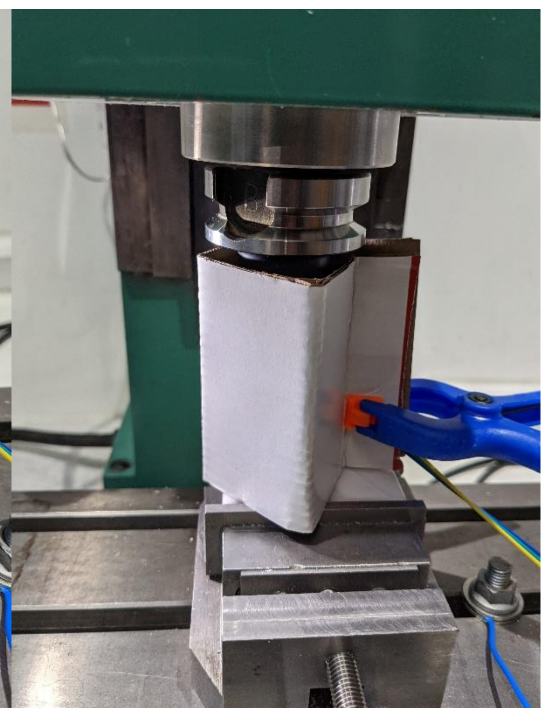
Many clock builders use optical pendulum position sensing, for timing and amplitude measurement or trigger impulsing, or both. Bateman built his own sensor using discrete LEDs and phototransistor, at a time before packaged sensors were available. His sensor had three functions: deriving timing pulses; driving the impulse; and sensing amplitude. Based on observations of the impulsing pattern he estimated[1] that the amplitude remained constant to within 1 second of arc. One second of arc for a seconds pendulum about 1 metre long is a linear measure of 4.85 micrometres.

For some years packaged "opto-interrupters" ("optos" for short) have been available, single units that combine a light emitting diode facing a phototransistor in a single package, arranged so that an object in the slot in between cuts the light beam. These are widely used in products such as printers, copiers, industrial machinery etc. They are obviously attractive for pendulum sensing but the question arises, how precisely can they sense for example the edge of a vane cutting the beam, since this will be the ultimate limit on timing or amplitude control accuracy? Product datasheets have little information on this. Some limited results have been published for their application as limit/home switches for CNC machines[2] which suggest that an Omron OPB917 opto will repeatably sense an edge to 1 micrometre provided that the supply voltage is kept constant and stray illumination kept out.

I have made further measurements using the Sharp GP1A57HRJ00F transmissive optical sensor as used in my "Arduinome" clock[3]. This is widely available, has a useful 10mm gap, and the sensor processing includes a Schmitt trigger so it gives clean logic edges.

Method

The measurement setup used my CNC mill with the sensor soldered to a breakout board and mounted on a small block held in a machine vice (left hand photo). The mill (a Denford Novamill with modern stepper drivers and Mach 3 controller) has 5mm pitch ballscrews on each axis with 200 steps/rev motors driving through 2.5:1 toothed belt reduction drives. Using microstepping drive electronics the normal resolution is nominally 0.625 micrometres, but for the purposes of this exercise the X-axis driver was reprogrammed for a nominal resolution of 0.2 micrometres.



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Two types of "interrupter" were tried. One was a blade made of a scrap of 0.1mm beryllium copper shim, of the sort I use for pendulum suspension springs; the other a short silver steel rod ("drill rod") 5mm diameter, as used for the finial on my "Arduinome" clock. Both were held in the machine's collet chuck.

The LED was driven using the recommended 220 ohm series resistor from the 5V supply. The logic output from the opto sensor was connected to the probe input of the CNC controller. The output goes "low" (zero volts) when the gap is obstructed, for example by the vane or rod. This corresponds to usual behaviour for my digitising probe, so the normal probing functionality in the Mach 3 controller can be used.

I wrote a Mach 3 macro which does the following:

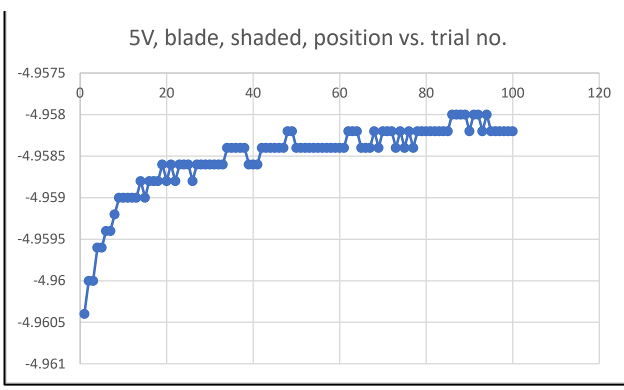
- Initially the vane is manually jogged to very close to the gap, about 1mm or less from the point where the beam is cut (this being monitored using the built-in diagnostics screen);
- Then the macro is run: it starts by making a slow (2mm/minute) "G31" probing move towards the beam. As soon as a low logic level is detected the movement stops and the axis value is recorded (this is standard probing procedure);
- Then the vane is withdrawn by 0.2 mm, and the process repeated 100 times, the stop value being recorded each time as an entry in the "tool table" – this is used just as a convenience for exporting the values.
- When 100 moves are complete the tool table is exported to a text file for analysis.

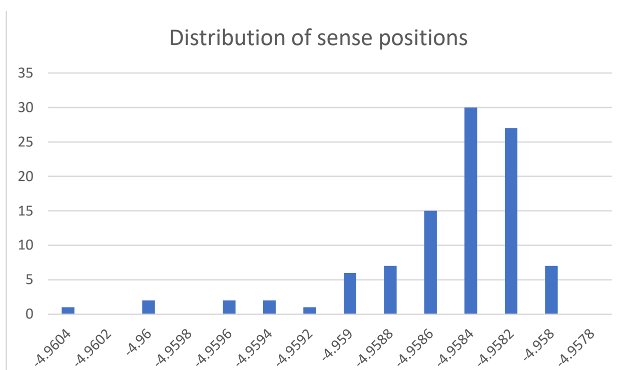
It is known that these optos are affected by ambient light so I made a crude shade from cardboard that completely surrounds the collet chuck and sensor (right hand photo above). Measurements were then made under 6 lighting conditions: dark (with shade on); daylight, shade removed and the machine illuminated by what light comes in from a skylight in the workshop roof; with an LED machine work light switched on as well; with additional floodlighting from LED spots above the machine added; and with the workshop background lighting added. It quickly became apparent though that even ambient daylight has a large effect on precision, so it is best to assume that the sensor should be shaded as well as possible.

The other ambient variable tested was supply voltage. This affects the LED supply current and therefore brightness; and the threshold value of the Schmitt trigger. Both of those can affect the position at which the device responds. With no ambient light the trigger point was tested for a supply voltage of 4.5V in addition to 5V nominal.

Finally one set of measurements was taken with my normal "galvanic" contact probe, normally used for setting the machine XY datum to defined faces on the work.

Results

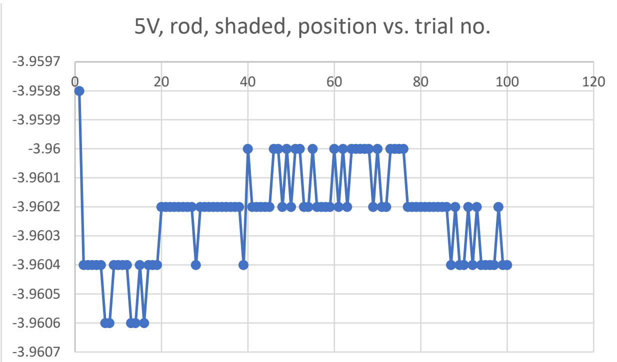


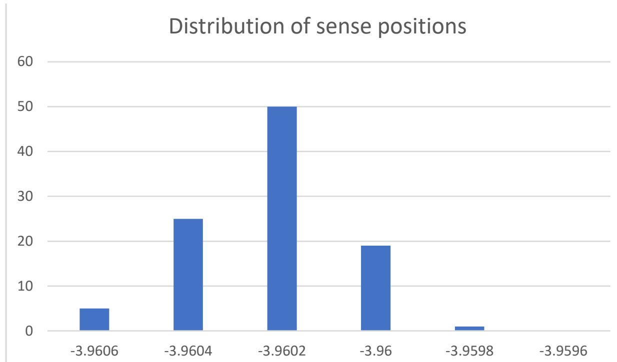


This shows the 100 sensed values for a trial on the left and a histogram of position on the right. (Note that the negative values are just a result of where the axis was zeroed.) For this trial the end positions converge to a limited range after about 40 trials – moving to a precision of 0.2 microns is quite an ask for a CNC machine so there could be all kinds of reasons for this but it does look as if the sensor is fairly consistent. The mean and standard deviation of the last 60 moves are **-4.9583mm** and **0.15 microns**. Other trials did not show the same slow approach to the final value but had a smaller spread.

A similar trial at the same machine zero and supply voltage gave values of **-4.9649mm** and **0.12 microns**. I suspect the slightly lower standard deviation is measurement artefact but the mean value has shifted by 6.6 microns as a result of the supply voltage change.

Using the rod interrupter, I made measurements only at 5V. A similar value of standard deviation was found, **0.16 microns**. The plots below show that for this the final position is being reached almost from the first move and the distribution is much narrower. The standard deviation is calculated for the full set of readings. I was concerned that performance would be worse with the rod as the light might have diffracted round the rod differently from the blade, but in fact it seems to be essentially identical.





Finally, using my "galvanic" probe gave a standard deviation of 0.8 microns, significantly worse than the opto devices. (This is still more than adequate for normal machine referencing.)

Conclusions
Even thought the opto tested is low cost and general purpose, it is capable of sensing an edge to a repeatability of **+/- ~0.15 microns provided that ambient light is excluded and the supply voltage kept constant.** There are probably temperature effects too but these have not been investigated.

This precision is about 30 better than needed to sense pendulum amplitude to 1 second of arc. There are inevitable errors in my measurement process, given the incremental movements imparted by stepper motors and imperfections in ball screws etc; but it seems to me that these would if anything impair measurement precision so in practice an opto may be more precise than this on a pendulum.

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[1] D.A Bateman; *An Electronically Maintained Precision Pendulum* Clock; Horological Journal, vol. 114, pp9-13, January 1972

[2] http://vinland.com/Opto-Interrupter.html

[3] John Haine; *Measuring and Analysing a new Clock – Part 1*; HSN 2020-5.