How do you make a filterwheel step more quickly?

Well, the short answer is of course to use a more powerful motor, but there's potentially a lot more to it than that. This note is to describe the various other approaches that can be taken, and which we ourselves have done in the design of our Optospin system. Ultimately, it's all down to the laws of physics. Although they can't be broken, they can be bent a little here and there. Let's see what we can do!

Spinning & Stepping

The first point to consider is the difference between spinning and stepping, since if continuous spinning can form a satisfactory solution, the problems pretty much go away. It's a potentially sobering thought that there are star-sized objects out there (pulsars) that are happily spinning away at speeds of up to hundreds of revolutions per second, which should be fast enough for most filterwheel applications, so size just shouldn't be a limiting factor here. Admittedly there is the small problem of how to generate the energy to get something so big to rotate so quickly in the first place, but the point is that it can be done, and once you're up to speed (and ignoring frictional effects for a filterwheel and relativistic effects for a pulsar), the further energy requirements to keep it going are relatively small.

In practice, the potential problems with spinning a filterwheel continuously are how to synchronise other equipment to it. Ideally, we would like or may even need to send light through the wheel only when it is reasonably aligned with a particular filter position, and for the detector (usually a camera) and its associated data-capture software to be synchronised to these specific events. Although this may not sound straightforward, we have in fact already done it all, as explained in Jez's application note on the subject. The basic rule of thumb is that as soon as you want to acquire more than just a few images per second, this is likely to be the best way to go!

A continuous spin mode was incorporated in the Optospin design from the start. It can either generate the required spin frequency itself, to which the other equipment can be synchronised, or it can synchronise to an externally-generated control frequency, so there is considerable felixibility on how the various components of the system can be co-ordinated with each other. The important point is that this can all be a lot easier to achieve than you may think – or it will be if you talk to us!

Another advantage of the continuous spin mode is that there is going to be a lot less vibration compared with the discontinuous rotations of stepping mode, although it just so happens that the stepping mode of the Optospin offers a very effective solution to this if if required. More on that solution later, but there remains the inescapable problem in stepping mode, that to go from one filter position to another, the wheel has to accelerate from one rest position and then decelerate again to come to an exact stop at another. That in itself is quite a design challenge, especially if the steps are to be as quick as the electromechanical constraints will allow, but even if this issue can be satisfactorily dealt with (as we believe we have), inevitably a reaction torque is generated as the wheel changes speed. As Martin our President (who once again has volunteered to write one of these Notes) likes to point out, the reaction torque from an accelerating or decelerating filterwheel tends to make the rest of the universe rotate in the opposite direction. Although the effect is unlikely to be noticeable at distances and object sizes approaching those of even the closest pulsar, in practice the nearest point of the rest of the universe is likely to be your microscope, which is likely to be close enough to matter. It is also going to be particularly sensitive to any sort of vibration, so this is potentially very bad news.

Rotating mass

But before we consider our specific solution, it should be obvious that we can reduce the effect by keeping the rotating mass as small as possible. However, what matters here is not just the mass itself, but rather the moment of rotary inertia, which also depends on how the mass is distributed. For fastest stepping we want to keep the inertia low in any case, since this determines how much energy we need to put into the system in order to accelerate it or decelerate it at a given rate – the lower the inertia, the faster these accelerations and decelerations can be for a given motor strength (torque). What comes next may be a bit of an eye-opener for some readers (and perhaps even filterwheel designers?)!

A fuller description of all this is given in the online Optospin manual, but basically the moment of inertia of a rotating disc of any given thickness is proportional to the fourth power of its radius! Again as explained there, the situation in practice isn't quite that bad, as the stepping time for a given motor torque increases "only" with the square of the radius, but it remains a huge effect. So for fast stepping the solution is to stay small! In practice the size of a filterwheel is at least partly determined by the required optical apertures, for which 25mm is the usual figure in imaging applications, but then we have to consider how many filters we want to put in it.

The smallest feasible number is three, in a closepacked triangular configuration, but that leaves little space for the central axle, and basically none for a powering system. We did make a few wheels like this once though, with an electromagnetic drive system operating around the edge, but that necessarily introduced additional size and hence inertia where it was least wanted, which did rather compromise the arrangement. For the Optospin we therefore chose a six-filter configuration, which left a roughly filter-sized hole in the middle. This was big enough to accommodate a small but extremely powerful motor, of a type originally designed for electric flight, where a high power-to-weight ratio is similarly important. The rotating components of the motor (steel and rare-earth magnets) are relatively massy, so having the motor in the middle, where its contribution to the total inertia is relatively less than in that edge-driven design, is a pretty much ideal solution.

10 filters in a wheel?

But are six filter positions enough? They may not be, so designs with ten or possibly even more filters are also available from several manufacturers. However, they are inevitably going to incur a stepping time penalty compared with an equivalent six-filter design. The geometry basically says that once you go beyond six filters in the central-motor configuration, the required wheel radius goes up with the number of filters, so on that basis the stepping time of a ten-filter wheel is likely to be nearly three times worse than that of an otherwise equivalent six-filter one! Ouch….

Acceleration

By the way, this analysis assumes that the wheel is being uniformly accelerated for the first half of a step, and uniformly decelerated for the second half, as we do rather precisely for the Optospin. This gives a stepping time that is proportional to the square root of the number of filter positions travelled, so the worst-case stepping time for the Optospin, which is the three-position step to go to the diametrically opposite one, is only about 70% longer than going to an adjacent one. A simpler control system, which might give a more nearly constant speed between filter positions instead, would therefore perform relatively much worse for the more "distant" steps, so do please bear this in mind when comparing filterwheel specifications!

Clearly, keeping the wheel and the filters thin will help, but this dimension has only a linear effect on the inertia, and hence a square-root effect on the stepping time. Still worth having of course, but the radius remains the killer, so we have addressed the issue in a different way. Our solution for more than six filters is to use two wheels in series, with an open position in each, thus giving a choice of ten filters in total. If that were to require more optical space it wouldn't be so nice, but in fact we've been able to design the Optospin so that the wheel is is somewhat offset in in its housing in the direction of light travel. This allows a second Optospin to fit into the same physical and hence optical space (which is it itself only 35mm) "the other way round" in an overlapping configuration, so the two units appear to be side-by-side, rather than in series as they actually are. To make this completely transparent from a user point of view, the control system (both hardware and software options) allows the two wheels to be driven just as if they were a single ten-position one, so there really is no downside to this approach.

And finally, this configuration provides a very elegant and effective solution to the "rest of the universe" problem. If the two wheels are simultaneously driven in opposite directions, which they already are in this configuration by default because of their opposite orientations, their effects on the rest of the universe rather precisely cancel. It's both easy and very satisfying to see this in operation! A single Optospin just placed on a worksurface will twist around like an epileptic icedancer (no insult intended against such people of course, although sufferers should probably avoid that particular activity) if driven at anywhere near its full power, because of the countertorque which now mainly affects its housing. In contrast, a pair connected in this way and driven together just sits there as if nothing is going on. In fact, the situation can be made even better than this. For the best torque cancellation effect it's important to have an equal number of filters in each wheel, so the obvious solution is to distribute them so that one wheel has filters in the odd numbered positions, and the other has them in the even ones. This means that the inertia of each wheel ends up being lower than that of a single one with all six filter positions occupied. An excellent solution to the problem all round!