K2 Star Tracker

K2 is a motor-driven star tracker that I designed and built to allow photographs of the night sky to be taken without the photographs showing star trails due to the rotation of the Earth. I wanted to be able to take the star tracker on holiday to Kenya (on the equator) and photograph the skies there that are unaffected by light pollution.

So the star tracker had to be:

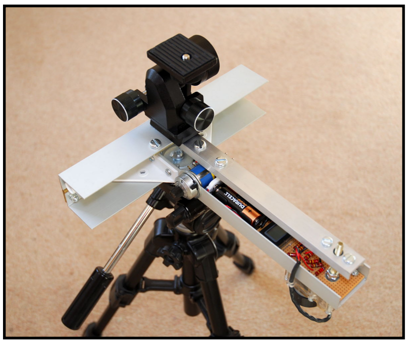
- Compact
- Light
- Strong
- Accurate
- Battery operated
- Low power
- Cheap
- Easy to construct

In practice, this means:

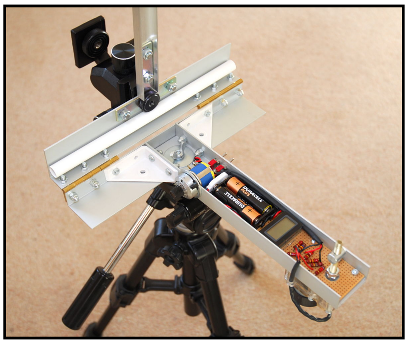
- Footprint no larger than A4
- Less than 1 kg
- Able to support a digital SLR camera
- Exposures of up to 15 minutes
- No mains electricity in the bush
- Must operate for up to 6 hours
- Cost < £50 for all components
- Manual tools and electric screwdriver

Construction

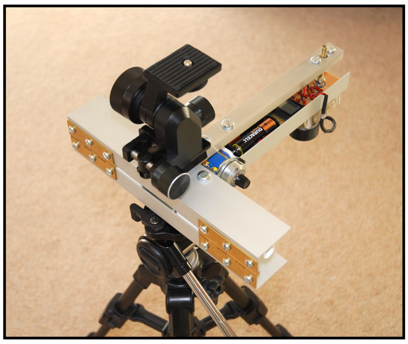
As this was my second star tracker (I built my first one when I was a student at college) I called it K2. I decided to construct K2 from lengths of L-section and U-section aluminium bolted together as this is very strong and very light. The sections make two 'T' shapes, the static base T and the moving top T. The pivot is provided by two brass hinges that connect the two T's together, positioned at the ends of the top bars of the T's. When operating the two T's are pushed apart by a bolt driven at 1 rpm by a small motor and gearbox. The design is optimised for low latitudes (within 20° of the equator), but will also work in the UK (latitude 52°) provided that the camera and lens are not so heavy that they put the whole system out of balance.



K2 in operating configuration



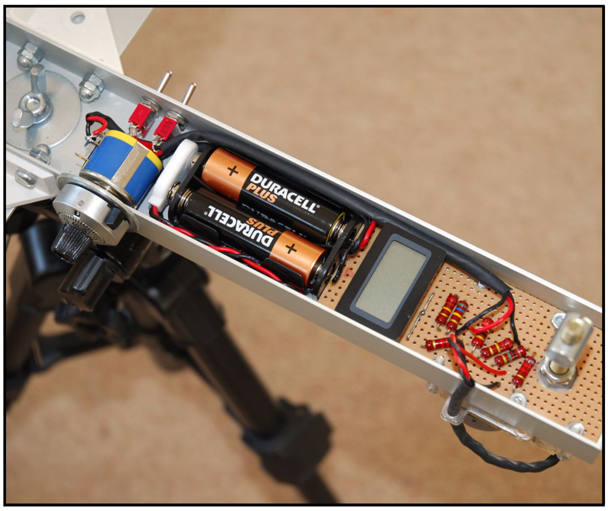
K2 opened to show components



Hinges give a smooth movement

The M6 bolt has a 1 mm pitch and is positioned 230 mm from the hinge axis. A nut sits on the bolt and is driven upwards as the bolt rotates (the nut cannot rotate as it is constrained within the U-section arm that forms the length of the top T). Driving the bolt at 1 rpm forces the top T to rotate at approximately 1/230 of a radian per minute, or one revolution per day, to counteract the rotation of the Earth. The design is not as accurate as a double-arm drive, but simpler in construction.

The long arm of the base T is made from two lengths of L-section aluminium bolted together to form a 'U' section of width 40 mm (the width of two AA batteries side-by-side). If my local B&Q store had had some U-section aluminium in stock that was 40 mm wide I would have used that instead. The arm forms a tray in which all the components fit: batteries, switches, potentiometer, voltmeter and circuit board (see close-up image on the right).



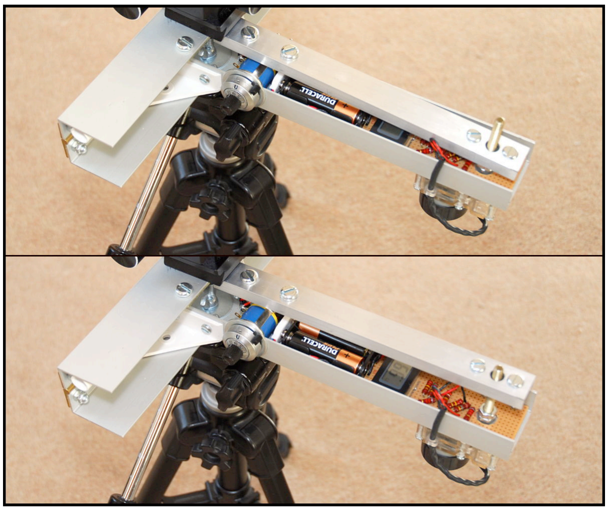
Close-up of components

The motor/gearbox is bolted underneath the end of this arm with the M6 bolt poking through a hole in the arm and in the circuit board. The head of the bolt is filed down to fit snugly into a slot in the gearbox output shaft.

The camera is mounted onto an adjustable mount bolted to the top T, close to the hinge axis. If the hinge axis of K2 is aligned with the Earth's axis, the the camera should follow the stars as they appear to rotate around the sky and hence the stars will not trail when a long-exposure photograph is taken. A plastic tube is fitted to the underside of the top T, parallel to the hinge axis, visible in the image above in which K2 is opened up. This can be used as a sighting tube to align on Polaris when operating in the UK. It does not work in Kenya as Polaris is on the northern horizon and is usually hidden by trees, hills, lions or elephants.

In practise, the tracking accuracy of K2 is determined by the degree of alignment between the hinge axis and the Earth's axis. A polar scope, used in some commercial star trackers, is useless if Polaris is on the horizon. An alternative method of alignment is to use an inclinometer and a compass to set the altitude and azimuth, respectively. A digital inclinometer is accurate to 0.1°, but even a digital compass is only accurate to about 1° and you have to know the offset between magnetic North and true North for your location. Inaccurate polar alignment is the biggest factor that affects the overall tracking accuracy of K2.

Note added in 2011: I have found a way to make this work on the equator by adding an additional sighting tube (not described here).

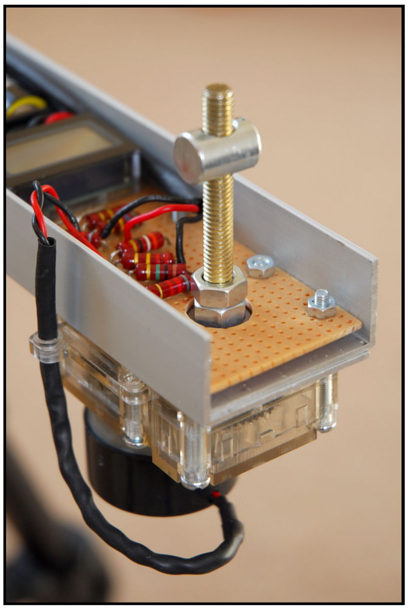


Movement after 15 minutes driving

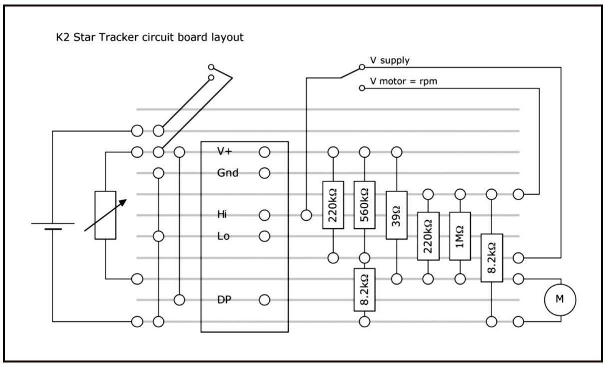
The image on the left shows K2 at the start (top) and end (bottom) of a 15-minute run. The motor has turned the bolt 15 revolutions, pushing the nut 15 mm upwards along the bolt and rotating the top T by about 4° from its starting position. At this point the top T can be lifted off the nut and the nut spun back down the bolt by hand, ready to start another 15-minute run. Note that the direction of the bolt moves slightly as the top T moves relative to the base T.

The nut moving on the bolt is cylindrical (see close-up image below right) and so the contact point on the underside of the top T 'rolls' over the cylinder. Small strips of teflon on the underside of the top T ensure smooth contact between the nut and top T.

The layout of the components inside the base T is shown in the close-up image above right. The resistors are arranged in two sets. One set is a potential divider to drop the 3 V supplied by the two AA batteries down to the 2.3 V that is needed to drive the motor at 1 rpm (3 V drives it at 1.3 rpm). The second set is used to drop either (i) the voltage supplied by the batteries or (ii) the voltage across the motor down to the appropriate value for display on the LCD voltmeter. As the voltmeter is set to read a maximum of 1.999 V (for maximum resolution) the battery voltage is divided by 2 and so displays 1.5 V when the batteries are fresh. The voltage across the motor is divided by 2.3 so that the voltmeter reads 1 V when the motor has 2.3 V across it (and is rotating at 1 rpm). Thus, the voltmeter effectively reads rpm.



Barrel nut on drive bolt



Layout of circuit components

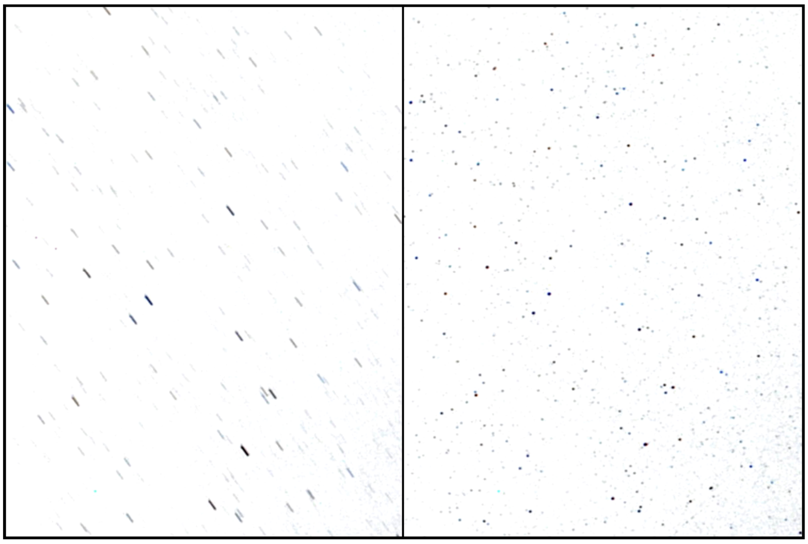
The layout of the components inside the base T is shown in the circuit diagram on the left. The potentiometer is in parallel with one of the resistors in the potential divider that drops the battery supply voltage down from 3 V to 2.3 V. This allows the voltage across the motor, and hence the speed of the drive, to be adjusted to compensate for the slow drop in voltage of the batteries as they gradually run down.

When starting a photography session, the potentiometer is adjusted until the voltmeter, set to read the voltage across the motor (divided by 2.3), reads 1.000 rpm. Over a 15-minute period, the battery voltage will hardly change at all, but it can be checked at the end of each 15-minute session when the top T is lifted to spin the nut back to its starting position. The voltage supplied by a battery changes with temperature, so it's worth keeping an eye on it over the course of a night as the temperature drops.

As K2 was built with hand tools, I could not guarantee that the dimensions were exactly as per theoretical design. This is not a problem. For instance, if when constructed it turns out that the distance from the drive bolt to the hinge axis is 231 mm, rather than 230 mm, then the motor can be set to drive at 231/230 = 1.004 rpm.

Performance

So, does it work? I have tried it with a Nikon D200 digital SLR with both wide angle and telephoto lenses. The combined mass of camera plus lens was up to about 2 kg, so this was a good test of the rigidity of the system.



30 sec exposures with K2 off (left) and K2 on (right)

The images are 600 x 800 pixel areas cropped from the original 10 Mpixel images. They were taken with a telephoto zoom lens set to a focal length of 100 mm. They are single exposures (no stacking of multiple frames) and no dark frames were subtracted.

The image taken with K2 switched off shows the extent of trailing that would be expected due to the rotation of the Earth. The image taken with K2 switched on shows essentially no trailing. So, yes, it works.

The image on the next page shows what you can do with K2 and a 35 mm lens from a dark sky site, in this case the Teide Observatory in Tenerife.

The centre of the Milky Way galaxy in Scorpius

Nikon D200 DSLR + 35 mm lens / 20 x 1 minute exposures / stacked and processed using *Image SXM*

Components

The components used to construct K2 are listed below:

2 aluminium sections 200 mm long	L-section 40 x 20 mm for hinged sides of both Ts
2 aluminium sections 250 mm long	L-section 40 x 20 mm for U-section arm of base T
1 aluminium sections 210 mm long	U-section 20 x 10 mm for arm of top T
2 plastic corner braces	To brace junction of base T
1 metal 'T' brace	To brace junction of top T
2 brass hinges	To provide the pivot axis
M6 bolt with barrel nut	60 mm, sold as 'furniture bolt'
Motor and gearbox (£30)	http://www.precisionmicrodrives.com part #256-101*
2 AA batteries in holder	Standard
2 mini switches	Single pole double throw
Mini LCD voltmeter (£20)	3.5 digit 0-1.999 volts – RS stock num 223-199
Potentiometer	1 kohm 10-turn helipot
Resistors	Values depend on motor – see circuit diagram
Circuit board	100 x 40 mm

* This motor is an integrated motor/gearbox/microswitch. Although the motor and gearbox are ideally suited for the job of driving K2, the integrated microswitch was an unnecessary addition. A cam on the output shaft of the gearbox operated the microswitch every revolution, which caused a small but noticeable periodic error in the motor's speed. If you use a motor like this, I suggest that you remove the microswitch.

** Note added in 2013: I have been told that Precision Microdrives no longer supply this motor in small quantities. That's a shame. Other motor/gearbox combinations with similar operating characteristics can be used instead.*

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