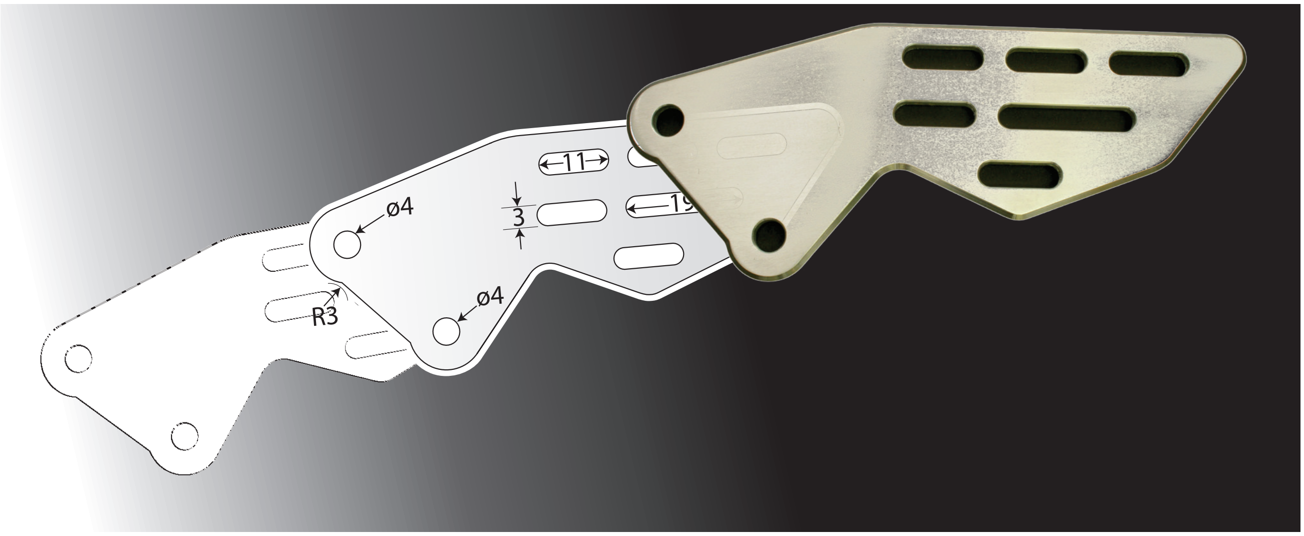
CNC in the Workshop



Part 2

Part 2

In this part of the series, we look at how to set up Mach3 to work with your mill, and how to make sure the movement of the slides correspond to the instructions used within Mach3. In Part 1 we discussed some of the important things which go on "under the bonnet" when the software runs.

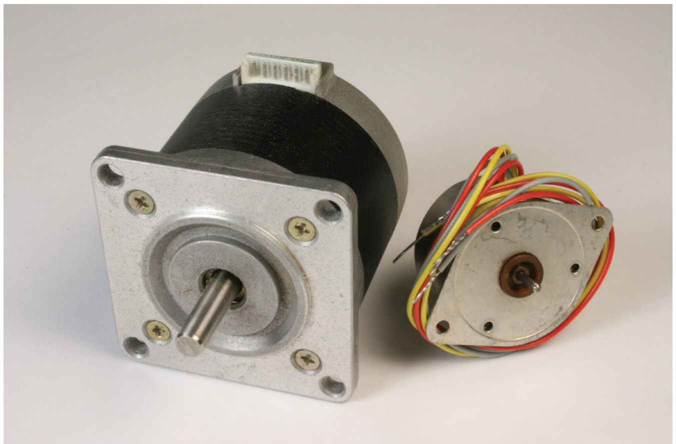


Photo 13: 200 step type 23 and 48 step flange-mounted stepper motors.

COMPONENT PARTS OF A CNC BENCH MILL

Bench mills all take a similar form, with a table giving side-to-side (X axis) and back-to-front (Y axis) movement, and a head carrying a spindle which can move up to take the spindle further from the table, or down to take the spindle nearer the table (Z axis). These motions serve to move the position of the Controlled Point (CP) in relation to a workpiece (see part 1). Most CNC bench mills are physically similar to manual versions of the same machine, but there are three possible differences. First, the handwheels are replaced by stepper motors controlled by computer software, so movements of the CP in relation to the X, Y and Z axis are under computer control. Second, the leadscrews operating the axes may be ballscrews. Third, the dovetail slideways traditionally used to guide the motion of the table and head may be replaced by linear guides.

Stepper motors

Stepper motors need to be sufficiently powerful that they can move the slides against the friction in the slideways and the leadscrews and the cutting forces generated during machining as the cutter machines the workpiece. Early projects suggested relatively low power stepper motors, but relatively powerful steppers are now available at reasonable cost, so that this it is easy to install motors of sufficient power nowadays. Stepper motors are specified by their torque value, with commonly available useful sizes ranging from 36Ncm (for small, low torque applications) to 610Ncm (big enough for a Bridgeport) and beyond. Steppers are often referred to by frame size (i.e. the length of the external mounting flange), so that a size 34 stepper measures approximately 3.4 inches across the flange.

Currently, different designs of stepper motor internals result in different maximum torque, so frame size alone is not a sufficient guide. It's the maximum holding torque that is important. That is the torque the motor can exert to hold its position, wherever it stops. The torque when the motor is turning falls as the speed increases, and that can be a considerable fall, with the torque at, say, 3000rpm being only ¼ to 1/8 of the maximum holding torque. This means that stepper motors are a good choice for low speed movement where high torque is required, as when moving machine slides, but are not the ideal choice where high spindle speeds are required, which is a pity. Figures available from a manufacturer of stepper controllers (Gecko) indicate that a NEMA 34 stepper of "triple stack" construction running at 80 volts and drawing 7 amps current can sustain around 250W or ¼hp. Any requirement for more power would generally indicate the need to switch to a servo.

Typically, stepper motors take 200 steps to make one revolution of their shaft, which is a movement of 1.8º per step. Some, though, take only 48 steps per revolution, and these are commonly found in printers and smaller consumer devices (photo 13). At 48 steps, the stepper turns 7.5º per step, so this does not allow as high a resolution as a 200 step motor. The steppers used on machine tools are generally 200 steps per rev. Although this is the designed step size, the electronics in the stepper drive controller can increase this to up to 2000 steps per revolution by forcing the stepper rotor to float between its normal as-designed rotor positions. This is termed "microstepping" and the controller does this by cunningly manipulating the way in which the poles of the stator are turned on and off. One effect of providing more steps is to allow smoother transitions as the stepper turns. With microstepping, each single "normal" step is divided into, say, 10 micro-steps, so instead of rotating 1.8º in a single movement, the stepper gets there by taking ten microsteps of 0.18º. This smooths out the motion and is particularly important where the stepper is turning at a relatively slow rate (less than 4 revs/sec or 800 full steps/sec). Imagine that step signals are being sent from the computer at a rate of 1 per second. This would mean rather slow movement of the slides, and cutting would take place in noticeable steps, which would affect the finish on the workpiece. Microstepping helps maintain motion

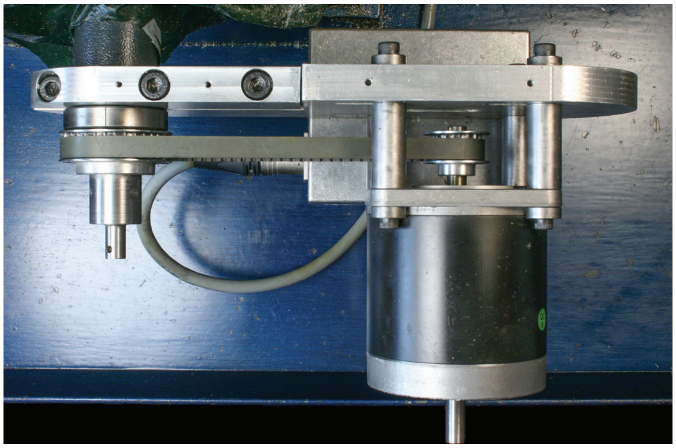


Photo 14: Stepper belt drive

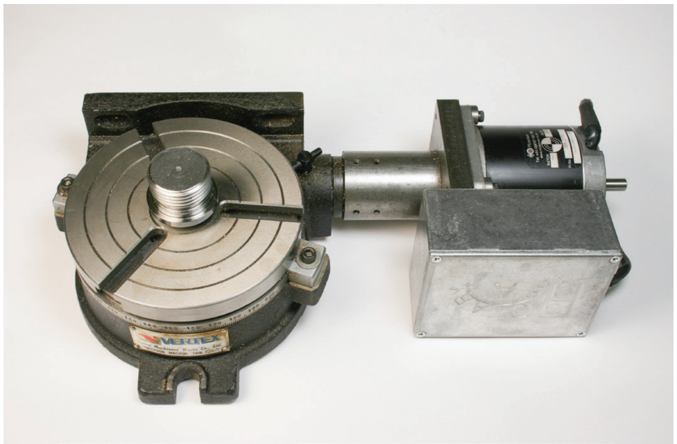


Photo 15: Rotary table, showing connection between stepper and table

between pulses, and smooth the movement of the slides, improving surface finish. However; microstepping results in lower power from the motor (roughly a 30% reduction) and torque falls off as speed increases, so microstepping is not helpful at higher speeds. A good motor controller deals with all of this, using a pulse multiplier to carry out microstepping at the stepper when pulses are arriving from the computer at a slow rate, and switching off microstepping when the pulse rate is higher. This means the stepper will move with optimum use of microstepping. There is a lot going on inside both the controller and the stepper, during microstepping, and there are practical limits on the size of microsteps because there is a trade-off between the size of the steps and the torque at the stepper's shaft. There is a good explanation of microstepping on the Gecko website, and a link to that (and other explanations on other sites) appears on www.cncintheworkshop.com Microstepping is a useful feature, but not essential.

Where a stepper is used to turn a feedscrew, it is important that backlash is minimised, so the linear motion of a slide corresponds to the rotational movement of the stepper. There are two aspects to this; stepper-to-feedscrew connection, and feedscrew backlash. One commonly accepted way of connecting stepper to feedscrew is by using toothed belts. While you might think a belt drive is inherently suspect due to flexing, slipping and stretching of the belt, toothed belts and pulleys are used to eliminate these problems. The belts incorporate inner steel cables, and the shapes of the teeth on belts and pulleys prevents slipping and lost motion. These are often called timing belts, probably because of their widespread use in car engine timing systems. There are a number of differently shaped proprietary tooth profiles, and it is most important that the profiles of belt teeth and pulley grooves match. My own mill uses the T5 profile belts (photo 14).

Using a belt drive makes it relatively easy to set the ratio between stepper shaft and feedscrew by choosing appropriate pulley sizes. One-to-one might be a good place to start, but more torque is available, at the cost of lower speeds, by using a small pulley on the stepper and a pulley twice the size on the feedscrew to give a 2:1 ratio between stepper and feedscrew. That's what I have done on my mill, and it has the advantage that the feedscrew can effectively be rotated in steps of 1/400 of a rotation while still maintaining a decent top speed (which is beyond what I can use in practice). My feedscrews have a 4mm pitch, so each step of the stepper will move the slide 4/400mm or 0.01mm. Mach3 will need to know this when we set up the software to control the mill.

For slower speeds and rotary shaft drive, such as on a dividing head or rotary table used as a fourth axis, belts are not necessary, and a stepper can be coupled to an input shaft directly, or, preferably, using a coupling which is designed to cope with a little misalignment of the shafts without introducing backlash e.g. the "Oldham" coupling. On my own rotary table, I have simple used a sleeved coupling with a hole for each shaft and grubscrews to retain the shafts in the coupling, and all covered by a thick tube (photo 15). There was not enough space for an Oldham coupling, in my design, and I can't say I have missed it; or if I have, I haven't noticed yet.

As with the linear slides, Mach3 will need to know the amount the rotary axis will turn for each step of the stepper. My rotary axis is a Vertex HV6 rotary table with a 90:1 reduction through a worm, so 200 steps (1 revolution) of the stepper corresponds to 360/90 or 4°. Each step results in 4/200 or 0.02°

Feedscrews

Most manually operated mills have feedscrews of trapezoidal section, like ACME threads which are strong, and relatively easily made. Using trapezoidal feedscrews in a CNC mill is quite practical, so that a manual mill can be converted to CNC operation without much difficulty.

Commercially, most CNC mills use ballscrews, as these present less friction than a corresponding trapezoidal screw thread. In a ballscrew, the nut contains a set of small diameter balls which travel in a spiral channel inside the nut. Rotating the screw causes the balls to roll from one end of the nut to the other. Once at the far end, the balls are guided back to the start of the nut, either along a channel inside the nut, or by travelling through tubes external to the nut. This system means the surfaces of the leadscrew and the balls in the nut roll against one another, compared to the sliding action of the flanks of a trapezoidal feedscrew against the thread of its mating nut. Rolling friction is lower than sliding friction, so a ballscrew generally means lower frictional losses in the system. In fact, I replaced the trapezoidal feedscrews in my manual mill with ballscrews (photo 16), and was able to move the table by pushing firmly against one end. That was impossible with the conventional leadscrew. Low friction has its downside, though, and while it will take less effort for a stepper motor to turn the leadscrew, there are fewer frictional forces resisting the motion of the slides when a cutter tries to pull a workpiece instead of pushing it while cutting. This is a real disadvantage. Several mills which use trapezoidal feedscrews have split nuts which allow the backlash to be adjusted to compensate for wear, and that system has been used to good effect in several CNC conversions, retaining both the trapezoidal screw and the adjustable nut. It's a system which could be used with ballscrews, but I haven't seen anyone applying it in a small mill, yet.

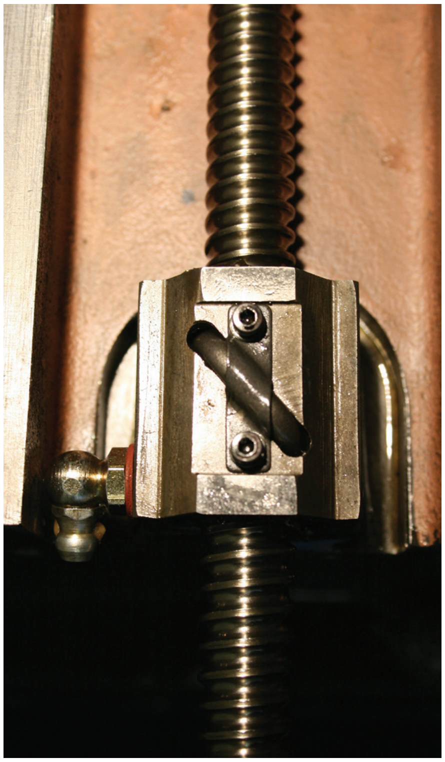


Photo 16: Ballscrew and nut.

Ball screws have different backlash characteristics, depending on their quality and diameter. Generally, rolled ball screws are less accurate than ground screws, and ball screws under 16mm diameter do not have zero backlash. Ground ball screws over 16mm can be obtained with zero backlash, although the cost is considerably more than for a trapezoidal leadscrew and adjustable nut.

One important characteristic of ball screws is that backlash is generally consistent along the thread, and wear rates are lower than for trapezoidal leadscrews so that accuracy and backlash tend to remain constant for a longer period, retaining accuracy of movement. Backlash is a pain, but provided we know the backlash of our mill, we can factor this into Mach3 when we set the system up, and can alter this from time to time, if necessary. The effect of backlash is such that when a slide is moving in one direction, and is then reversed, some of the steps made by the stepper motor will be used in moving the feedscrew without any corresponding movement of the slide, as the feedscrew takes up the backlash. This means there will be a discrepancy between where the software thinks the slide is, compared to where it actually is. The difference is the backlash in the slide. Mach3 can automatically take the backlash into account when changing the direction of movement, *provided that backlash is accurately specified*, so that there is no lost motion when a slide reverses direction, and the software continues to track the actual position of the slide, knowing that the steps required to take up the backlash did not result in any real movement of the slide. Where backlash is small, and there are only a few reversals of direction during a machining session, the effects are often unnoticed. But some operations involve hundreds or thousands of small movements with frequent reversals, and errors then accumulate, producing a visible result. In engraving, for example, the Z axis moves up and down frequently, so that in a simple engraving with thousands of movements, accumulated errors can become quite large, with sometimes startling results. The Controlled Point may gradually lower, resulting in cuts which are progressively too deep; or the Controlled Point may gradually rise, resulting in the tool cutting air rather than the workpiece. Cutting air is merely frustrating; cutting too deeply is damaging, and potentially expensive.

Converting mills with conventional feedscrews to ball screws generally involves having to find extra space for the ball nut which is usually much larger than the corresponding trapezoidal nut. I feel moved to caution against machining chunks from the underside of a mill table. These are generally castings, and all castings move when machined. My own mill was a manual mill purchased with the express purpose of following a published design for conversion to ball screws and CNC. Despite knowing better, I followed the instructions to the letter and machined a small channel on the underside of the table. On reassembly, it was clear that the table was no longer flat. In this area, I was lucky to be able to find a large bed grinding machine and a company willing to tackle the job of grinding it flat once more. That was shortly before the company sold the last of its manual machines, so that is a job I could not now have carried out anywhere within reach. Be warned, please.

Slideways

Conventional machine tools have, until fairly recently, used a system of dovetail slides to guide tables and vertical slides. That's a good system, proven over many years, but it suffers from the same frictional disadvantage as trapezoidal feedscrews. Modern machine tools often use linear rails instead. These are hardened rails on which run carriages containing ball bearings. Like ball screws, the friction between balls and rails is rolling friction and so is lower than the sliding friction between the sides of a dovetail slide. If your mill has dovetail slides, it is extremely unlikely that you would be able to replace those with linear rails. If you are looking for a new CNC mill, you may want to ask about the availability of linear rails, as several small CNC mills do now offer these, either as standard or as an option.

For the home constructor, it seems to me that linear rails provide a much easier way of constructing slides than machining dovetail slides from solid cast iron.

Switches and sensors

Ideally, a mill will have switches (mechanical or optical) to signal to Mach3 that a slide has reached the end of its travel (2 switches per slide; one at each end) or the Home position. Home is simply a known position, and we will deal with where it is, later, so it would be useful if that position was adjustable. You could use one of the Limit switches as a fixed Home position. The brave amongst you (and experience suggests that is most of you) can dispense with all of those switches. Just don't come crying when a slide comes off the end of its travel and the little balls fall out of the ball nut and disappear… Mach3 can operate without Limit of Home switches, if it is set up to do that. Having operated for some years without any switches, due to inherent laziness and a very long To Do list, I have now fitted a full set, and believe the benefits outweigh the time taken to fit them.

Brackets, boxes, bits and bobs

Photo 14 shows the mechanical arrangements I used on my mill to mount the steppers and photo 17 shows how I dealt with the connections between the steppers and the cables connecting to the computer and power supply. The leads from the stepper motor are wrapped into one cable, using heat-shrink tubing. The leads are twisted gently together, then slipped into the tube. On application of a little heat from a hot air gun, the tube shrinks to grip the leads and produce one cable. The cable passes through a rubber (or plastic) gland into a die cast joint-box into a connector block where they are connected to the ends of short leads soldered to an XLR socket mounted in the side of the box. This allows pairs of leads from the stepper windings to be connected to single leads going to the socket. The idea here is that the stepper can be disconnected by undoing 4 screws, instead of having to unsolder the leads from the socket.

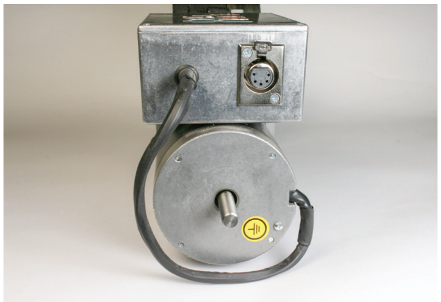


Photo 17: The cable from the stepper motor goes into a connection box via a sleeved grommet..

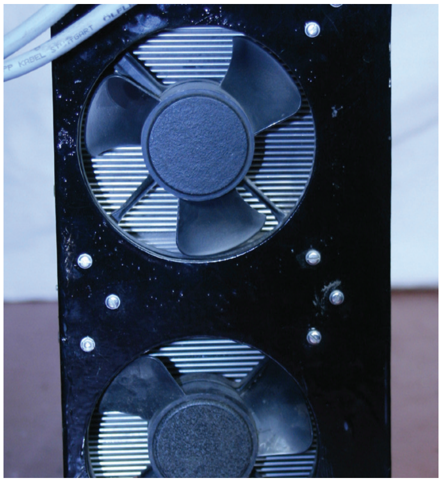


Photo 18: Leads from stepper motor connection boxes connect to the rear of the power supply/interface..

Long cables with an XLR connector on each end run between the joint-boxes for X, Y Z and A axes and the rear of my power supply unit (shown resting on its side, in photo 18). I used 5 pin XLR plugs and sockets at the joint boxes and the back of the power supply/interface unit as these can carry power and ground to the stepper motors, as well as the step and direction signals. 5 pin XLR plugs and sockets are commonly used for DMX audio equipment so they are readily available. Good quality XLRs are robust (cheap ones are not, of course) and I use the locking versions for security. I used cable which did not have an overall foil shield. Most folks recommend that shield as a protection against electrical interference, and that is a wise precaution. I chose the individually shielded inner cores. It is worth emphasising the need for a quality of connectors which suits the current and voltage they will be expected to carry. I was aware of this when I chose connectors for my own mill, but was tempted towards connectors I had used before, which were nicely colour-coded and snapped together with a satisfying click. They were certainly much cheaper than the most expensive make. Sadly, photo 19 shows the effect of more current than that quality of connector can consistently carry over a period of some years, and I have just had to replace that plug and socket.

Photo 19: Socket showing the effect of too much current..

I expect to have to do that for the others on the mill, as preventative maintenance. The cheaper connectors did not have a published specification for current and voltage, while the expensive alternatives did specify their maximum current and voltage ratings to be a little more than my steppers might draw under extreme conditions. Cheaper connectors at half the price turned out to be a bad buy. I am now using the Neutrik NC5MXX plug and the NC5FP1 socket from RS Components, at £5.76 and £6.67 respectively.

Power supply unit

Commercially-available power supplies are probably the best solution nowadays, but, as mentioned in part 1, I built the mother of all power supplies, and took the opportunity to incorporate several additional features on the front and rear panels. I also built the motor controllers into the power supply case. Aside from the electrical characteristics, the principal consideration was heatsinking for the motor controllers (an issue which affects all motor controllers), so the rear portion of the case is a separate chamber with some very expensive and very high-spec heatsinks. Heatsink effectiveness is expressed as thermal resistance, or temperature rise per unit of power, i.e. degrees Celsius per watt or power, or °C/W. The better heatsinks will dissipate all the heat an attached electronic device produces, without allowing the temperature of that device to rise so high that the device fails. The heatsinks I have used are large and efficient (low °C/W) and have additional cooling provided by two large computer fans. The large size of the heatsinks allows each to carry a pair of stepper controllers. There is a layer of heat conductive paste between each controller and its heatsink. In use, the heatsinks run cold all the time, so the system works quite well. Given the astonishing cost of the heatsinks, that's just as well. Nowadays, there are some interesting cooling devices available for computer processor chips, including some wicked looking liquid cooled devices, so those may be worth investigating. I wonder if they need to be installed by a certified plumber?