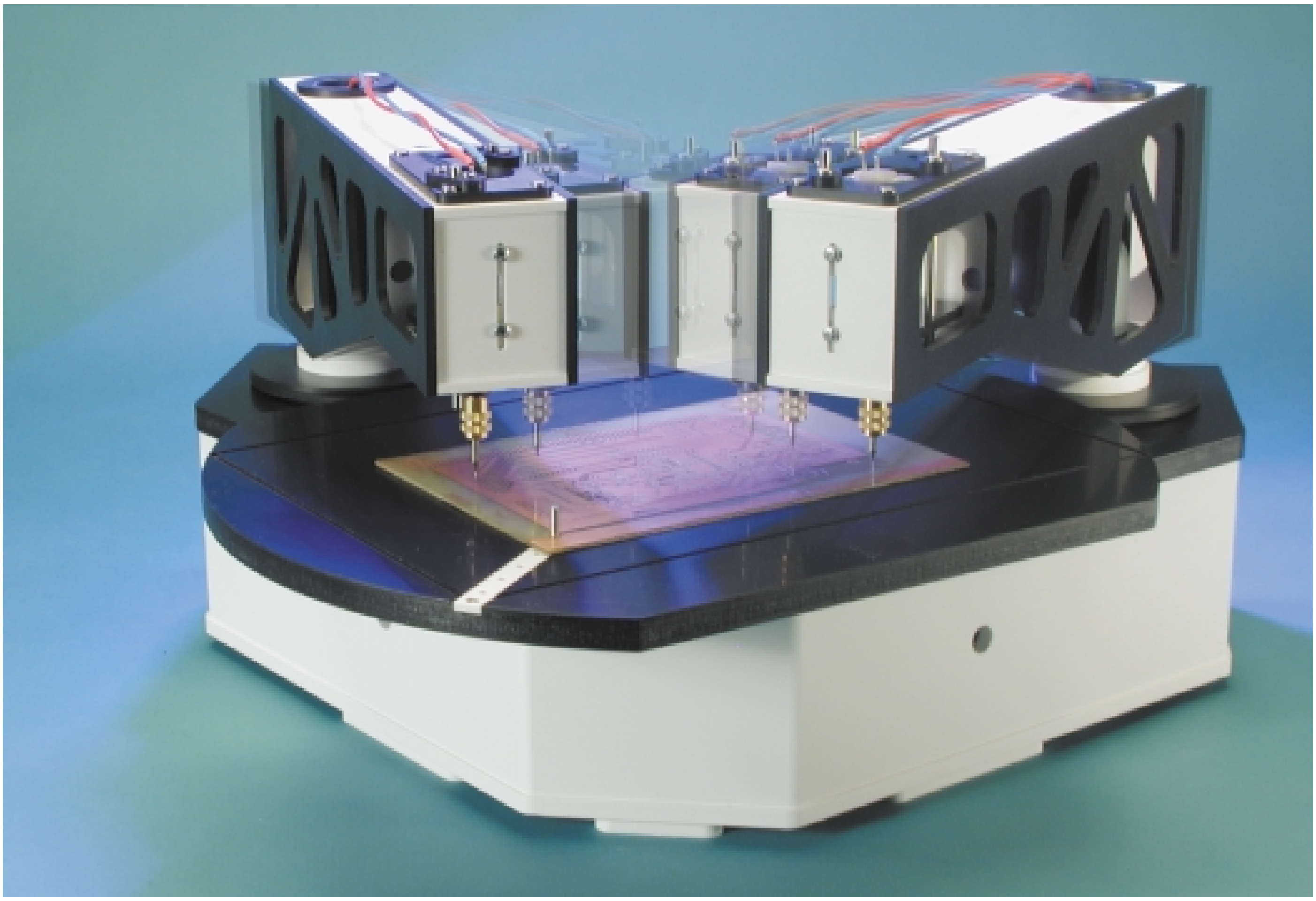
PCB Drilling Machine

Part 1: New solutions to old problems

By T. Müller (Radix GmbH)

Elektor Electronics is proud to present an unprecedented home construction project: a CNC PCB drilling machine which is economical, accurate, quick, and bristling with new ideas.



Large-scale electromechanical projects have tended to be the exception rather than the rule in *Elektor Electronics*; but these exceptions have always been well received. Many readers will have fond memories of the Plotter and Plotter Mark 2 projects, which hundreds of constructors across Europe have built and which even fifteen years after publication still boasts a large fan club.

There is a very good reason behind the idea of presenting an electromechanical project for home construction. Rather than the fascinating and in places supremely elegant and unusual design, it is the cost saving that drags the ambitious hobbyist away from the soldering iron to less familiar tools. Home construction of a plotter made a lot of sense when a ready-made commercial device was outside the financial grasp of the electronics hobbyist.

These days, however, plotters only find specialist application, and low-cost ink-jet printers do the 'plotting' work; and no-one would consider producing a printer for home construction when mass-produced commercial devices are so cheap.

So such a project in *Elektor Electronics* must be timely and have a 'best before date' well in the future. The computer-controlled PCB Drilling Machine described in this article and the instalments to follow fits the bill. Commercially available machines with comparable specifications are around four times as expensive as the one presented here, and are hardly likely to become mass-produced commodities sold at bargain basement prices. In conventional CNC drilling machines the mechanical parts are too expensive and too complex, and cannot be made from cheap materials.

This opens the way for new ideas. The author has developed a CNC PCB drilling machine that is distinctive in two ways: first, in its economical mechanical construction, using moulded plastic parts rather than the conventional multitude of aluminium and steel components; and second because of the supremely elegant and unusual design.

We would like to describe a little of the story of the PCB drilling machine in a series of constructional articles. If you decide to construct the machine, you do not of course have to make the components yourself. Through his company, the author is offering to supply a complete kit of mechanical parts; *Elektor Electronics* (and certain component distributors) the electronics. The basic construction kit should not cost more than about five hundred pounds. More on this, and delivery details, will appear on the second instalment in the next issue of *Elektor Electronics*.

Specialist mechanical skills are not required. You will be as surprised by how foolproof construction of the machine is as we were in the *Elektor Electronics* laboratory when we first saw it run. And even if you are not planning to build the drilling machine, we hope you will still find the articles interesting!

PCB Drilling machine

Concept

CNC machine with 2.5D operation capable of vertical drilling in circuit boards up to 300x200 mm^2

Construction features

– No torsion on machine, since all points where forces are applied lie at centres of rotation
– No expensive sliding components such as V-grooves, linear bearings or ball races
– Self-calibrating drill advance using magnetic drive
– Low torque about base fixing points

Functional features

– Up to four tools in use simultaneously
– No tool changing required
– Greatly improved speed moving from drilling point to drilling point
– Clear and easy access to table from above

Benefits

– Circular turntable allows fixing points outside the usual rectangular workpiece: conventional tables lose working area to fixing points
– Small footprint due to efficient use of area
– No ball races, no worm gears
– No thermal problems due to non-planarity
– Simple construction, no calibration for planarity or squareness
– No force on drilling head from trailing cables
– All heavy and sensitive components underneath or clear of working area
– Swarf cannot jam mechanism

From Idea to Circuit Board

The individual steps in developing an electronic circuit, from the idea through to the populated prototype circuit board, usually follow on from one another more or less smoothly.

First of all there is the initial design. Depending on the experience of the designer and on the complexity of the circuit, small parts of the design may first be tried out on prototyping board or by tacking components together. Then the parts are placed on a printed circuit board, leaving space for expansion, power supply, and the like.

In the past printed circuit board layout was a tedious job, involving the rubbing down of transfers onto transparent film. These days things are much easier: using a suitable software package, the tracks and pins are simply sketched on the computer and the layout can subsequently be modified and processed as desired. The layout program will allow the results to be output in many different ways: frequently the layout is simply printed out on paper, but for higher quality (and at greater expense) the results can be photoplotted onto high-resolution film at a reprographics bureau.

The light-sensitive surface of a suitable piece of copper-clad board can now be exposed and developed. This removes the light-sensitive resist coating in those areas where the copper is to be etched away. At this point, for most electronics hobbyists and prototype builders, the nightmare begins. To develop and remove the unwanted copper chemical processes are used which employ various unpleasant chemicals. We surely do not need to explain to Elektor Electronics readers that the properties of the etchant are such that not only the copper on the circuit board, but also hands, tables, chairs and clothing — all can get eaten away. Some advice: if you use a colourless etchant, you only notice a splash when it is too late, and you find a hole in your clothing; use a coloured etchant and you can see the impending disaster before your clothes are ruined. A brown iron (III) chloride (ferric chloride) stain is easy to spot and can be neutralised with sodium hydroxide (caustic soda), before using a specialist stain remover.

Etching need no longer be carried out, as it was in the past, in open trays: closed etchant-spray tanks are readily available, and

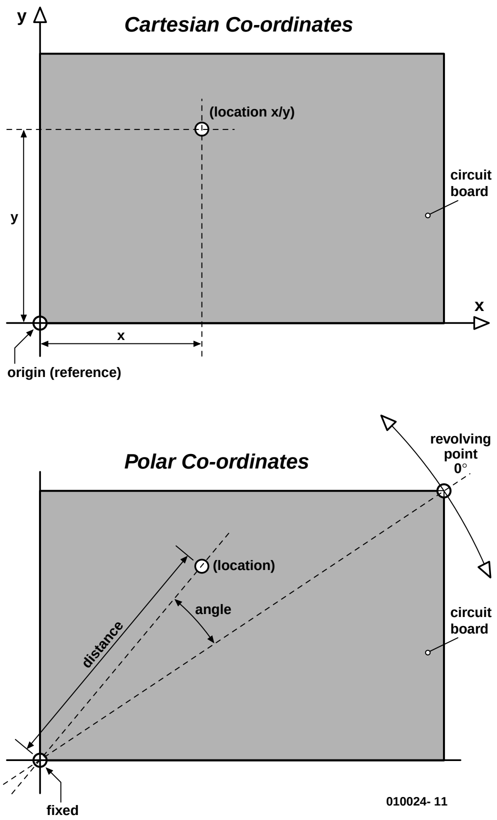


Figure 1. Cartesian and polar coordinates.

affordable. Closed systems keep the unpleasant chemicals to a defined area.

Do not forget that any remaining etchant must be washed from the newly-etched board first with water and then any still clinging to the board can be treated with developer.

Caustic soda is cheap and in any case does not keep well. Plain water will not do the job: it does not clean the board properly. After drying, the copper side should be sprayed with a lacquer to make soldering easier and to prevent the copper from oxidising.

A Boring Story

Next, holes are bored in the circuit board using drills of various diameters. In general, three drills are used: the commonest is 0.7 mm or 0.8 mm, used for almost all small components such as resistors, capacitors, ICs; it is even suitable for the leads of some electrolytic capacitors. A 0.9 mm or 1 mm drill is used for most connectors, square pins and the larger diodes. Larger connectors, solder pins and similar components require a 1.2 mm or 1.5 mm drill.

Usually a mini-drill is used in a simple pillar stand. Great concentration is required to ensure that the holes are drilled centrally in the pads, so that the holes line up in straight rows and columns. Otherwise, fitting components such as D-connectors and 40-pin ICs will present a major problem.

Larger holes, perhaps 3 mm for mounting bolts or screws, are best not drilled with the mini-drill. More powerful machines, however, tend to pull away at the circuit board material, which gives an unsatisfactory appearance to the holes. It is better to drill first with a 1 mm drill and then use a hand reamer.

High speed steel (HSS) drills can be used for all except fibreglass boards. Hard metal drills are not suitable for fibreglass because the glass embedded in the plastic wears away the cutting edges of the drill so fast that it struggles through the material and does not produce a clean hole. Hard metal drills have a 3 mm or 1/8” thick spindle and a small cutter. These drills, costing upwards of two pounds each, are brittle and break at the slightest provocation. It is an expensive way to make holes.

Drilling under Software Control

The best thing about PCB layout programs is that they automatically generate lists of coordinates of points where holes are to be drilled. If a computer-controlled drilling machine is used, the circuit board simply needs to be fixed to the table and the machine does the rest. The only intervention required is to change drills, which can however be quite tiresome. The program must be stopped, the drilling head must be moved to a specific position, or at least raised away from the board, in order to gain access to the chuck. The height of the drill must be correct, to ensure that the new bit is at the same height as the old one: for this purpose rings can be marked on the drill spindles. Alternatively, drills ready-marked with rings can be bought — but all from the same manufacturer, since different manufacturers put their rings at different heights! And if, after all this effort, the new drill is only used for a few holes, the whole process will have to be repeated just a few seconds later.

Manufacturers soon realised that this was a problem, and developed chucks which can be opened from above using a small handle. This is a great improvement over chucks, such as those frequently found on milling machines and mini-drills, which require a special tool to open them.

Such chucks make a rather expensive addition to a small drilling machine, but for the perfect solution you can expect to pay as much as a thousand pounds: you will need an automatic compressed-air tool changer with tool magazine and a compressor, and everything will work as if by magic. The control program will run a little slower, because the drilling head has to move over to the tool magazine to drop off the old drill and pick up the new one; even here, comfort has its price.

But there is still a big step from the perfect machine to a satisfactorily drilled circuit board. Have you ever considered how registration is preserved through the process of circuit board manufacture? In the PCB layout program the drilling coordinates are known exactly. The positions appear on the film and are then transferred to the circuit board — but where is the reference point?

Getting the film cleanly and accurately aligned with the edges of the circuit board is made impossible by the frequently dirty and roughly-cut base material. The circuit board is generally not rectangular, the material being cut after production using a guillotine.

A computer-controlled drilling machine requires a device that guarantees that the drill lands repeatably at the specified point. This device should be firmly fixed to the machine and in any case designed to make precise alignment easy.

There are many approaches to registration, using try-squares, pre-drilled holes (a real problem when modifying a circuit), optical registration devices, sticking the film to the circuit board, or ‘intelligent’ motion analysis systems using a camera, TeachIN and coordinate transformations according to reference marks, and many other wonderful methods.

In twenty years of experience developing printed circuit boards in small quantities, the author has found a much simpler solution:

Polar Coordinates!

Here a point on a surface has its position defined not by X- and Y-coordinates as in the Cartesian system, but by a length (distance from a fixed point) and an angle. Polar and Cartesian coordinates can be interconverted without loss of information.

In the PCB layout, draw a circular pad with diameter exactly 3 mm in an unused area; alternatively, use a mounting hole. In the circuit board itself, before exposure, drill a hole with diameter 3.1 mm, in the corresponding place to the pad on the layout. Position the film over the board so that the pad is over the hole. The 0.05 mm wide crack of light around the pad allows exact centring by eye. The centre of the pad is called the reference point. If the unexposed board already has the right dimensions, the film carrying the printed layout can be rotated until its edges are also in alignment with those of the board.

In the layout, as far as possible from the reference point, a second 3 mm diameter pad is drawn. The greatest distance is across the diagonal of the circuit board, but if there is no suitable space, a different place can be chosen. The important thing is that it is far from the reference point. This second point is called the rotation point. Cartesian and polar coordinates are compared in **Figure 1**.

After exposure and etching of the circuit board the reference point will have been etched away, because of the hole previously drilled there. Each other hole to be drilled is at a known distance from the reference hole. This gives us one of the polar coordinates. All we need now is the angle, which is derived from the rotation point. At the rotation point, drill another 3.1 mm diameter hole. This hole must be made extremely accurately, because the position of all the other holes depends on it. It is best to drill first a 1 mm hole and enlarge with a small round file or reamer. The copper of the pad gives a good indication of how well centred the hole is.

All we require now on the table of the computer-controlled drilling machine is a pair of small pegs that fit smoothly and without play in the two holes we have drilled. The peg for the reference point is fixed, while the peg for the rotation point can be slid along a line allowing for various distances between the two points. The coordinates of the fixed peg are known, as is the angle of the sliding rotation-point peg. The drilling data comprise the X- and Y-coordinates of the two points, and so the distance between the two and the angle they make with the Cartesian axes can be calculated using a simple program on the PC. After a translation and a rotation the position of all the other points can be determined, no matter how askew the film was placed on the circuit board during exposure or how the board lies on the CNC table.

This method of registration is suitable for the manufacture of one-off circuit boards, or for a number of different boards. For small-quantity production runs a slightly different procedure can be followed.

Cartesian coordinates: a heresy

Has anyone every seriously wondered why CNC machines always work using the Cartesian coordinate system? Why are X-, Y- and Z-axes always used? Why, when such machines are so difficult to build? The linear guides must be absolutely parallel, because otherwise the carriage will jam. The axes must be at exactly 90 degrees to one another, or else everything goes askew. The table must be absolutely true and the whole machine must be solidly fixed to a base.

These are all disadvantages. But the greatest disadvantage is the linkage between the axes. Consider the X-Y table, the original form of hand-operated milling machine. This has two handwheels, one to move the table in the X-direction, the other to move the table in the Y-direction. There are thus two linear guides, one fixed at an angle of 90 degrees to the other, supporting one another. If the lower mechanism has play in it, this is transferred to the upper one, even if the upper one is absolutely precise. And the lower guide also has to bear the weight of the upper one.

This traditional mechanism stems from a time before computers, when positioning along the axes was controlled manually by a technician using handwheels. Technical drawings are normally marked up with XY coordinates so that the successively required positions can easily be reached by use of the handwheels. In the age of automation the technician is no longer employed and the handwheels are replaced by motors under computer control. But the coordinate system has not changed: in the human imagination everything has a length, a breadth and a height. Curious, when most human actions are polar: ‘take three steps in this direction and then turn right’!

Imagine now how you would drill a circuit board by hand without a pillar drill. With the fingers of one hand you would hold the board steady and with the other hand you would hold the drill. Your drilling arm would be rather higher at the elbow than the other arm, since the mini-drill has a certain height. But you do not move your arms in the X- and Y-directions — no, you turn your drilling arm about the pivot at the elbow and turn and slide the circuit board to suit. You optimise your movements using your visual system — not perfectly, however, as sometimes you might miss a hole hidden by swarf. You do not need a firmly fixed base on which to work; your drilling arm is fixed at the elbow pivot, and what is between this pivot and the circuit board does not matter. Even a small tool between the two makes no difference. Your arms and your sitting position need not be absolutely parallel, or even anywhere near, and there are no 90 degree angles to be seen: two pivots are enough!

The Concept

The system uses two pivots, one for the workpiece (the circuit board) and one for the drilling arm. This allows any desired point on the circuit board to be brought into range on the turntable. This system has the big advantage over a linear construction that only two bearing points are needed whose exact separation is the only quantity that needs to be known. This requires no expensive specialist components: the bearings simply have to remain vertical and free of play. To align an axle to professional standards of accuracy, two so-called taper bearings are used. These can withstand enormous forces and are

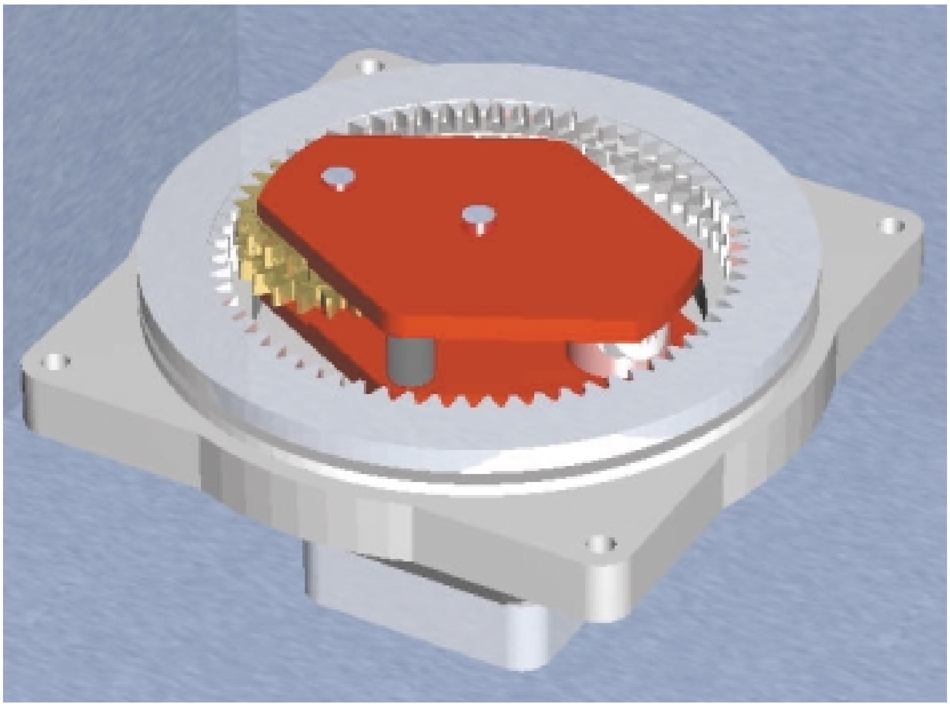


Figure 2. The well-known principle of the 'axle drive'.

expertly made to remain solid and permanently free of play. This is the main reason why our machine is so economical to build.

A rather significant disadvantage ought to be pointed out. Normally, in conventional linear machines the axles are long threaded rods supported by bearings and turned by a motor. A nut is fixed to the moving part and moves backwards or forwards according to the direction of rotation of the screw. This mechanism naturally gives a high effective gear ratio. Suppose that the screw gives a linear movement of 4 mm per rotation and is driven by a stepper motor with an angular resolution of 200 steps per revolution. The linear motion corresponding to one step is 4/200 = 0.02 mm. That is ideal for this kind of machine. Gearing is therefore completely unnecessary.

Our machine is not driven by a threaded rod, but rather works directly with angular motion. The 240 mm long tool arm has a travel of

240 mm × 2 × 3.14 = 1510 mm

(circumference of circle with arm length as radius)

A stepper motor driving this directly would take 200 steps to make one revolution; the distance corresponding to one step is therefore 1510 mm/200 = 7.55 mm, rather too great for a CNC machine. For a desired resolution of less than 0.04 mm we need to gear the motor down by a factor of at least 7.55 mm/0.04 mm = 190:1. That is not exactly straightforward.

Gearing Mechanism

In the opinion of experts in the field there is no simple gearing mechanism that gives such a high ratio apart from a worm drive. It is mathematically impossible to achieve the ratio with two or three gears without using an unreasonably large number of teeth. At least three stages of gearing down are required with many individual arbors that must each have good quality bearings.

This difficulty, and the unreasonably large amount of play in such a mechanism (and hence problems with repeatability), would cancel out all the advantages of our idea. But you would not have this article in your hands if the problem could not be overcome even despite the firm belief of the experts; and without employing such arcane devices as flexible components fitted between gears with intricately-cut teeth, ball-bearings moving in contorted orbits on even more contorted guides, or belts with different patterns of teeth on either side. If you want to know more, there is plenty to read on this subject on the Internet: you will find ideas there considerably more curious than our drive system. We achieve the desired gearing ratio using four gears. The principle has been known for a very long time, and there is even a VDI (German Association of Engineers) document on the subject (see box); however, practically no-one has yet realised the potential of the idea.

Our drive uses the principle of subtraction. Imagine a travelator such as those found in airports. Our travelator is circular and runs with constant speed. You are running on the travelator in the opposite direction to its rotation; the nearer your speed to that of the travelator, the lower your speed in relation to a fixed point. If you match the speed of the travelator exactly, your net speed is zero: you have a maximum 'gearing ratio', the two speeds cancelling one another out.

The situation is similar in our drive system. A spur turns within an annular gear with internal teeth: the actual value of the gearing ratio is not important. Fixed to it is a second spur gear, which turns in a second annular gear. Note that the two spur gears are fixed to the same axle. The two combinations of two gears — i.e., the ratios of spur gear to annual gear — are slightly different from one another, but the more similar they are the greater the overall gearing ratio obtained. Since the second spur gear turns at the rate determined by the first stage rather than that determined by the second, the second annular gear must make a compensating motion. In fact, we subtract the two speeds, just as in the travelator example. This explanation may seem rather complicated, but the illustration in **Figure 2** should make matters clear.

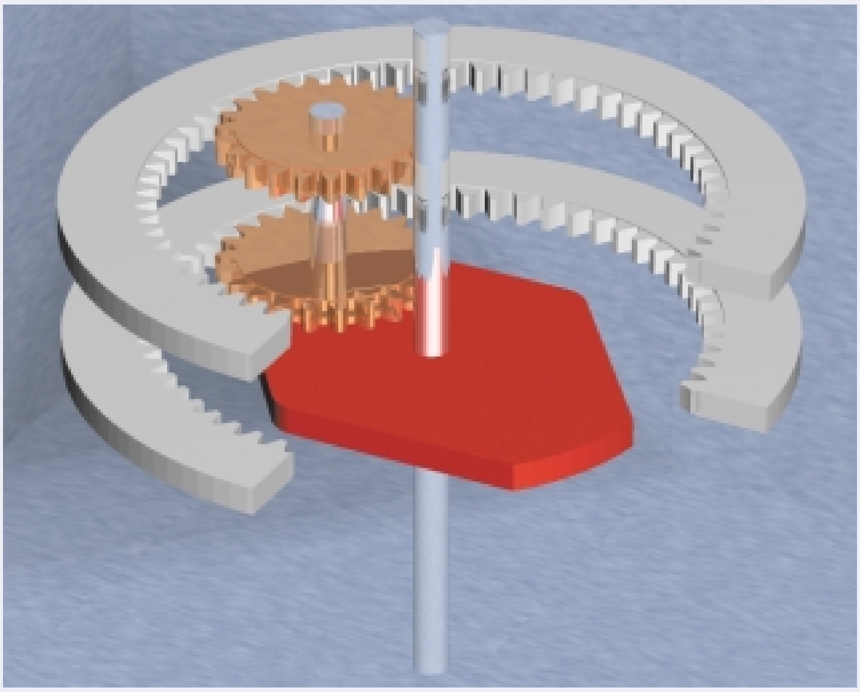
Normally more teeth are required to achieve a higher gearing ratio. Here, however, that is not the case, because it is merely the difference between the two ratios that matters. The author calls this drive system 'axle drive' and a patent has been applied for. The chances of success look slim, however, since the design has been known for a long time.

A glance at the internals of the drive system in **Figure 3** immediately suggests many possibilities. For example, there is enough space in the housing to include the parts of a motor; then one would have an incredibly small unit which would be not just a gearbox but a motor with a slowly-turning output shaft with a very high torque. One need only think of the countless applications in vehicles, such as for electric mirror and seat adjusters, or for electric windows, where a flat drive system is required to fit between the door panels. In robots; in component handling systems; this drive is ideal anywhere where a slow but powerful motion is required.

The Drive in Action

Our design not only has constructional advantages over normal linear systems, but also works better in many ways. What happens when the drilling head of a linear machine is at one end of its travel and must move to the opposite end? The head must be moved the entire distance. In our design, things are circular: define 360° as one 'end' of the travel and 0° as the other, and the two are the same! If we are at 360° and need to move to 10°, we do not need to

The drive system: how it works



When we started looking for a simple design for the drive system to give precisely the high gearing ratio required for our machine, we were met by shaking heads: the experts told us that high ratios could only be obtained by using multiple separate stages, each with a small ratio, multiplying together to give the total desired.

Using an ordinary planetary drive a practically-realisable gearing stage with a ratio of up to about 7:1 can be built. This is due to the fact that multiple spur wheels must turn within the annular gear and must clear one another. The diameter of the spur wheels must be less than half that of the annular gear to allow clearance, but must of course not be too small of they will have too few teeth to run smoothly. If higher ratios are required, multiple stages can be cascaded: with two stages we can obtain a ratio of 7x7:1, or 49:1. Add another stage and we have at most 343:1 (although for constructional reasons the maximum obtainable is only just over 300:1). Each stage takes up space, and a three-stage drive with a diameter of 40 mm with attached motor might easily have a total length of over 100 mm.

Further, each stage brings with it play in the mechanism and angular error, which all add together. Economical three-stage planetary drives have a play of about 3 degrees in the output shaft. Although that may sound small, in our design it would translate into an unusable 12 mm of error at the drilling head.

Precision drives in the middle price-bracket — say around one hundred pounds — reduce this play down to just below one degree. For our application, this is unfortunately still completely unusable.

Take a look at the figure and imagine the following sequence of motions.

We will use different tooth counts from those shown in the figure. Suppose the lower annular gear has 45 teeth, its spur wheel has 10 teeth, the upper annular gear has 50 teeth and its spur wheel has 11. These values will provide an excellent example of how the drive works.

The lower annular gear is fixed, and the long main shaft, shown passing through, is free to turn. This is the motor's output shaft, which turns the plate on which the small spur wheels are mounted.

The spur wheel is free to turn on bearings in the plate, and if the main shaft is turned then as the spur wheel runs around the inside of the annular gear, it turns on its own shaft. If the main shaft is turned through 360°, then the spur wheel will have turned on its own axis through 4.5 revolutions since its gearing ratio is 45:10, or 4.5:1. Although the two spur wheels are free to turn relative to the plate they are fixed to one another. So, when the lower spur wheel turns through 4.5 revolutions, the upper one must do so too.

Now if the upper spur wheel, with 11 teeth, turns through 4.5 revolutions, that equates to 49.5 teeth. But the upper spur wheel turning through 49.5 teeth in the upper annular gear causes a problem: the annular gear must make a compensating motion, and the size of this motion must be 50 minus 49.5 teeth, or exactly half a tooth.

Since the upper annular gear, with 50 teeth, moves by a half tooth for each revolution of the main shaft, this means that 100 revolutions of the main shaft are required to obtain an entire revolution. With this combination of 45:10 and 11:50 ratios we have therefore obtained, in one stage, a gearing ratio of 100:1. In our application we use ratios of 60:22 and 23:63, and with no other modifications to the construction obtain a gearing ratio of 231:1. The diagrams show the construction to scale and with exact teeth counts.

In the 19-page VDI (German Association of Engineers) guideline document number 2157 of September 1978, which deals with planetary drives, basic constructional rules and calculation methods are given. The exact arrangement dealt with in that document is called a 'simple planetary drive' which for technical reasons is not suitable for higher gearing ratios.

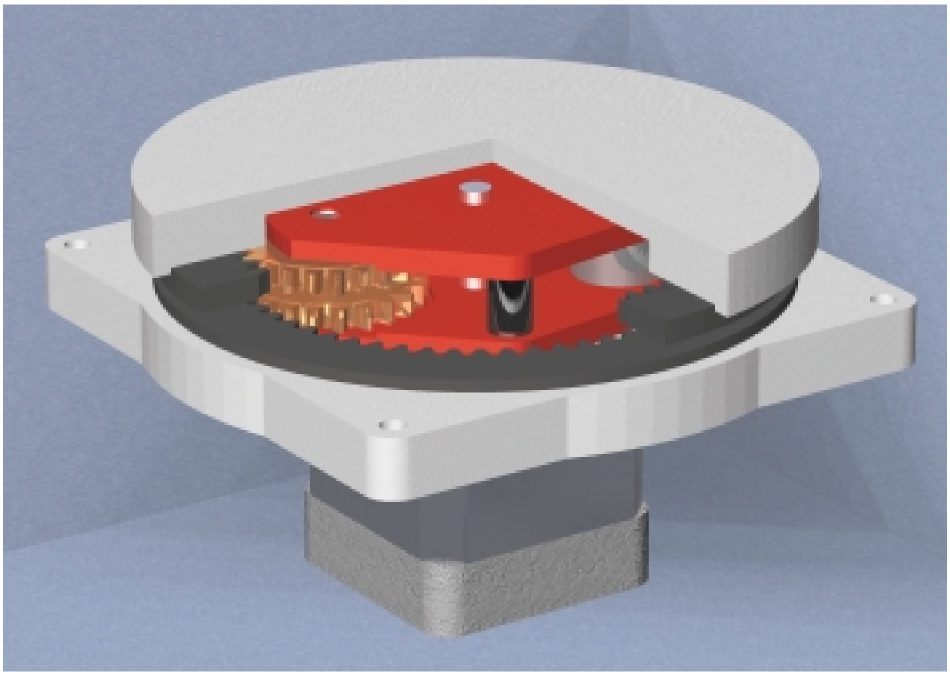


Figure 3. The 'axle drive' as used in our machine.

move through 350°, but only through 10°. For this reason our system is four times faster than a conventional CNC machine working over the same area. Also, the mass moved in our system is much less, which allows the machine to work faster still.

The construction of the machine, as can be seen in the photographs (**Figure 4**), aimed a maximum stiffness and minimum weight. The arm and the table can be moved at 70 mm per second, and the stepper motors only require a simple drive circuit because they draw less than 1 A.

Naturally, our machine suffers from the problem of changing the drill bit in the same way as conventional machines as described above. Our design does not provide for automatic tool changing. The construction of a suitable arm would be too complicated and elaborate. But here again we solve this problem in an elegant and surprising way that could not be considered for a conventional machine. There is plenty of space on the drilling table, so we simply add a second arm with a second drilling head. It would of course be possible for the two arms to foul one another, but we can easily arrange things so that one moves out of the way when the other approaches.

The machine is now even faster, since it does not need to wait idly while the tool is changed, does not need to move to a dedicated location to change the tool, and — the clincher — can work with the two arms simultaneously. And further, in order to work with three different drill sizes as is typically required (see above) we can add a third arm. This third arm is, however, not part of the basic design as seen in the cover picture and requires additional parts. The additional bearing housing can be simply screwed to the baseplate. Using three drills simultaneously in a conventional CNC machine would be out of the question.

It is possible to add a fourth arm. Since three drill sizes normally suffice for printed circuit board work, the fourth arm could perhaps carry a different tool such as a router for cutting around the edge of the board. However, the mechanics of the drilling arm are optimised for drilling, and the large sideways forces encountered during milling and routing will adversely affect its accuracy. We will leave the reader in suspense as to whether the author will solve the many problems associated with routing!

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In the next instalment we will be going into more detail concerning the control of the drilling machine from a PC via a microcontroller with an output drive circuit. The command transmission protocol for the microcontroller includes a couple of rather neat ideas!

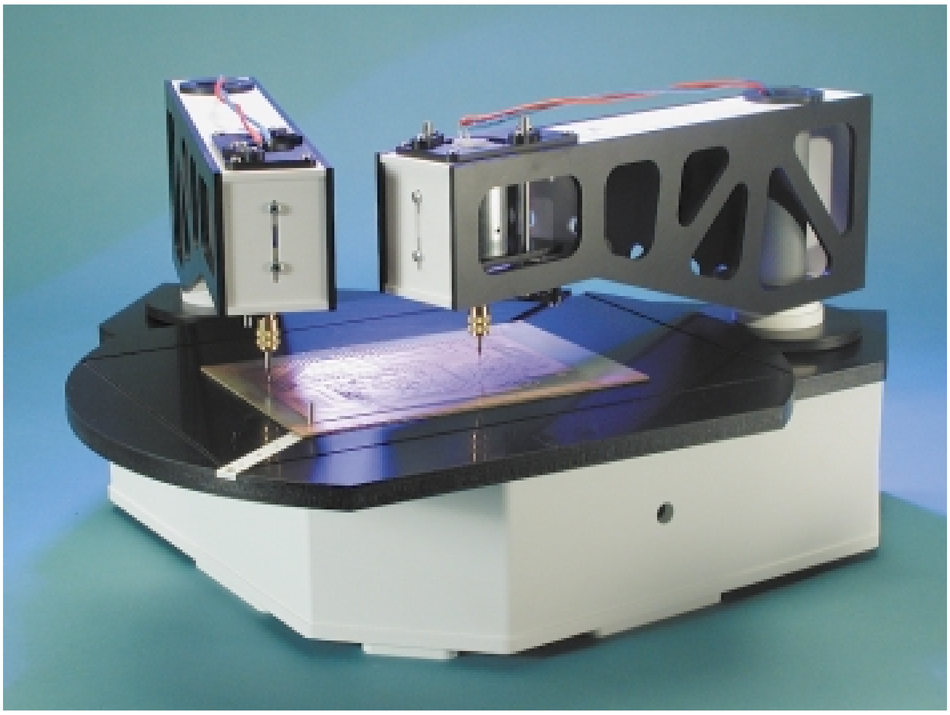

Figure 4. The drilling machine at a glance.