Personal CNC Design

"The Soul of a New Machine"

That's the title of Tracy Kidder's 1981 Pulitzer Prize-winning book. It is about the engineers and ideas behind an intense computer development project at Data General in the late 1970s. While our project at Tormach was not a multi-million dollar effort by a major corporation, we did pour our souls into it. We had expected the project to take a about a year in development. It took more time, more effort, and more money than we had originally planned, but after three years, we met our goal: to develop a small CNC mill, a precision machine that would represent a major step forward in value. It was to be a cooperative venture between Tormach and a high quality machine tool manufacturer.

During those three years we designed five unique machines working in cooperation with five different manufacturers. The initial manufacturers were selected after meetings and discussions with dozens of interested companies. After the first generation prototypes were finished, we selected the best among those five, focusing on one machine and building a relationship with one company. Then we began another sequence of design, build, test cycles. Our design evolved through four more machine builds before we put the final design into production. What follows is a short summary of our thinking and a bit of the design evolution itself. We offer this in the hope that it will provide some insight into the creation of the PCNC 1100.

Personal CNC

The concept behind personal CNC is similar to that of a personal computer. Above all, it must be affordable. Expensive machines must be kept constantly in production, their high cost demands it. Only when a machine becomes truly affordable can it become a personal tool. Second in importance after affordability is ease of use. A personal CNC needs to be easy to move, easy to learn, easy to use, and easy to maintain.

A Personal CNC provides immediate access to the power of CNC machining. This enhances the work of engineers, inventors, technicians, hobbyists, educators, and anyone who needs to make things. When a machine tool costs 1/5 of a standard small VMC (vertical machining center) each student in a machining class can run his own machine instead of waiting in line. In R&D, turn around on prototype design takes minutes instead of days when a machine is "at the ready" and on site. In general engineering, the designs sent to production are much improved because the design engineer can be more directly involved in the prototype creation.

General Machine Design

Open Architecture

The term "open architecture" has been so abused in marketing hyperbole that it has been rendered meaningless. Nevertheless, the design philosophy behind the term has important implications. Rather than laying claim to "a fully open architecture," we offer here the simple What, How, and Why of our machine architecture.

<u>What</u> Open Architecture Means to Us

Open architecture means the use of a modular design with industry standard interfaces between the modules. Open architecture also means we give full disclosure of the nature of the interfaces between internal modules.

<u>How</u> Open Architecture Concepts are Applied

- Industry standard control computer (PC & Windows OS)
- Standard RS274 code language (G-codes and M-codes)
- Standard drawing and image file support (DXF, HPGL, BMP, JPG)
- Industry standard machine dimensions
  - 5/8" T-slots
  - R8 spindle taper
  - 3.375" spindle nose
  - NEMA 34 axis motor mounts
  - IEC spindle motor mount
  - ABEC bearings
- Industry standard internal electrical interfaces
  - PC – Machine interface is PC printer port
  - Universal VFD motor driver interface
  - Standard stepper motor driver interface
  - Standard voltage transformers
  - Industry standard switches and controls
- Modular Mechanical Assemblies
  - Base, Column, and Head sub-units
  - Cartridge Style Spindle

Why These Things are Important

- Machine uses commonly available tooling and accessories.
- Machine is easy to maintain, no specially trained service personal needed.
- Machine manufacturer cannot "hold you hostage" on replacement parts.
- Obsolescence risk is eliminated.
- Flexible use; machine can be easily modified or incorporated into a larger manufacturing system.

Application Characteristics

Our goal in creating a personal CNC is to offer a CNC mill that can meet the needs of short run applications at the lowest possible cost. R&D, business startups, education, and hobbyist users all require a machine that can handle short runs easily and economically. In order to understand the design implications of a short run, let's compare it to a more conventional application.

Machine setup for cutting a new design part is normally several hours, yet the cutting process itself may take only 10 minutes on a conventional machine. A conventional small CNC may have a 5 hp to 7.5 hp spindle. If you reduce the spindle power to something more like the classic Bridgeport mill (1 hp to 1.5 hp), the run time will likely be more like 14 minutes. In addition, a conventional mill will have rapids on the order of 200 inches per minute (IPM). If the rapids are reduced to 65 IPM, the run time might go up to 16 minutes. If there is no automatic tool changer available, only a quick-change manual system, the run time might go up another 2 minutes. The final result is an 18 minute run time instead of 10 minutes. This is an insignificant difference in the context of the hours required for design, setup, fixture, and code development. A 1.5 hp CNC mill with 65 IPM rapids and no tool changer is ludicrous in a production environment, where minutes per piece are crucial. However, in prototype development, where run time is a tiny fraction of setup time, those extra minutes are simply not relevant. What is extremely relevant is the substantial cost saving afforded by that design.

It's clear that in a short run machine precision is as important as in a production machine, but the need for spindle power, motion speed, and automatic tool change are not nearly as important in short runs.

Achieving Precision on a Lightweight Machine

In general practice, any milling machine under 5000 lbs is considered lightweight. Precision is possible with a lightweight machine, but certain necessary characteristics must be kept in mind. One of the most important considerations is dynamic stiffness.

Dynamic stiffness refers to the ability of a machine to resist forces while it is moving. The degree of a machine's dynamic stiffness depends upon a number of factors: speed, inertia, static stiffness, and damping. As an example, imagine a ¼" diameter rod with a rounded end; imagine trying to push that blunt rod through an empty aluminum can. While you might get through the can, the can gets crunched in the process. Now take that same aluminum can, set it on a fence post, and fire a 22-caliber bullet at it. You get a clean hole with little deformation. The can is weak against static forces, but very stiff against dynamic forces. The cleaner cut is the result of dynamic stiffness.

Similar principles can be applied to machining. A cutting tool cutting into the work piece is equivalent to the bullet hitting the can. The inertia of the can and the viscosity of the air are analogous to viscosity of oil film slide ways, the damping properties of cast iron, and the overall mass of the system. In these applications the hydrodynamic damping of sliding ways is superior to linear bearings and iron is superior to aluminum.

Mass and strength are important, but they must be in the right place. Iron is best used within the chain of components that lead from the end mill to the work piece. If you only have 1000 lbs of iron to work with, it simply does not make sense to put a lot of it in a supporting base.

Operating parameters making use of dynamic stiffness include cutting at the highest possible surface speeds and using relatively light depth of cut. This means smaller cutting tools and higher spindle speeds. One of the design parameters indirectly affected is the need for coolant. If you're trying to maintain the highest possible surface speed, coolant becomes essential. If you have an 8000 lb mill it might make sense to use a 1" end mill and chug away at 500 RPM. If you have lightweight mill then you're better off to make multiple passes with a smaller end mill and keep the RPM high.

KISS Principle (Keep it Simple, Stupid)
Simplicity and robust construction lead to low cost, long-term value, and reduced maintenance. That is a given. KISS has been a guiding concept for us throughout the design process of the PCNC 1100.

Basic Parameters
Keeping in mind the necessity of dynamic stiffness and considering the range of materials one might cut with our CNC (plastics, aluminum, steel, iron, and stainless steels), we concluded that the best speed range for the PCNC 1100 was around 300 to 4500 RPM. Because we were designing for short runs, prototype production, and education, we decided that 1.5 hp was adequate for spindle power, while 65 IPM was plenty of speed for machine motion. Noting also that coolant would nearly always be necessary, we decided to make coolant control a standard feature of the machine.

Modularity – A la Carte Sales
CNC mills are used in a wide variety of applications. While a basic machine tool can be designed to suit the majority of needs, details such as coolant type and enclosure style are much more variable. Some applications will require an open machine like a drill/mill or Bridgeport, while others are more suited to an enclosed machining center.

Another dimension of application variability is the “make” versus “buy” decision. While it’s impractical for the small shop owner to make his or her own machine tool, it is fully practical for a user to build a stand or enclosure for a small machine tool.

In order to satisfy the widest possible community, we decided to offer the machine, stands and enclosures, and other accessories as discrete items. Everything is available à la carte: you buy only what you need.

Detailed Machine Design

Machine Frame
The most common machine designs for lightweight vertical mills are the knee mill and the bed mill. Knee mills are common as manual mills: the Bridgeport design as a universal standard. Knee mills are not nearly as common as CNC mills because the design forces a difficult decision for Z motion. The designer can either provide computer-controlled motion on the knee or on the quill. If the knee moves, expense of the control system increases greatly because of the mass involved. It needs to move both X and Y motion systems, the whole table, tool holding fixtures, and the work piece itself. If the quill moves, the range of motion is severely limited, often to 6” or less. If the quill is designed to be longer, the system loses mechanical stiffness.

Another disadvantage of a knee mill is the difficulty of managing chips and coolant. Manual mill operations are often limited to cleaning up a surface, drilling a hole pattern, or cutting to a dimensional outline, operations where a small chip brush is adequate. CNC operations often end up turning the majority of the stock into chips; cutting a shape out of a solid block of metal the way Michelangelo would cut a sculpture from a block of marble. Chips and coolant will be flying everywhere. Containment is difficult with the open frame setup of a Bridgeport style knee mill.

Bed mills are far more common in CNCs. Compared to knee motion, it is relatively inexpensive to provide significant Z motion when moving the entire head. Compared to quill motion, moving head designs maintain machine frame stiffness while still allowing a good range of motion. The bed design with a moving head eliminates the high forces of knee motion and allows a greater range than quill-only motion.

As we designed the PCNC 1100, we interviewed as many machinists as we could. A lot of bed mills under 10,000 lbs have computer controlled Z axis motion of the entire head as well as manual Z axis motion on a quill. The manual quill operation resembles a drill press. Most users told us that they retracted the quill (the stiffest position), locked it in place, and never moved it. Since use of a manual quill seems uncommon, we deemed it unnecessary and decided not to provide redundant Z axis motion. The detailed design ramifications of this decision were enlightening: fewer machined surfaces, no rack and pinion, and no split head. The design of a spindle lock becomes much simpler, the spindle itself is stiffer, and the machine costs less. It was the KISS principle in action. The PCNC 1100 only has one way to move in Z: the whole head moves. If you really want to pull on a handle, buy a drill press, or go to Vegas and play the slots.

Spindle & Drive System
The spindle & drive system is comprised of the spindle motor, the transmission, and the spindle itself. The design of these parts is all interrelated, so it’s best to approach it as a system design.

In deciding upon a motor, we considered induction motors, servo motors, and DC brush motors. Servos and their electronic drivers add considerable complexity and cost. Brush motors have maintenance issues and are not nearly as standardized at induction motors. In terms of value, simplicity, and long life, the best solution is definitely an induction motor.

Another important decision we faced was whether to include infinitely variable speed. With the development of inexpensive VFDs (Variable Frequency Drives), the complexity of a mechanically variable speed transmission is no longer a reasonable solution. Mechanical drives worked great for Bridgeport machines in the 1960s, but they were also a common failure point. Solid state electronics are lower in cost and higher in reliability than mechanical alternatives for infinite resolution speed control

We had considered offering variable speed as an optional upgrade. However, a cost effective upgrade should be a simple addition that builds upon a foundation, rather than requiring an elaborate reconfiguration. If it were simply a matter of adding a VFD for variable speed, this would be a good solution. In reality, a machine designed for manual speed change would incorporate a single phase motor and a multiple speed transmission. An upgrade to variable speed would involve replacing the single phase motor with a three phase motor, as well as adding the VFD driver. After that conversion, the machine is left with a complex multiple speed transmission that is completely unnecessary. We decided that rather than offering variable speed as an upgrade, we should include it as part of the basic machine design

The reduced cost of a three phase motor over a single phase motor and the reduction of complexity in avoiding a mechanical transmission saved us some dollars that could be dedicated to the VFD. The increase in cost was thus relatively small. The desired speed range still requires a two speed transmission, but it is a much simpler solution than the 6, 8, or 12 speed transmissions common on most small milling machines with single speed motors.

Geared transmissions offer a reasonable way to deliver high torque at low speeds, but gears become much more troublesome when the output shaft is required to exceed 2500 RPM. At 3500 RPM a standard gearbox will foam the oil bath and heat the oil above 250 degrees F. At 4000 RPM and above the oil viscosity can absorb as much as 1.25 HP, leaving little power for the cutting tool. Standard gearboxes are also very noisy. Our gearbox evaluations here are not simply conjecture. The development of the PCNC 1100 included two early prototypes designed with gear transmissions.

Planetary gearboxes with specialized lubrication can obviate some of the problems, but at a very high cost. Perhaps the largest limitation with gearboxes is the huge penalty when they fail. When something comes loose in a high speed gearbox, it’s generally a catastrophic failure: the complete gear set will need replacement. A minor failure issue, more often simply a nuisance, is the tendency of gearbox oil seals to leak oil. This is not much of an issue for slow speed gearboxes, but as the output shaft speed increases, you either suffer high seal heating from the friction around a spring loaded seal, or the risk of leaks by switching to an oil seal with a very light pressure against the rotating shaft.

Compared to gears, belt drives are the ultimate in simplicity. V-belts offer efficient transmission at low cost with a lot less noise. There is no gear oil to leak. Modern designs such as the Gates Super HC® belts can deliver 1.5 HP on a 3L (3/8”) belt. The narrow belt makes speed changes easy. Nevertheless, shifting a gear lever will always be quicker than changing V-belt pulleys.

The final factor in our design decision between belt drive versus gear drive arose from the VFD and induction motor. A ratio change must be available because the desired speed range of the machine (300 to 4500 RPM) is about 15:1. This exceeds the speed range capable of a standard VFD and fan-cooled motor. However, a speed range of 5.8:1 is easy to achieve. This means not only that the desired speed range can be attained by just two ratios, but also that there will be considerable overlap between the ranges of the two ratios. For example, where the low speed range is 300 RPM to 1750 RPM (5.8:1), the upper speed range will be 750 RPM to 4450 RPM (also 5.8:1). In practice, this overlap means that pulley ratio changes will rarely be needed. Most machining operations of plastics or aluminum alloys can probably be done in the high speed range, without the need to change to the low speed ratio. Machining operations involving steel, iron, or stainless will probably be done in the low speed range.

The need for quick speed ratio changes is considerably reduced by the wide overlap of spindle speeds between the high and low speed ranges. This makes the quick ratio change of a gearbox design less significant. With the superior reliability and efficiency, in combination with quieter operation, the modern belt drive became an easy choice for us. After trying several combinations, we developed a belt drive in which the pulley ratio can be changed in 25 seconds, a small compromise compared to the greater limitations of a gearbox.

The final design element of the PCNC 1100 spindle and drive is a 2 ratio V-belt transmission run by a standard 3 phase induction motor. The motor is powered by a single phase VFD that can operate on either 230 or 115 VAC while putting out variable frequency 3-phase power. Direction can be reversed under computer control, thereby allowing tapping operations when using a floating tap holder. It is infinitely variable through the range of 300 RPM to 4500 RPM in two overlapping pulley ratios. This spindle and drive system is simple, robust, efficient, and quiet.

Update:
This document is a review of the engineering that went into the original PCNC 1100. In development from 2002 unitl 2005, the PCNC 1100 was released for public sale in October of 2005.

While leaving this document intact, we do need to note that in September of 2008 the PCNC 1100 was replaced with the **PCNC 1100 *series II*** model. While other details of the design remain essentially the same, the series II model moved from a 1.5 hp analog VFD to a 2 hp sensorless vector VFD. The speed range is now 250 RPM to 5140 RPM and offers significantly improved low speed torque plus enhanced acceleration and deceleration characteristics.

Mechanical Design Aspects

Basic Size

Our objective for the Personal CNC project was to develop a machine that is more accessible, affordable, and convenient than anything previously offered. Size was a very important aspect. We began with a design point of about 1000 lbs and a shipping crate that can be moved with a pallet jack. This size allows for delivery with a standard lift-gate truck; anything much larger requires a flatbed truck and a forklift. This specification allows the machine to be moved in a typical office elevator—a special freight elevator is not necessary. In our research we found that only a slight increase in physical size of the machine would more than double overseas shipping costs, triple local delivery costs, and greatly complicate the owner's logistics once the machine is delivered. As the design cycle progressed, our machine grew in weight from about 900 lbs to 1130lbs, but we kept the physical dimensions that we started with.

When comparing different machines, you can get a rough idea of rigidity by comparing the volume of the working envelope (X, Y, and Z travel) and dividing by the machine weight. The result is cubic inches per lb, where a larger number indicates a less rigid machine. This comparison cannot be fairly made between a bench top machine and a floor standing machine, where much of the weight is in the base does not contribute to rigidity. A fair comparison also assumes the machine designer has put the iron in the right place.

Frame Material

The machine frame is cast iron. Iron offers both high mass and significant damping properties. The mass and damping aid the dynamic stiffness of the machine, improving accuracy and reducing vibration. Cast aluminum alloys, aluminum extrusions, plastic/stone composites, and a variety of other materials have been tried on small milling machines, but none offers the value and performance of iron.

Frame modularity

While we would prefer that owners keep their machine assembled, we also realized that there would be situations requiring disassembly. Moving a machine up or down a stairs can be difficult unless it's partially disassembled. In those instances the precision elements of ballscrews and slide ways should be left

intact. The spindle head is made as a separate casting from the Z axis saddle. The head can be removed at a 6 bolt flange, thus leaving the Z axis slide ways intact. The column can be removed from the base by removing 4 bolts (and a few wires). The column also includes an eye bolt which can be used for crane lifting the entire machine, or just the column when it's unbolted.
The base includes 4 through holes through which bars may be slid, making the machine easy to lift using the forks of a lift truck.

Spindle
The popularity of the Bridgeport manual milling machine has lead to a plethora of low cost tooling and accessories. One sub-category of this might be titled "Things that clamp on the quill." The 3-3/8" quill diameter of the Bridgeport has become an industry standard. Although the PCNC 1100 does not have an independent motion quill, it does have a nice round end (spindle nose) on the spindle cartridge that just happens to be 3-3/8" in diameter. Most anything that clamps onto the quill of a Bridgeport will clamp onto the PCNC 1100.

The PCNC 1100 incorporates a cartridge style spindle. Rather using a design that cuts the spindle bearing mounts directly into the iron of the head, we chose instead to mount the spindle bearings into a lathe-turned cartridge. The cartridge slides into a close-fitting hole through the head and is attached via a 6-bolt flange. There are several advantages to this construction:

- Lathe turned body allows for better concentricity of bearing mounts.
- Lathe turned body ensures concentricity to spindle nose.
- Cartridge can be removed for bearing replacement. This allows replacement of bearings to be done on a workbench instead of on the machine.
- If you don't want to replace bearings, the cartridge can be shipped back to Tormach for rebuilding.
- Cartridge mount allows for easy machine modification. With the cartridge removed, the head can easily be fitted with anything a manufacturing engineer might dream up. The cartridge might be replaced with an ultrasound plastic welder, a glue applicator, a 40,000 RPM spindle motor, or EDM system. What might you come up with?

Spindle Details
Nearly all small manual mills have an R8 taper. Most CNC machines have a steeper 7/24 taper (3.5" per foot), such as ISO, CAT, and BT tapers. The 7/24 tooling is stiffer than R8 and allows for higher forces. This feature is important because CNC machining centers often send 15 to 50 hp or more through the tool holder. An R8 taper is simply not suitable for delivering 15 hp to an end mill.

The common 7/24 tooling only contacts the spindle along the taper. Recent innovations have produced a number of dual face tapers, in which both the taper and flange of the tool holder contact the spindle. These include the European HSK taper, the Japanese 1/10 Double Face, and the 7/24 Dual Face. Double contact, or dual face systems. provide more rigid support and better repeatability in height.

The wide use of the R8 taper has resulted in a very competitive marketplace for R8 tooling. The cost difference between R8 tooling and 7/24 tooling is significant. A CAT spindle is in the family of 7/24 tapers. One of the common mail order discount suppliers lists the following:

3/8" end mill holder for R8 taper	$17
3/8" end mill holder for CAT30	$73
Jacobs 33 to R8 adaptor	$13
Jacobs 33 to CAT30	$122

R8 is commonly used on milling machines with 3 hp spindles. While not as rigid as any of the 7/24 types, R8 is certainly stiff enough to deliver the 1.5 hp of the PCNC 1100. We selected the R8 taper for the PCNC 1100 because of its wide availability and low cost of the tooling. For many people, the PCNC 1100 is an entry-level CNC machine. The R8 taper will allow those people to make use of the tooling they have collected over time for their old manual mill.

Tooling System
We had reservations about using the R8 taper at first. While stiff enough to deliver the spindle power we wanted, R8 tooling is longer than the alternatives and requires greater clearance. A full 4" clearance is required to remove a standard tool holder, and it takes time to unscrew the drawbar. While a short run machine doesn't need an automatic tool changer, it

does get tedious when tool changes take a minute or two. Quick changes are possible when using collets instead of solid holders, as long as the next tool is the same diameter. The problem with collets is that you cannot repeat the Z height of the tool.

Another issue that troubled us was that it is difficult to setup R8 tools offline. Offline setup allows the tools to be measured and entered into the controller tool table, eliminating the need for repeated Z referencing. What was needed was a seemingly impossible combination of factors:

- Quick change: as quick as simply loosening a collet, sliding the tool out, and retightening.
- Low clearance: standard R8 tooling requires too much clearance.
- Easy offline Z height measurement, thus eliminating in-machine touch off.
- Absolute Z positioning, independent of variability in drawbar tension.

After lots of thinking, discussing, and testing (that is, R&D), we developed TTS, the Tormach Tooling System. TTS tool holders utilize a standard R8 collet, yet they provide all of the features listed above. TTS makes use of the principle of dual face contact that is incorporated in the most modern (and expensive) tool holders such as HSK and Big+Plus, yet the prices compare favorably with low cost R8 tooling. Details can be found at www.tormach.com/tts_products.htm.

It's not necessary to use TTS with the PCNC 1100 machine; any standard R8 tooling will work. Nevertheless, with the development of TTS, we are much more satisfied with our selection of an R8 taper. The combination of TTS and R8 provides low cost, ease of use, high precision, and simplicity. TTS makes an R8 taper acceptable for CNC applications.

The finishing touch for our tool changing system is the addition of a spindle lock. A standard design for a manual drawbar requires two wrenches to loosen the drawbar. Once loosened, the operator needs a third hand to catch the tool before it falls onto the work piece or vise. A simple spindle lock allows a tool change with one hand on a wrench and the other hand on the tool.

An electrical interlock on the spindle cover prevents inadvertent spindle motor operation while the cover is open. A mechanical interlock prevents the spindle cover from being closed while the spindle lock is in place.

Table Design

Though it seemed a simple matter, there was considerable design discussion on the table slots. If it were not for the universal distribution of Bridgeport machines (they have 5/8" slots), we would probably have opted for something smaller, like 14 mm or 7/16", and put 5 slots on the table. In the real world, 5/8" slots are so common that you will generally find a 5/8" alignment key on the bottom of your Kurt vise (or Kurt vise copy), your rotary table, and 5/8" T-nuts in the hold down kit of your favorite discount mail order supply house. If there is an industry standard, it's 5/8".

There should always be an odd number of T-slots so there is always a center slot. A center slot allows symmetry on the machine and provides greater flexibility for fixtures. We tried using 5 slots on one of the prototypes, but there was too much slot and not enough flat space on the table. Three slots provide a lot of extra flat space, so we dedicated that space to two narrow outside slots. The outside slots are for drainage or fixture alignment.

Axis Motors

There are three options for axis motion control:

1. Brushless AC servo motors
2. Brush type DC servo motors
3. Stepper motors

The industry standard for CNC machining centers is brushless AC servo motors. This is an excellent design because the motor coils (where the heat is generated) are on the outside of the motor case. This allows for rapid head dissipation. Commutation (coil switching) is done electronically, and the rotor is little more than a solid shaft with permanent magnets attached. The motors provide a flat speed/torque curve, usually out to several thousand RPM before they reach voltage limits. There are several limitations to the AC servos.

- They are expensive, adding significantly to the machine cost
- They are not standardized. You need to get matched sets of motors and drivers. There is no such thing as a universal replacement.
- They require feedback encoders. These are normally glass disk optical encoders. The encoders are sensitive to electrical noise, shock, heat, and corrosion.

Older CNC systems used brush type servo motors. None of the mainstream servo manufacturers offers brush motors any more, but they are still available from some sources. Brush motors have the advantage of being less expensive, however, the brushes wear out over time. The coils are on the rotor, so it becomes more difficult to cool the motor. Much of the coil heat is released through the rotor bearings. A commutation bar that rotates under carbon brushes does commutation. At higher speeds there is considerable arcing between the brushes and the commutation bars. Brush type servo motors use feedback similar to the AC brushless motors, so care must be taken to isolate the motor/encoder package against shock, coolant, and electrical noise. One advantage of brush type servo motors is that they are easier to replace. The complexity of commutation is done mechanically, not in the driver. This means that you can often replace a dead brush type motor with another brand as long as the rotor mass, torque constant, voltage rating, and encoder interface is identical. Outside of the mechanical mounting, there are no useful industry standards for brush type motor specification.

Stepper motors are quite different from servo systems. They are considered “open loop” position systems. This means they can deliver precise position control without the need for optical encoders. Stepper motor systems had a variety of problems until about 10 years ago. Older designs had problems with resonance and position loss. Developments in the areas of microstepping, anti-resonance circuits, and high performance motors have improved the situation considerably. Modern stepper motor designs are widely used in industrial control, medical instrumentation, and other computer controlled applications.

Similar to an AC servo motor, a stepper motor is basically a solid rotor with permanent magnets. The coils are on the outside (stator), so heat dissipation is rarely a problem. Without the sensitive encoders or motor brushes, stepper motors are normally lifetime devices, as there is little to go wrong with permanent magnets and a coil. They are also inexpensive. A stepper motor motion control system can be assembled at a fraction of the cost of a typical AC servo system.

One disadvantage of stepper motor systems is related to their lack of feedback. If the operator suffers a machine crash the motor can be forced off of position. Operating without encoder feedback, stepper motor systems have no way of reporting position error when crashing into something. When a machine crash occurs with a feedback based motor, the motor will also be forced off position, but the machine will see the error and stop with a fault. In either case, the real issue is to avoid crashing into things.

While there are a variety of winding styles for stepper motors, the industry seems to have settled on a basic design. The standard is a high performance hybrid motor using a bipolar winding. Stepper motors are much more standardized than servo motors, generally offered in NEMA sizes 17, 23, 34, and 42.

Stepper motors are high torque, low speed devices. The low speed means that bearing failures are rare, far less common than bearing failures on servo motors. When taken into higher speeds stepper motors will show very significant decay of torque. While a servo motor may provide flat torque out to several thousand RPM, a large stepper motor will show significant decay in deliverable torque beyond a few hundred RPM. They work very well at slow speeds, but at higher speeds cannot approach the usable torque of a servo motor.

High speed is essential for production machinery, and that necessity makes AC servo motors an excellent choice for that application, despite their high cost. The PCNC 1100, however, has no need for high axis speeds. Our design point of 65 IPM is well within the performance envelope of a high performance stepper motor. When we considered the excellent economy and superior reliability of stepper motors, we decided to use stepper motors for the PCNC 1100. We use 640 oz inch motors. This provides enough torque such that a severely overloaded machine will normally break an end mill long before it comes near the force levels required to stall a motor.

We selected motors with a standard NEMA 34 face mount, and worked closely with the motor manufacturer to develop the MTM (Machine Tool Motor) series of stepper motors. The design has sealant between the laminations and the end housings, with an overall powder coat primer to prevent intrusion by exposure to cutting fluids. The motor’s high torque, low speed characteristics provide further advantages in that they allow a direct drive configuration. The motors are directly mounted on the end of each ballscrew, thereby eliminating the need for pulleys, belts, and tensioning systems. The design is simple, accurate, robust, and inexpensive.

Brief History of Linear Motion – Axis design

Linear motion mechanics have evolved through many stages. In the earliest days machine slides were equipped with brass strips on hardwood ways. This technique was used in the earliest woodworking machines, but also in some metal working machines.

For many years machine ways were build of iron on iron. Irons on iron was improved with scraping techniques that both improved geometric accuracy and created patterns that maintained a better a hydrodynamic oil film to reduce wear and chatter. Degradation of the iron surface was also reduced with various surface hardening techniques.

An improvement to iron on iron was the addition of chrome. Chrome further reduces wear. Chrome ways are still common today on some premium manual milling machines.

The development of low friction plastic surfaces was a major improvement. PTFE (polytetrafluoroethylene), trademarked Teflon®, is the most renowned of the fluorinated polymers. It has a very low coefficient of friction. There is a problem with it, however. PTFE is subject to a phenomenon known as cold flow. Under a modest pressure it will flow like a highly viscous liquid, losing whatever geometry the designer intended it to maintain. When it is combined with stronger polymers, such as an acetal homopolymer (trademark Delrin® as an example), the cold flow is eliminated while its low friction properties remain. A variety of proprietary products have been developed, mainly variations of PTFE filled acetal. These are sold under trademark names such as Rulon®, Turcite®, Delrin® AF, and others. These products reduce friction and wear to a remarkable extent. Not only is the coefficient of friction for these compounds exceptionally low, they also exhibit another very important characteristic: their static coefficient of friction is very similar to their dynamic coefficient of friction.

Sliding surfaces generally have a static coefficient of friction (friction force while sitting still) that is significantly higher than their dynamic coefficient of friction (friction force while moving). Nothing is perfectly stiff; everything has some spring action to it—even a heavy iron machine frame. When a force is applied to a slide to move it, the machine components will deform a bit (like a spring) until there is enough force to overcome the static friction. When static friction is overcome, dynamic friction takes over and the energy stored in compression turns into motion. The result is a slip/stick phenomenon, some times called stiction. Moving heavy loads with very slow motion can result in intermittent motion; in the worst case in machining, this manifests as chatter. Because the static and dynamic coefficients of friction of PTFE filled acetal are so similar to each other, there is virtually no chatter. Overall machine accuracy is improved.

Polymer surfaced ways are created by gluing on a thin layer of material, often about 0.031 inches. The material is relatively cheap, but it's a time consuming process to apply it, requiring skilled labor. Consequently, one of the disadvantages is that, like chromed surfaced ways, polymer surfaced ways are expensive

Most production machine tool designers have replaced sliding ways with linear bearings. Like ball bearings, linear bearings use rolling contact instead of slide ways. While often more expensive than sliding ways, they offer some unique advantages. First, they are easy to install. There is not much skilled labor involved in bolting down a linear bearing assembly. Perhaps the most important property of linear bearings is the low force required for high speed motion.

Sliding bearings, even those with plastic surfaces, depend on a hydrodynamic oil film. Similar to an oil filled shock absorber, the faster they move, the more force is required to move them. As demands for production speeds increase, CNC machining centers must move faster and faster. A speed of 200 or 300 IPM (inches per minute) was once adequate; now high end machining centers move at 1000 to 1500 IPM. At those speeds, the forces that sliding bearings require are too high; linear roller bearings are a must.

Linear bearings, however, are not without their limitations. Like ball bearings and ballscrews, linear bearings must always be protected against contamination. They also have low damping characteristics. Without the damping effect provided by the viscous oil of a hydrodynamic film, the use of linear bearings can increase the tendency of a machine to vibrate and decrease the overall machine damping.

It's clear that linear bearings, with their low resistance at high speeds, are a must on large high speed CNC machines. They are an effective solution for small CNC machines where the work is limited to low forces and high speed cutting. This is the case for wood and plastic routers where these same characteristics allow routers to be constructed of aluminum, despite its low damping properties. In our design considerations, we concluded that because the PCNC 1100 does not require high speed linear motion, but must withstand the high cutting forces of metalworking, that sliding ways, with their higher damping characteristics, was the best choice. For long life and high accuracy, we decided to use PTFE filled acetal surfaces on all ways, X, Y, and Z.

Ballscrews

Ballscrews are found on nearly all machine tools. Alternatives such as acme screws with self-adjusting nuts or plastic nuts simply cannot withstand the high force world of metal cutting, and are best left to low force applications.

For those new to the concept, a ballscrew is the marriage of a ball bearing and a screw. Instead of balls running in a circular track on one plane, as in a ball bearing, the balls of a ballscrew run in the spiral track of a screw. The sliding, high friction motion of a conventional screw is replaced with a rolling motion of balls in a track. Conventional lead screws have significant backlash and are about 60% efficient as a transmission of rotary to linear motion. Ballscrews can be built with zero backlash and 95% efficiency of transmission.

The accuracy of ballscrews is paramount in machine accuracy. Precise motion control begins in the motor. The ballscrew translates the motion of the motor into linear motion. Any errors in the screw or nut will directly translate to errors in machine position.

Ballscrews and the associated ball nuts are available in a variety of precision levels. The screw portion is offered in two basic dimensions: the grade and the application. Applications are marked as P, T, or C:

- P grade is generally taken to mean position or precision. P grades are intended for high precision work, such as that of CNC machines.
- T or C grades are referred as transport grades, designed for utility applications such as lifting, pressing, or other non-precision applications.

The grades refer to basic accuracy of motion. With P applications, both incremental and cumulative accuracy are important. With T/C applications, only incremental accuracy is specified. As an examples:

- P3 allows 12 um error within any 300 mm. In imperial units, this is 0.0005” per foot. Cumulative error at 900 mm is limited to 21 um (0.0008” at 35”).
- C3 allows 12 um error within any 300 mm (0.0004” per foot). Cumulative error is not specified, thus allowing as much as 36 um error at 900 mm.
- P4 allows 16 um error within any 300 mm. In imperial units, this is 0.0006” per foot. Cumulative error at 900 mm is limited to 22 um (0.0008” at 35”).
- C7 allows 52 um error within any 300 mm (0.0020” per foot). Cumulative error is not specified.

The C7 grade is relatively low in cost and often used in retrofits or conversions of manual machines to CNC. The low tolerance allows the screws to be manufactured through a rolling rather than grinding process.

The design rules we set for the PCNC allowed lower speed and less spindle power than a conventional machining center, but we felt it needed the same precision. With this in mind, we selected the P4 grade for the PCNC 1100.

The screw is only half of the ballscrew issue; the other half is the ball nut. A standard ball nut will have free movement of several thousandths of an inch, which will produce considerable backlash on the screw. Anti-backlash (preloaded) ball nuts are used to prevent this. There are two techniques used to build an anti-backlash ball nut:

- Oversized balls. The ball nut can be made very tight by using balls that are slightly bigger than normal. This is a hand fitting process: someone puts in one ball at a time, checks for rotating torque, then puts in the next ball. The hand fitting process is required to set the preload.
- Opposed nuts. This involves two complete nuts. The nuts will have a precision ground spacer between them, forcing an offset. The preload is determined by the thickness of the spacer.

While both techniques effectively provide preload, there are important differences. The oversized ball technique creates 4 pressure points on every ball, with each ball loading against motion in both directions. The opposed nut technique has one nut dedicated to each direction; each ball then has only 2 pressure points. The opposed nut technique of preload is more expensive because it requires two ball nuts, but the balls last longer. The oversized ball technique is slightly less expensive, but the balls wear out sooner.

There is certain compressibility in ball nuts. Under heavy cutting forces there will be some apparent backlash even when ball nuts are preloaded. This is more properly referred to as lost motion than backlash because there is really no open clearance in the nut; it's just getting compressed under the forces. With a light preload the compression can be significant. A high preload provides less lost motion, but it also increases internal stresses. These stresses heat the screw, reduce efficiency, and shorten the life of the screw. It's essentially the same compromise made when determining the preload to put on spindle bearings.

For the PCNC 1100, we selected the opposed nut configuration. The ball nuts have a medium preload for long life and precision motion.

Lubrication, Protection & Way Covers

Ballscrews require both lubrication and protection from debris. Wipers at each end of the ball nut are helpful for keeping debris out of the ball nut; they are also effective for wiping off oil. Oiling the screw is not an effective means of getting oil into the nut. The inside of the nut is the critical place for lubrication, and it should be oiled directly. The PCNC 1100 has a one shot lubrication system with an oil line directly plumbed into each ball nut.

Overall, the lubrication system has 15 points. On each axis there are 5 lubrication points. These include the left slideway top and side, the right slideway top and side, and the ball nut. On each slideway surface there is a pattern milled the length of the saddle. The oil point is drilled through to that pattern to allow the oil pressure to be evenly distributed over the entire slideway. All of the oil lines are manifold plumbed to a single shot hand pump.

This may seem excessive to the machinist accustomed to a manual machine. Conventional practice is to keep a oil can or oil brush handy, occasionally putting a little way oil on the exposed surfaces. This is fine for a manual machine. Most manual machine operations are limited to cutting an occasional flat surface, drilling a few holes, and perhaps trimming an end or making a pocket. You will generally find yourself removing a lot more material with a CNC at your disposal. This means chips everywhere and much more motion of the axis, often 40 times more motion than a manual machine. With all this motion, maintaining the oil film becomes essential to long life of the machine. An oil can is not enough.

Another reason for plumbed lubrication is for the protection of slideways. The PCNC 1100 has no convenient access to most way surfaces. Way wipers can keep large chips from getting jammed under a slide way, but they cannot remove microscopic abrasive particles. Not only do exposed slideways tend to pick up abrasive contamination, they also seem to have a magnetic attraction to heavy work pieces, vises, cutting tools, and anything else you just don't want to drop on them. We felt it was important to have complete way covers to protect all ways and ballscrews.

Manual Operation: Hand wheels

It's unusual to encounter a task that is easier to do on an old fashion manual machine than on a CNC if the CNC mill is designed properly for combined manual and automated operations. Most buyers understand that they will have a lot of little tasks to accomplish that will not involve drawings, G-code programs, or automated sequences. To that end, many people look for hand wheels on the axis drives of a machine. Lots of small mills include hand wheels.

Small mills from Haas, Milltronics, Milport, and many other manufacturers have axis hand wheels. After watching operations and talking with the operators, we came to realize that the hand wheels were never used. Any machine that has a decent operator interface is easy to jog or increment position through the operator interface. Slow speed, high speed, small distance or large—it's all easier on the operator interface than it is on the hand wheels. Operators whose previous experience was mainly on manual mills predicted the need for hand wheels, but once they understood the machine operation and gained some facility, they realized the hand wheels were just not useful.

Those operators' experience parallels our own during the development of the PCNC 1100. The first 3 prototype models included hand wheels. For safety reasons we tried the folding handle hand wheels, the clutch engagement hand wheels, and plain round hand wheels. We found that we never used them when running the machines, even for odd jobs without G-codes. We found they were often in the way, and that they may even be dangerous, despite the special features.

One aspect of hand wheels most people don't realize is that hand wheels are pretty much limited to setup or drilling operations. They really don't work well when milling if the machine is fitted with ballscrews. A standard lead screw is self-locking. You can apply a turning force to a hand wheel and make a table move, but you cannot applying a force at the table and make the hand wheel turn. Ballscrews are never self-locking. When a force is applied to the table, the screw will turn unless it is locked down in some way. If you release the CNC motor control and start turning the X hand wheel, you will see the table move in Y as soon as the cutter engages the material, unless you're holding the Y hand wheel in position. With conventional milling the machine will tend to dive into the work. With climb milling the cutter will push the table back, but pull in the direction of the cut. In either case, hand wheel milling with a ballscrew machine is difficult and generally inaccurate.

The killer came in the cost analysis. The precise position of the ballscrew shaft comes from a preloaded bearing set at the driven end of the shaft. A bearing at the other end does not add precision. As a matter of fact, it needs to be a floating bearing or the system becomes over constrained. The bearing at the other end is necessary to 1) keep the shaft from whipping at high speeds, or 2) support the hand wheel. When ballscrews are turning at slow speed (remember we don't have 150 IPM rapids), they do not need a bearing to eliminate whipping.

In a detailed design analysis, we found that as long as linear speeds are below 120 IPM, when you remove the hand wheel from the design, you also remove a machined bearing mount, a bearing, and about 6" of ballscrew shaft. This makes the net cost of the hand wheels considerably more expensive than they would first appear.

The bottom line is that hand wheels on combined use manual/automatic machines appear to be little more than a marketing tool. They're eye candy. During the purchase decision they probably provide a certain comfort level for the machinist making his first entry into the world of CNC machining. However, after he gets to know the machine, he finds he never uses them. While it is reasonable to include them solely from a marketing perspective, this sort of thinking does not follow the design philosophy of the PCNC 1100. The PCNC 1100 does not have hand wheels.

I'm certain that we will eventually get a letter from a machinist who uses the manual hand wheels on his CNC machine every day for some very good reason. That's fine—we look forward to hearing from him. We just haven't heard from him yet.

Control System
Our search for a manufacturing partner originally spanned the globe. We discussed the project with companies in Eastern Europe, India, Taiwan, and China. It quickly became apparent that the best cooperation and quality was coming from Chinese companies. What also became clear was the inability of those companies to provide low cost, high quality industrial electronics. Early on in the project we decided to provide all of the electronics for the machine.

The decision to use PC control for the machine was never really questioned. The lowest cost embedded CNC controller would have approximately doubled the cost of the machine, while also reducing features such as program size, display, and connectivity.

There are a number of PC-platform CNC control architectures that are based on a PC operator interface. In many of those designs, the central control is in a proprietary circuit board that fits inside the PC; it requires proprietary control software. While some companies claim this as an open architecture, it's really only open regarding the selection of the PC. Conversely, in our control architecture we use a standard PC without any special internal circuits. All signals to the CNC are generated through the standard PC parallel printer port.

Printer port control architecture has evolved over the last 15 years through the efforts of a number of companies, dedicated individuals, and even the United States National Institute of Standards and Technology (NIST). After reviewing a variety of alternative PC based CNC programs, we selected a program that we believe offers the best in features, performance, and value. Nevertheless, the PCNC 1100 remains a fully open architecture—there are several competitive programs capable of running the machine. There is even a free Linux program available, originally developed through a NIST grant.

Manual Controls
The machine includes a 115 VAC outlet for coolant power. As a convenience, there is a 3 way switch that allows these variations:

1. Outlet is powered (coolant on manual)
2. Outlet is off (coolant definitely off)
3. Outlet is under computer control

One of the advantages of this configuration is that the outlet is not dedicated to coolant. You could use this to plug in a Dremel® tool, an air valve for a pneumatic vise, or even a vacuum pump for hold down of flat stock.
The operator console also has controls to over ride the computer for spindle control. When it is switched into manual spindle mode, the console provides controls for spindle speed and direction.

We offer a low cost CNC pendent that operates out of the USB port on the computer. The pendent is not a complete machine controller, but it is very handy for setting up positions, as well as for manual operation. The combination of a pendent for motion and the manual controls for spindle and coolant make manual operations easy to perform.

There are two additional outlets that are intended for the control computer and monitor. These are switched through the main operator console. By providing a console-mounted switch for the PC, we have made it a easy and practical to mount the computer in a completely protected environment, such as in an enclosed machine stand.

Other Controls
The basic control design includes a universal signal input that is accessible through a DIN connector on the front console. The input can be used for a variety of purposes, such as

- Probe input for digitizing
- Touch off for automatic tool reference
- Interface to 3rd party equipment
- Home switch for 4th axis reference

The door to the control cabinet opens forward. This allows the operator full access for maintenance even when the machine is backed up against a wall.

The control system is pre-configured for easy addition of a 4th axis. All of the power and signal connection points are in place. The panel is pre-drilled for the 4th axis driver and the cabinet is pre-drilled for the 4th axis motor power connector.

Coolant seems to get everywhere in a machining process and has a tendency to stream along electrical lines, getting into places it shouldn't be. All of the power and accessory wiring in the PCNC 1100 comes out of the bottom of the control cabinet. Since the wires are pointed down, a natural drip leg occurs, preventing coolant from following the wires in. The design includes a shield that both protects the connection points and forms a wire tray for the computer and power cables.

Safety features include a spindle power circuit that is enabled by both a key switch on the operator console, and a spindle cover door switch. The key switch lockout adds security in places where there are students, children, or unauthorized users. There is also a key entry to the control cabinet. Rotating the primary fuses into the off position and then locking the cabinet door can provide electrical lockout.

The machine can be rewired for 115 VAC power. However, because it will draw at the limit of 115V circuit's capacity, some people might experience problems with circuit tripping or brownouts. Nevertheless, we recognized that 230 VAC is simply not an option in many situations.

Summary: "I think it's time to shoot the engineer"
Most engineering managers understand this phrase—it could be something out of a Dilbert cartoon. The engineer in charge of a new design always wants the perfect product. A good engineer is never satisfied with his own work. Through the design and development process, new and better ideas continually percolate into the mix. As these ideas evolve, there is always the urge to delay product release in order to incorporate the most current ideas. To "shoot the engineer" means that the design is declared "finished"—no more improvements accepted—and the product design moves out of R&D and into production.

While the future will likely bring changes to the PCNC 1100, we are very happy with the design now, and it has been released to production. Rest assured, we have not shot any engineers. They have just been put to work developing more accessories for the PCNC 1100. The machine design is proven and stable.