CNC overview white paper

Introduction

This paper gives a high level overview of how Computer Numerical Control (CNC) systems are setup and work. The document is structured along the lines of producing a part rather than the design of an actual machine. If design of a machine is the readers' primary interest then it would make sense to read the document in reverse order. This would give greater emphasis on the finished part, how it is made and the optimal machine configuration rather than the process flow of making on-going parts. The intended audience of this document are hobbyists with an interest in the field or wanting to set up their own systems but it may also be useful for professionals in associated areas seeking an understanding of the field.

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CAD

The acronym stands for Computed Aided Design. The acronym was initially Computed Aided Drafting when the software was initially developed and focused on automating the creation of technical drawings. The use of a computerised system was a huge productivity boost for technical drawings as it allowed quick changes, modifications and edits without pen and pencil changes performed by hand on a drafting board.
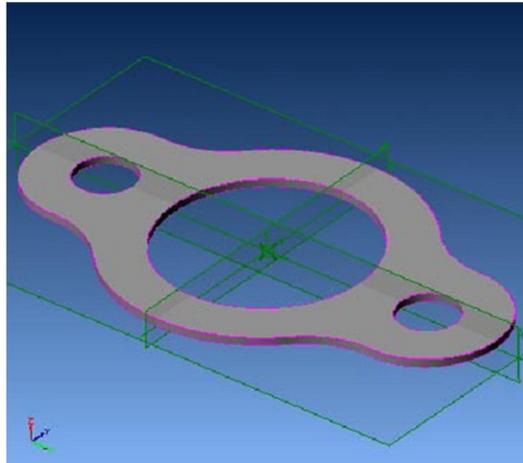
Figure 1: Example of a computer modelled part

The huge boost in computer speed and graphics has allowed computer systems to model full 3D geometries. This is a huge advantage in the design process as it allows parts to be designed, viewed and rotated in 3D in a process called solid modelling. An even bigger advantage is the ability to combine a series of parts and assemble them together within the computer. This creates a model of an entire machine or mechanism where fits, clearances and function can be checked before any parts are made. This design method is now used extensively throughout industry.

Industrial, full feature solid modelling software is expensive but simple free software for 2D drafting can be used for simple engraving or routing applications.

CAM

The acronym stands for Computed Aided Manufacture. At a simple level CAM software takes a CAD model of a part and produces codes that the controller can use to make an actual part. The important function of the CAM software is interpretation of material, tooling and machine characteristics to produces paths that the tooling must follow to manufacture a part.

CAM software usually incorporates databases of materials and their "machinability". From this the software functions as an "expert" system and produces appropriate speeds and feeds for a given material, machine and tooling. Knowledge of machinability however is still required by machine operators in order to maintain machines and fault find program operation.

For any given part there will always be multiple ways of making the same item. Whilst the software does function as an expert system it will always need guidance as to the best sequence of operations to take. Significant gains in machining time and part quality can be made by the intelligent use of the software.

Most CAM software also uses a concept call the post processor. This functionality sets up the codes that the software will use to take tool paths and turn them into positional codes that the CNC machine can use. Good CAM software will have preconfigured postprocessors to suit common CNC machines.
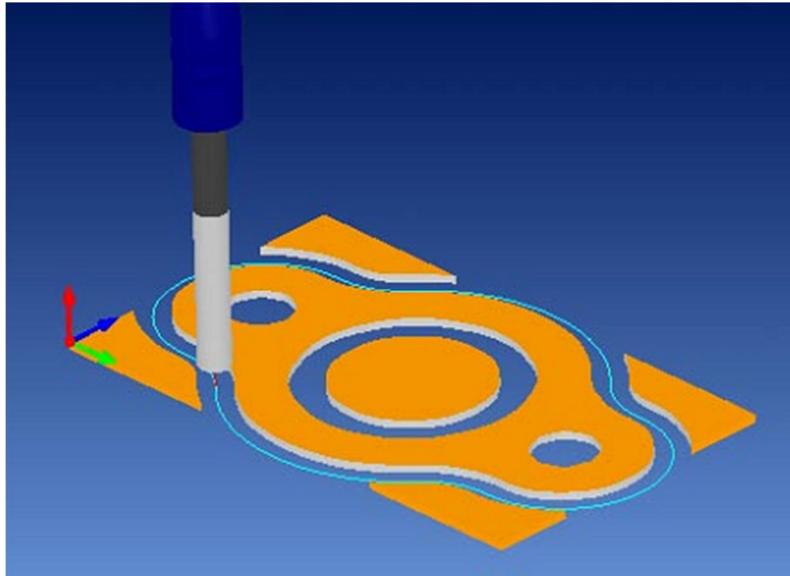

Figure 2: Example of a tool path in CAM software

The complexity and expense of the software varies greatly with the complexity of the machine. For simple routing, engraving and cutting applications (often called 2.5 axis machining) fee software such as gsimple or FeeMill can perform adequately. As soon as you move to 3 axis surfacing then complexity and costs go up rapidly.

By far the most common language that CAM software produces and sent to the CNC controller is G-code.

G code

A sequence of G code grouped in a single file and used to make a part is often called a part file. In principle a part can be created by hand coding G-code from scratch. This is normally only used for simple parts and by experience operators. When properly set up high end modern CAM software is capable of producing reliable part files that require little or no modification.

A working knowledge of G code is essential for CNC operators so that they can understand what their controller is trying to perform at any given time. There is an excellent Wikipedia article with more information at - http://en.wikipedia.org/wiki/G-code.

Whilst there are standards for G-code in practice there are subtle variations from controller to controller and even in the setup of a specific machine with the same controller. Some G codes, such as spindle speed and tool change, refer to functionality they may be specific to an individual machine. The function of the postprocessor is to take account of these variations.

CNC controller

The acronym stands for Computed Numerical Control. When CNC machines were first developed specialised hardware including application specific integrated circuits were required for any practical

machines. With the performance of modern PCs It is entirely practical to use a standard PC to make a useful machine. In fact the majority of commercial controllers are now simply ruggedized PC architectures which include some form of isolated high speed digital inputs and outputs.

A standard industrial CNC controller will typically have a screen, and ruggedized membrane keyboard and an operator panel with buttons for e-stop, machine jogging, mode switching, cycle control, chip conveyors and a host of other controls specific to each machine. At this end of the market specialist application specific interface cards are also used to handle the high speed IO required for high accuracy and dynamic response.

Figure 3: An Industrial CNC control interface

At the hobby end of the market where high reliability, dynamic response or durability are of less importance then standard PCs are often be used. The simple setups use the parallel port of the PC and connect to the various motor drives with a breakout board. More sophisticated break out boards are starting to become available that use Ethernet or USB connections to the controller software.
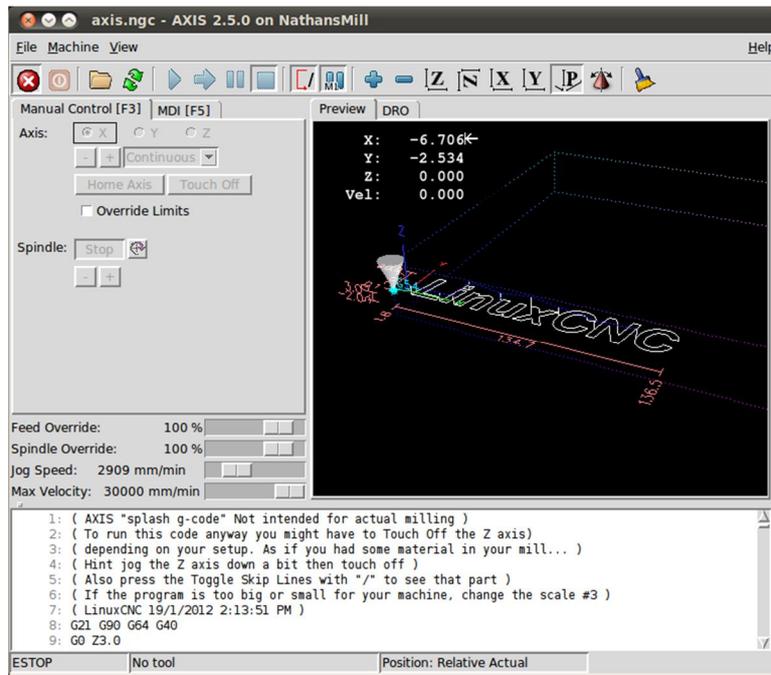
Figure 4: A simple PC based CNC interface

Software that emulates a CNC controller on PC is readily available. The most popular types are Mac3 for windows and EMC2 (or LinuxCNC) on Linux.

Control signals

In the early days most signals used to control motor speed were analogue, usually 0-10V, signals. Although this sort of signal is still frequently used in industrial motor controls it's susceptibility to drift and the need for slower binary to analogue conversion limits analogue control to less precise or dynamic applications.

The advent of stepper motors that moved a set percentage of rotation with every electrical pulse effective digitised motor rotation. This made the motor motion more like the binary language of a computer, eliminated the drawbacks and overhead of an analogue signal and this control method is now the primary communication method used for precision motion control today. Conceptually difference between 0-10V and pulse is analogous to analogue vs digital audio.
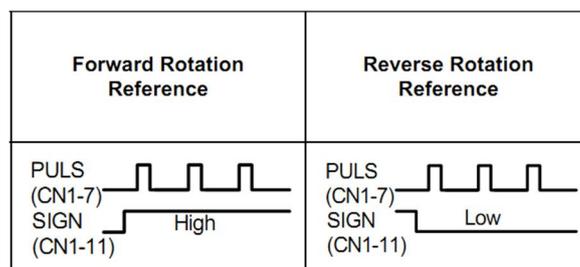
**Figure 5: Pulse and direction signal**

Types of motors

Industrial CNC machines make extensive use of AC servo motors. These use rare earth magnets, have built in encoders and high speed, closed loop frequency drivers. AC servos give exceptional

consistency, speed range and dynamic response. Their price typically excludes their use in hobby systems but more economical AC servo systems are starting to become available.

DC motors can also be used effectively especially if they are coupled to an encoder. Their use can be a bit limited as they have a non-linear torque response and require expensive closed loop controllers to be effective. They can product high torque which can be an advantage in some applications.

The most common motor used in hobby systems are stepper motors. These motors have magnetic "teeth" in the rotor and an arrangement of windings or poles in the frame of the motor. Energising the poles forces the rotor to align to a specific pole, and energising the poles in sequence causes the motor to rotate. These motors are economical to manufacture and are ideally suited to a digital pulse signal. In any practical system a driver is also required to amplify the low power control signal (typically 5V and a few milliamp) into high current and voltage motor signals that can provide useful torque.

Figure 6: Inside construction of a stepper

Stepper motors have a low speed range and a nonlinear response with torque dropping away rapidly with increasing speed. When the torque exceeds that of the motor the rotor will stall and fail to move to the next pole in a phenomenon commonly called missed steps. As the motors don't normally have closed loop encoders the controller is not notified of the positioning fault and it will only appear as an inaccuracy in the final component. Slower feed rates reduce the likelihood of this occurring and in hobby applications this is usually acceptable.

Coupling and thrust loads

Motors produce a rotary torque that is then coupled to some form of linear drive. It is important for the life of the motor to avoid thrust loads or shaft misalignments. Thrust loads from the drive are handled by bearing arrangements such as shaft supports while misalignments are taken care of by a shaft coupling.

Figure 7: Block type shaft support

Figure 8: Precision coupling

For precision applications it is important that a coupling has good balance between the misalignment capability, rigidity and torque capacity. Couplings for CNC use are typically called precision couplings and are different to the flexible couplings commonly used in pump and conveyor drive applications.

It is possible to mount pinions or pulleys directly to motors but this should be avoided in high load or duty cycle applications.

Linear drives

There are wide range of devices that can be used to turn the rotary motion of the motor into linear motion. At the low end cable and chain systems or lead screws can be used for cheap and low accuracy applications. Higher speeds and medium accuracy can be achieved with timing belt drives and higher precision requirements use ball screw or rack and pinion.
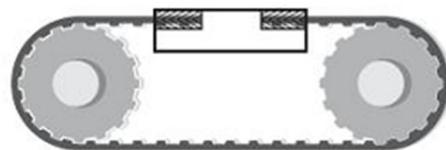
Figure 10: Timing belt drive

Figure 9: Rack and Pinion

Figure 11: Ball screw

Rigidity and lead (distance travelled per revolution also called pitch) are also important requirements with ballscrews and rack and pinions offering highest rigidity. Ballscrews also offer the smallest lead which in turns gives the greatest mechanical advantage. While ballscrews would seem to be the best drive they can be expensive and are not suitable for longer travel lengths. They can also have reliability problems in dusty and dirty environments.

Guidance

There is a seemingly bewildering array of guidance options in the market and all have some basic strength and weakness.

It is entirely possible to make a CNC machine with cheap rotary bearings, draw sliders or even plan friction bearings. It is a worthwhile academic exercise to take apart an old printer to see what can be used in low duty cycle and precision applications where cost is critical. - Just keep in mind that the manufacturers invest a great deal of time in the design and testing of these devices which may be unrealistic for a hobbyist in a one off project. For any higher loads, duty and precision requirements hardened ground guide ways are required.

Ball bushes are a traditional guidance solution and in some cases still one of the most economical approaches. In longer length applications the shafts need to be supported along their length (often

called support rail). This adds considerably to their expense, compromises the load capacity and the open bearing creates a contamination risk.

Figure 12: Ball bush

A roller solution has the advantage of higher load capacity, longer service life and contamination resistance. These can be constructed with rollers running on steel or aluminium profiles but relatively economical roller guides are available that have integrated rails. Many also feature eccentric rollers that allow adjustment of the preload and hence rigidity to suit the individual machine requirements. High end types have hardened and ground rails for accuracy and durability and have offer-aligning capabilities for ease of installation.

Figure 13: High end roller guides
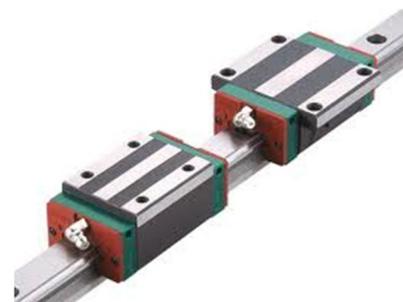
Figure 14: Profile rail

Profile rail has the same basic concept of a ball bush with recirculating balls inside a slider. Rather than a round shaft however a specially profiled rail is used. The slider wraps around the profiled rail and the ball races lock into the profiled shaft. Profile rail offers high precision, long service life good contamination protection and high static loads. This is often considered the optimal solution for heavy duty situations and is widely used in commercial machines. A consideration for the hobby constructor is the precision required for mounting and the cost.

Machine layout

There are a wide variety of methods used for the physical layout. The optimal layout depends on what the machine is specifically designed for.

Industrial mills of small to medium travels usually use a moving table of a knee mill type of design. This construction offers high rigidity and accuracy and is well suited to precision steel machining. Manufacturing the frames is typically a complex and costly exercise. Small travel systems of this sort

of layout are still made by hobbyists doing small size routing of wood or engraving but not generally used for working with steel. Conversion of a manual knee mill can be a good option for hobbyist wanting to work with steel.

Figure 16: Gantry router

Figure 15: Knee mill

Larger work envelopes cause problems with rigidity and a rapidly increase in the physical size of machines. For travels of a 1mtr or more traveling gantry style construction are more common. The work piece is held stationary while the gantry moves the head around the work piece. Some rigidity is sacrificed but the physical foot print is greatly reduced.

Spindles and heads

The CNC machine provides the ability to position anywhere within the travel limits of the machine. Laser cutters and engravers, grinders, fabric and plasma cutters, routers and 3D printers all use the same basic functionality but what is attached to the head will dictate what the machine can perform on the work piece.

3D printers, laser and plasma cutters are in many ways a mechanically easier machine to manufacture as the head does not have to be forced through the work piece. This reduces the loads on the machine frame and only the weight of the head itself needs to be considered in the design. In many cases control of the head process can also be a simple on/off switch.

Figure 17: Plasma cutting

This would certainly be the case if a hand held plasma torch were to be used to create a plasma cutter or for a basic fabric cutter. For more flexible systems and quality control however some form

of control of the head tooling is required. A good example would be a plasma cutter where torch height and power needs to be carefully control to give a clean cut.

Industrial spindles can be expensive and require a separate driver so handheld routers are frequently used for hobby applications. These are capable of adequate performance for low duty applications and can be relatively easily setup using a relay to start and stop the router from the controller. A significant problem with these spindles is they are designed for edge router applications and generally do not have thrust bearings. This means the thrust loads generated by plunging into the work piece or performing 3D profiling significantly reduces the life of the router. For edging only or low duty hobby setups replacing a router every few years may be an acceptable option.

Figure 18: Industrial spindle

Figure 19: Plunge Router

Speed control of the router is a critical feature in commercial systems as different tooling and materials work best at a range of speeds. Most hobby systems work primarily on only one type of material and don't have automatic tool changing so the manual control of speed can be entirely adequate.

Industrial CNC controllers usually have spindle control as either a voltage and/or pulse control. Physically the signals are the same as the axis control and in many controllers a 3 axis controller is actually a 4 axis controller with one axis being able to function as a spindle or a 4th axis. Most hobby setups do not have voltage control so frequency to voltage conversion or a spindle driver with a frequency input is required.