CNC Routers for Luthiers

by Mark French

THE DAYS of extensive handwork in the guitar manufacturing industry have basically ended, with computer-controlled machine tools taking over many jobs. The result has been more precision, lower build variation, and probably lower manufacturing costs. Almost all large guitar companies are now highly automated.

This type of advanced manufacturing had been limited to large companies. However, the emerging world of robotics and mechatronics has created a growing market of sophisticated, low-cost CNC routers that are available to the average luthier. Some have already integrated CNC routers into their shops, but for the rest of us, it can be hard to know where to start. This article is my attempt to help.

A CNC router is essentially a router body or a specialized motor called a spindle that moves under computer control. The computer moves the router so that the spinning bit cuts out parts precisely and repeatably. In the guitar world, CNC routers are used to make a wide range of components, forms, and jigs. Having one offers the possibility of increasing quality, decreasing build variation, and perhaps offering a wider range of designs.

CNC machines that would have been made of low-volume, high-cost components are now routinely assembled from cheap, standardized, off-the-shelf parts. The result is a class of small CNC routers inexpensive enough for individual builders. Some luthiers have already taken the plunge (Don MacRostie has done some particularly nice CNC work) and are finding that they can increase productivity and improve precision.

There are basically three problems with introducing CNC routers to a small shop:

- Finding the right machine for you.
- Selecting and learning to use the software that makes the machine run.
- Designing a guitar to be built using a CNC router.

The third bullet is worth at least one article on its own, so I can only touch on it here. The hardware is easier to characterize, so let's start with finding the right machine for you. A CNC router is really just a three-axis traverse system that moves a spindle. If you, like me, are old enough to remember XY plotters, imagine a big XY plotter with a router where the pen would be. The vertical travel (Z Axis) on many routers is small enough that they are almost 2D machines. They are sometimes

Photo 1. *Interior of a Hurco industrial CNC machine carving necks eight at a time at Taylor Guitars.*

ALL BY MARK FRENCH EXCEPT AS NOTED

Photo 2. *Exterior of the same machine, showing the control panel and the substantial safety doors.*

even called 2.5D machines, but they work fine for most lutherie applications. Much of what we do is essentially planar, so that third dimension is not always as important as you might think.

It may help to divide the available machines into three different classes: industrial, small shop, and home shop. I've never heard of any classification system for CNC routers, so perhaps these names will do until something better comes along.

Industrial Machines. These are large machines which are often derived from three-axis mills designed for working metal. In some cases, they are basically repurposed metal mills. Industrial machines are expensive (often more than $100,000) and usually require 480v 3-phase power. When they are integrated well into the production process they can be very productive. However, they are too expensive for all but largest manufacturing operations.

In concept, these machines are no different from a simpler CNC router, but are more powerful, more precise, and have automatic tool changers so that one job can use several different cutting tools. Cutting wood usually requires higher spindle speeds than cutting metal, so CNC mills used for guitar making have to be upgraded. The worldwide customer base for industrial CNC mills is very large, so there many suppliers, including ones that make specialized machines for the guitar industry.

Large guitar manufacturers may have a dozen or more of this type of machine in their factories. **Photo 1** shows acoustic guitar necks being cut out, eight at a time, on a CNC mill at Taylor. This operation uses a large ball-end tool and the resulting surface finish is very good.

Photo 3. CNC router making an electric guitar.

Photo 2 shows the same machine from the outside. It is made by Haas, a large manufacturer of industrial machine tools. The cutting area is enclosed with doors that feature safety interlocks. Also, it has a dedicated control panel that allows sophisticated setups and even some programming. Note how clean the area around the machine is; good factories take dust control seriously.

Small-Shop Machines. These are much less expensive than industrial CNCs and are designed specifically for woodworking. They are often found in schools, and there are two in the Guitar Lab at Purdue University where I teach. They can run on 220v or 110v power and use either a router body or a variable speed spindle-and-driver box to spin the cutting tool. They are powerful enough to cut thick pieces of wood, like those used for electric guitar bodies, reasonably quickly. A slab body, like those used by Fender electric guitars, might be cut out in something on the order of fifteen minutes. A body with more contouring, like a Les Paul, takes longer.

These machines almost always use a gantry design and sizes range from desktop models to those large enough to accommodate a 4×8 sheet of plywood. Purchase cost, which usually includes basic software, ranges from about $6,000–$20,000. Tool changers are sometimes available, but can be prohibitively expensive.

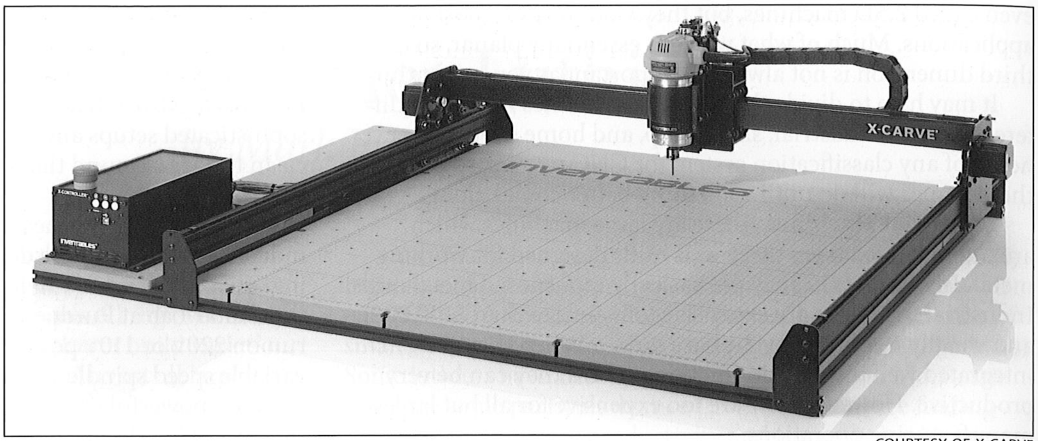
There are numerous manufacturers for these machines, and the components are available from many different suppliers. The development of low-cost robotics and mechatronics means that relatively standardized stepper motors, controllers, bearings, and lead screws are easy to get. The result is that there are many small companies making CNC routers.

The two suppliers I have the most experience with are ShopBot and Forest Scientific, though there are certainly other reputable companies. ShopBot offers several machines that are well-suited for guitar making and Forest Scientific even offers a series they call LuthierMax. **Photo 3** shows a Shopbot CNC router cutting out a neck-through guitar in the guitar lab at Purdue University. This is a larger machine that can handle a 4×8 sheet of plywood and the guitar in the picture is laid out across the width of the table.

The two numbers that define how fast a machine can cut are the cutting depth and the move speed. Deep cuts are seldom done in one pass. When making guitars on a small-shop router, cut depths are often 0.25″ (6.3mm), so a 1.75″ (44.5mm) thick body takes seven passes. Sometimes, a light final pass is made at full depth to take the part precisely to a final shape and remove tooling marks. Depending on the tool, small-shop routers often have feed rates of 1–3 in./sec. The largest practical bit on my Shopbot with a variable speed 220v spindle is ½″ diameter with 2″ cutting length. One time, I tried a 6″ long bit with a 3″ cutting length in an effort to cut out an acoustic side mold in one operation. The vibration and resulting chatter were terrifying — never again. I later had 1″ cut off the shank with a water jet and that helped quite a bit, though it is still at the limit of what the machine can handle. The smallest bit I've ever seen used on a small-shop router is a 0.023″ bit used for cutting fret slots. Fanned-fret slots should be pretty easy with a CNC, but feed rates have to be very low to avoid breaking the cutter. Even handling them can be a challenge; I found that just dropping one onto the table could be enough to snap off the tip.

Home-Shop Machines. These typically use laminate trimming routers for spindles and have cutting sizes ranging from 12″×12″ or 305mm×305mm (CNC Pirhana) to 29.5″×29.5″ or 750mm×750mm (X-Carve with 1000mm rails). They are designed to be easy to use and sometimes use the same software as small-shop machines. Purchase cost ranges from about $1500 to about $4500. **Photo 4** shows an X-Carve from Inventables.

I recently bought an X-Carve and have been using it to make fixtures and parts for acoustic guitars. Mine uses a DeWalt 611 trim router for the spindle and has the 1000MM rails. It came as a well-packaged kit and it was easy to assemble.



COURTESY OF X-CARVE

Photo 4*. X-Carve with DeWalt router as spindle (inventables.com).*

Spindles for hobby machines are typically router bodies — the DeWalt 611 is a popular choice for other machines as well — so they are not suitable for really heavy cuts. While they are capable of reasonably good precision, typical cut depth might be 0.050″ (1.27MM). The result is that a part that might take fifteen minutes on a small-shop machine will take a lot longer on a home-shop machine.

Some machines move the spindle with lead screws, which are robust and accurate as long as backlash is controlled. I had a CNC Shark from NextWave Automation in the Guitar Lab that used lead screws. Less expensive machines, such as my X-Carve, use toothed belts. As long as belt tension is adjusted correctly, the belt-drive machines seem to be accurate enough for most purposes. Once, I did have a belt slip and ruin a part I was cutting. But tightening the belt just took a minute and a quick test showed that the machine was still cutting accurately.

NextWave machines are built around rigid extruded-aluminum channel frames. X-Carve machines have a larger cutting surface and the frame is less rigid. A careful user should be able to do reasonably precise work with either type. Another popular machine is the Carbide3d Shapeoko XL/XXL, though I have no personal experience with it. And no, I don't know who names these things.

Home-shop machines are precise, but not fast. The tradeoff made to keep the cost low is slow feed rates and shallow depth of cut. Thus a large or complex piece may take hours to cut out, but there is no reason you can't just let it run, keeping an eye on it while doing something else.

Home-shop machines typically have limited vertical travel, often only a few inches. For example, my X-Carve has 65MM (2.5″) of vertical travel. For electric guitars with 1.75″ thick bodies, this may not be a problem. The spindles can accept only ¼″ or smaller diameter bits which can't have cutting lengths much longer than about 1½″, so there is no way to make really deep cuts anyway.

The more popular home-shop machines have a large enough user base that there are videos and websites devoted to them. Having a supportive community can be a big help, particularly when starting out.

The market for small-shop and home-shop machines is maturing, but no clear market leaders have emerged. The machines themselves are made from common components whose cost has dropped lately because of the growth of robotics and 3D printers. As a result, the cost of entry is not as high as you might think, and there are many small vendors offering everything from partial kits to complete machines.

The market has parallels with the automotive industry in about 1905. There are many small companies making similar products and the market hasn't consolidated yet — no equivalent of Ford or GM has emerged. The good news is that there are many different product choices. The bad news is that one runs the risk of buying a machine from a company that might not be in business when you need parts or support.

If you really want to feel the wind in your hair, there is a community of people who make their own CNC routers from components they buy or make. There is at least one open-source package called GRBL (really) that translates G Code (the text instructions that move the spindle) into the signals that control the motors which move the spindle. Some tinkerers really like making CNC machines and it's easy to see why. However, time spent building and refining a CNC router is time not spent actually making anything with it.

Photo 5*. Headstock with molded binding.*

A quick Google search shows that buying the parts for a CNC router can be much cheaper than buying a complete machine. However, going that route means that you will be in the CNC-router-making business, not the guitar-making business. One obvious advantage is that you can tailor your machine to your exact needs and try out new ideas. There are many websites, forums, and YouTube videos devoted to making CNC tools; if you decide to build your own, you should be able to find help and supporting information. A popular source for parts is cncrouterparts.com.

Of course, there are many generic imported machines on the market and the prices can be very low. However, they often come with little to no support and few instructions. If you know enough and don't mind some fiddling around, this might be a cheap way to get a CNC router.

In the home-machine market, cost pressure is particularly intense. There seem to be basically three market strategies. The first is making the machine itself as simple and inexpensive as possible while adding value through direct user support and fostering an active user community. The second is controlling purchase cost by focusing on the hardware itself to make the machine robust while offering more limited support. The third, which frankly doesn't seem to be working very well, is for a familiar power-tool company to market a small CNC router, either as part of their own brand or through their distribution channels. A few tentative attempts by established manufacturers to enter the CNC market haven't been successful, though it might be nice to have a large, established manufacturer to throw its resources into a good CNC router.

The low-cost, high-support approach is the one followed by Inventables with their X-Carve. The machine itself is very simple and almost modular. It is made of inexpensive, standardized components, right down to the X-Controller, and requires some user assembly. Mine cost about $1800 including some options like a dust collection shoe, though there seems to have been a slight price increase since I bought mine in mid-2018. It's probably not the best hardware available — Shapeoko machines are sturdier — but I wanted user support and I knew I didn't have time to spend debugging a CNC router. For me, it was a good choice.

The X-Carve community is as large and active as any I know of in the CNC router world. Online user reviews are full of stories recounting good service by the company and the responsiveness of the online community. To keep things cheap and simple, their CAD/CAM software runs online from a web browser and your computer just plugs into the router controller with a USB cable. I should be clear that I have no connection with Inventables; my comments here are based only my own experiences.

Closed- and Open-Loop Systems. One arcane distinction between the machines is whether they use closed-loop or open-loop controls. Closed-loop controls directly track the position of the spindle and adjust the drive motors to ensure that the spindle is in the right place. An open-loop system simply tells the drive motors to move a certain number of turns and assumes the spindle is then in the right place.

Closed-loop systems are more accurate, but more expensive. Industrial machines almost always use closed-loop control systems. Small-shop machines often have both open-loop and closed-loop models, with the closed-loop systems being more expensive. As far as I know, all home-shop machines use open-loop controls.

Practically speaking, the difference between the two approaches is accuracy; closed-loop systems put the spindle closer to the intended location. Companies that use large industrial machines and carefully control the environment within their factories can routinely work to within a few thousandths of an inch. This gives them the freedom to implement design features that the individual luthier might find impossible.

For example, Taylor Guitars sometimes routs a headstock binding channel before the headstock is cut out. Injection-molded binding is then glued into the channel and the headstock outline is milled to expose the binding. This only works when tolerances are held very closely. This level of precision would probably be tough to duplicate with a hobby machine or a small-shop machine unless it had a closed-loop controller. **Photo 5** shows a headstock with the binding in place, but before being cut out. Note the three alignment holes that locate it precisely on the fixture for milling. Note also the pocket for the Taylor logo, which will be installed later.

Another example is from Fender at their facility in Corona, California. Their operation is also heavily automated and they, like other manufacturers, use some clever design features to take advantage of the capabilities that CNC routers offer. **Photo 6** shows a stack of necks after initial machining. There are three features of interest to luthiers. The first is the nice surface finish, which comes from sharp tools combined with well-chosen spindle speeds and feed rates. The second is the tabs with locating holes that allow precise alignment for the next operation. The third is the inset fretboard that offers a clean, precise alternative to binding the fretboard; it would be tough to pull this off without the precision of a CNC router. Fender calls this a channel-bound neck and has patented it.

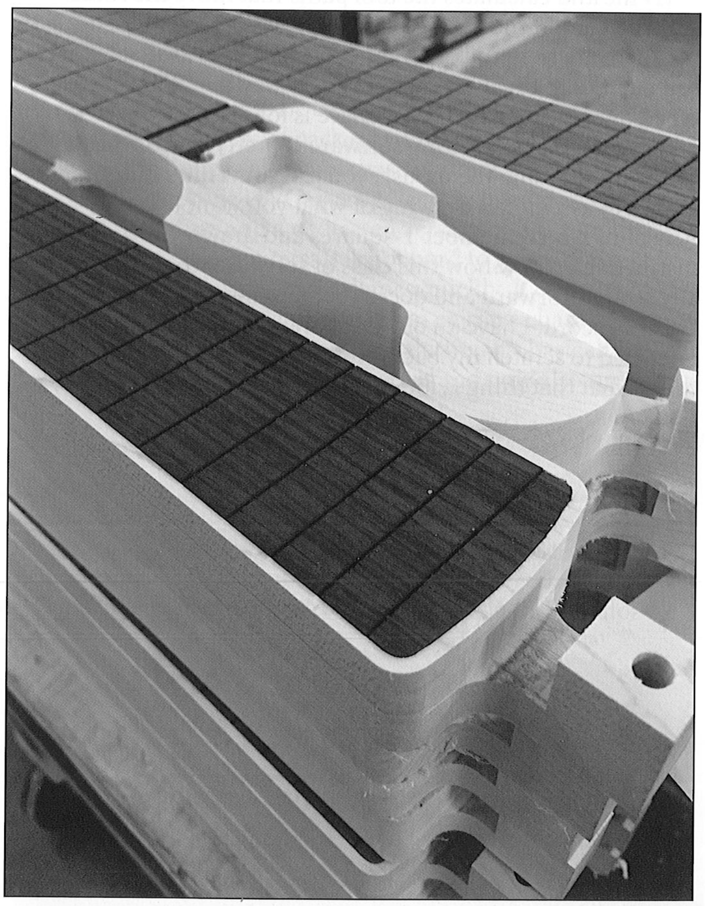


***Photo 6.** A stack of partially completed necks at Fender in Corona, California.*

Making Parts or Forms? The first thing you need to decide when buying a CNC router is what you want to do with it. A luthier can make parts directly using the new machine or use it to make precise jigs and templates. If the machine is fast enough or the production rate is low enough, it's possible to make parts directly. Otherwise, the router could be used to make precise forms that will tighten up the existing build process.

Manufacturing engineers know that simply automating an existing manual process isn't always a good idea. Having computer-controlled equipment offers the chance to modify your build process to take advantage of your new capabilities. For example, when it becomes possible to work to tight tolerances by precisely manufacturing components, you could refine your designs so that parts require less fitting. A simple example might be cutting an accurate radius into the bottom of an acoustic bridge so no time is spent sanding and fitting it to the top.

Software. No matter what machine you decide to get, you'll drive it with software. And, no matter what software vendor you choose, your system will have three parts: CAD, CAM, and control software (**Fig. 1**). The control software is provided by the router manufacturer and is what sends signals from the computer to the stepper motors to move the spindle. Unless you build your own machine, you usually don't have to select control software since the manufacturer does it for you. You will have a choice in CAD and CAM software and it can sometimes seem like too many choices.

Computer aided design (CAD) is what you use to draw a picture of the part you want to make. The result is a geometry model (a drawing) of your part. Computer aided manufacturing (CAM) is what takes the geometric model from the CAD file and calculates the tool paths that move the router to actually cut out the part.

There are so many different CAD packages available that it can be hard to organize them in some way that makes sense. One possibility is whether software is for 2D drafting or 3D modeling. The 2D drafting software is pretty much what it sounds like: Using the mouse, you can draw lines and simple shapes to assemble a drawing of what you want to make. Any of us who remember T-squares and drawing boards will instinctively know how this class of software works. It is generally straightforward and doesn't require much abstraction. For the record, I have an old T-square in the guitar lab. Once, I decided to scratch my back with it and a student said, "So that's what that thing is for!" Sigh.

Solid modeling software lets you create true 3D shapes, and it can describe much more complicated objects than is typically possible with 2D drafting software. However, it usually requires a level of abstraction that might be new to someone who was trained to draw on paper.

My undergraduate students learned to use solid modeling software in elementary school or junior high, so they have no problem using any of the CAD packages. I, on the other hand, needed a little practice to get used to thinking in terms of how 3D modeling software works, though it was easier than I feared. **Fig. 2** shows a section of a guitar neck I modeled using Google SketchUp, a simple, free 3D modeling package. This is the result of about two hours of playing around. I could probably do it in twenty minutes now. I tried to make a shape that would have the router remove most of the material so that I could refine it by hand. Certainly, it's possible to do more sophisticated models, and many people do. However, working with collections of flat surfaces is easier and suits my purpose.

Working with SketchUp, as with any 3D modeling software, requires a slightly different approach to drawing. For example, to make this shape, I defined the cross section of one end of the neck and extruded that shape to make a constant cross-section prism. Then, I shrank one end to match the dimensions at the nut. The next step was to extrude a section from the heel end where the neck would bolt to the body. Finally, I added some triangular transitions. Note that doing it this way gives the heel a constant cross section rather than a tapered one. For the real thing, I'll use a straight taper along the whole length of the neck.

A couple hours at a coffee shop, watching a few short YouTube videos, and playing with the software will get you to the point of being able to do useful things. Really good CAD jockeys, like really good luthiers, have generally acquired their skills through long practice. The good news is that you don't need to know very much to be able to do useful things and, like anything else, you will learn with experience.

Another way to organize software is by its intended audience. At the most complex are the powerful industrial packages. They are expansive software packages that do geometric modeling and analysis. The addition of analysis functions like finite element analysis (FEA) and computational fluid analysis (CFD) have turned them into what are now called computer aided engineering (CAE) packages. These are way more than most luthiers need but are very handy if you have mastered them and have access to them.

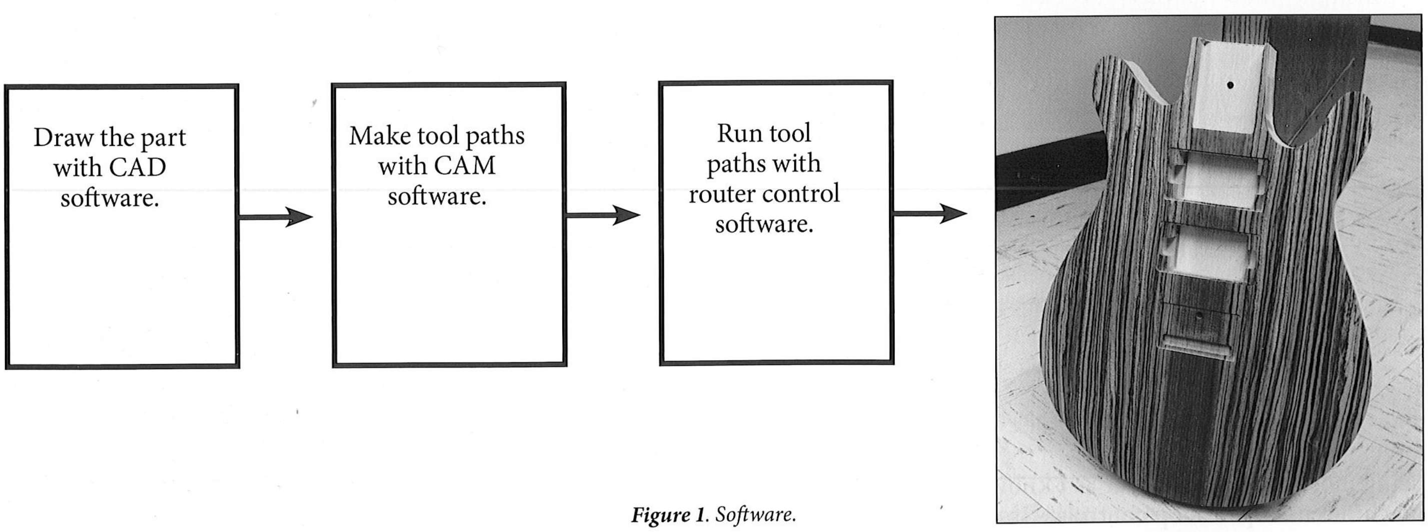


Figure 1. *Software.*

There is no one standard piece of software, but there is a handful of commercial packages that probably account for most of the industrial CAD/CAM market. Two popular ones are SolidWorks and Inventor. These are very powerful and expensive, though free for many students and teachers. There is definitely a learning curve for these packages, but anyone with patience and some persistence can learn them. High school kids routinely become fluent in them through both classes and projects like FIRST Robotics. Having asked around, it appears that two of the most common industrial CAD packages in the guitar manufacturing industry are likely SolidWorks and AutoCAD.

Asking people what CAD software they like is akin to asking what kind of pickup truck they prefer — there are some strong and divergent opinions, but the differences are in the details, not the fundamental capabilities. In trying to find out whether there was a common hardware/software combination among luthiers, I started asking around. I hardly got the same answer twice. As a group, we are all over the place. It's possible that there will eventually be a relatively common solution, but we are far from it right now. The good news is that all of these hardware/software combinations seem to work for the people who use them. There are lots of right answers.

There is a newer class of simple, more widely available solid modeling packages that are easier to use. Among these are Tinkercad (by Autodesk) and Google SketchUp. They emphasize ease of use and are able to model shapes sophisticated enough to be useful for luthiers. Tinkercad is the easiest to use and, unsurprisingly, the most limited. It's an online app so anyone can get access. It's probably a good starting point for people interested in solid modeling, but not a good ending point. It's too simple for many lutherie applications, but is fun and easy to pick up. I have firsthand experience watching 3rd graders make objects for 3D printing using Tinkercad and they learned it without apparent effort. The first thing I ever modeled in Tinkercad was a volume knob that goes to 11. I eventually 3D printed a couple from that model. Tinkercad and SketchUp only do the solid modeling. They don't make tool paths.

Some software packages integrate the modeling (CAD) with tool path generation (CAM). Perhaps the simplest CAD/CAM software is from Inventables. Their Easel package runs from a web browser, so you always know you have the newest version and there are no installation problems. If you have a web browser, you are in business. When you have generated tool paths, just plug your computer into the control box with a USB cable and start milling.

A mostly free integrated CAD/CAM package is Fusion 360, also by Autodesk. It feels more like one of the heavy duty industrial packages, but is very capable and writes tool paths in a fairly seamless way. It takes longer to learn than the simpler software, but it should be able to handle just about any task you have. It can do 2D drawings, 3D modeling, and CAM. It stores all its data in the cloud, though it can export files to your computer. At this writing, a subscription is \$300/year, though it is free for small startups (<\$100,000/year) and noncommercial users. In practice, this makes it free for many luthiers.

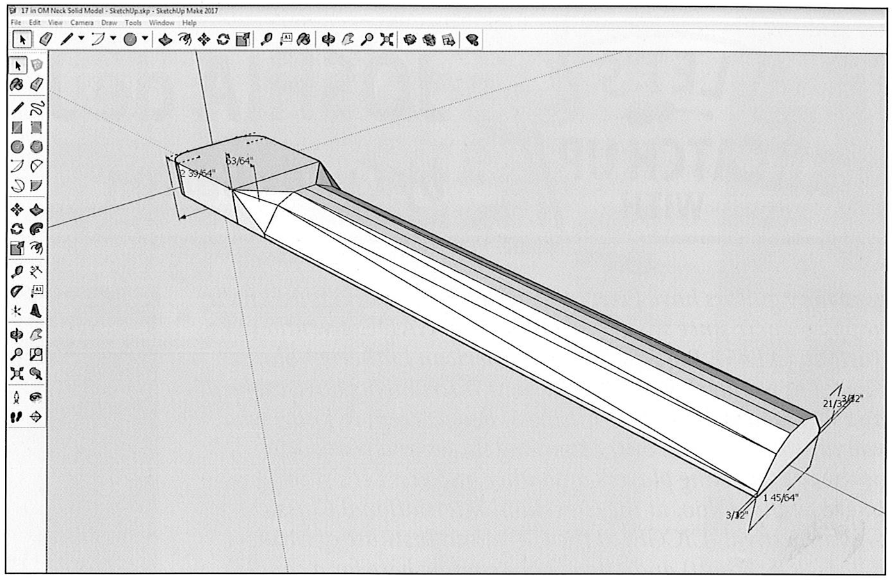


Figure 2. A guitar neck modeled in Google SketchUp.

I am part of a project that uses guitar making to teach technical subjects to high school students, and we just standardized on Fusion 360. If you'd like to download all our production solid models for solidbody electric guitars, visit the project website at guitarbuilding.org.

While there is not one standard CAD/CAM package, there are some standard file formats, so it's often not hard to move files from one to the other. CAM packages generally output G Code to drive the router. This is a very simple set of commands that just moves the spindle from place to place. It is a text file and someone with a rudimentary understanding of the syntax (the author, for instance) can edit or even write G Code directly with any text editor.

The software typically used in small-shop and hobby machines is designed to be easier to use and is typically more limited than commercial packages. Often, the CAD/CAM software is included in the purchase of the router. A popular CAD/CAM package is VCarve by Vectric. It supports many different machines and a dedicated version of it is supplied with ShopBot CNC routers. It is not hard to learn, and a new user can learn to lay out basic shapes quickly. It does 2D CAD rather than a solid modeling, so it can engrave characters and images, cut pockets, and do limited fluting. It's basically a 2.5D package. I've gotten a lot of use from it and now also use it on

*(See **CNC** on page 57)*

(CNC from page 21)

my X-Carve. The Inventables CAD/CAM software can import tool paths from it using a free plug-in. However, it probably isn't the tool for really sophisticated geometries. Guitar necks are surprisingly hard to model well, and I'd be hard pressed to lay out a really good guitar neck in VCarve. **Fig. 3** shows a screen shot of a ¾ acoustic neck. The text is just for reference — I didn't actually make toolpaths from the text. Note the two alignment holes. These match alignment holes that the router drills directly into the waste board fixed to the table.

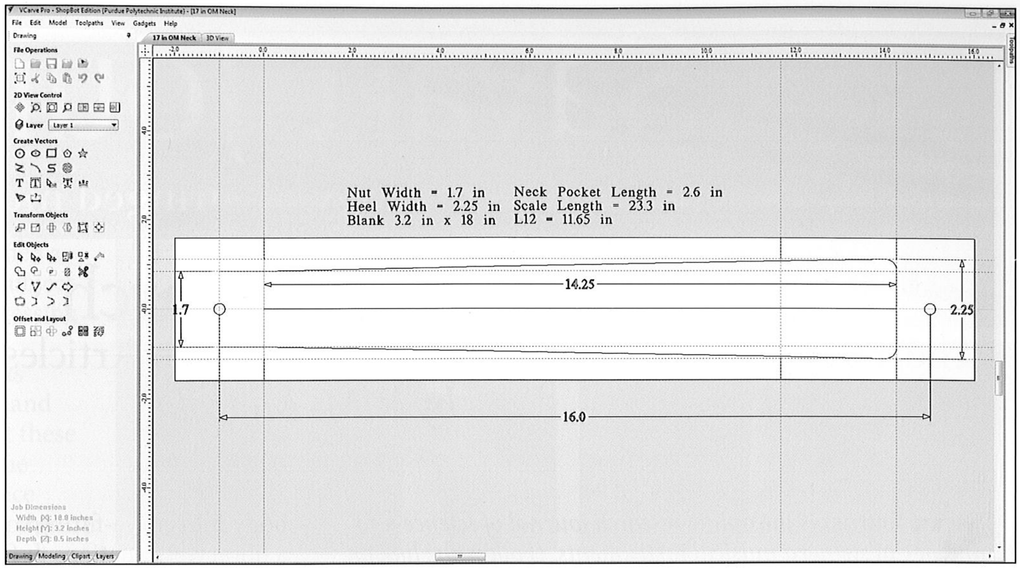


Figure 3. *Screen shot of VCarve Pro.*

Few software packages are free, though there are often generous discounts for students and educators. Even some of the sophisticated commercial packages are free for educational use, with AutoDesk being probably the most progressive. An individual luthier may need to purchase CAD and CAM software for solid modeling to accompany 2D CAD software that comes with the machine. **Table 1** shows an incomplete list of popular CAD and CAM software.

A few pointers:

► Autodesk makes about a squillion different software packages and it's easy to get lost in the product list on their website. It's hard to imagine a luthier needing anything more elaborate than Fusion 360 or AutoCAD LT, the light version of AutoCAD.

► When learning how to use solid modeling software, it is common to find yourself knowing exactly what you want to do, but unable to convince the software to do it. Learning how to use a piece of software is sometimes just the process of working your way through these moments. You only have to learn a few basic capabilities in order to become productive and there are some good tutorial videos on YouTube for the popular software packages.

► There are a small number of interchangeable file formats for both 2D CAD models and 3D solid models. If you save your work in one of these formats, it's less important which software package you choose.

► There is no single correct answer to choosing software. If you find something you understand and that works for you, that's a good answer.

► Confession: I never became expert in CAD or CAM software. When I was in college, there hardly was such a thing and when CAD became common, my employer thought I was too valuable to send me to training. After an embarrassingly long delay, I'm biting the bullet. Tinkercad took a few hours of playing around, Google SketchUp is coming along nicely, and I've gotten good with VCarve since it runs my CNC routers. Fusion 360 is next, though it looks to be a little more work. If I can do it, anyone can do it, so don't overthink the problem — an afternoon at a coffee shop with your laptop is probably enough to get you productive. ——

Acknowledgements

As always, my thanks to R.M. Mottola for his patient assistance in reviewing drafts of this article. The final draft is always lot better than the first one. Thanks also to Taylor Guitars and to Fender for opening their factories to visitors; it's probably good business, but it also advances the state of the guitar for all of us. Thanks also to Josh Hurst at Fender for his insight on CAD and CAM software being used by luthiers. Finally, thanks to Doug Hunt for his insight into CAD and CAM, particularly in how they can be used in small shops and by new users.

2D CAD		3D Modeling		CAM	
Easel (Inventables)	Basic and easy to use. Web based. Comes with X-Carve.	SketchUp (Google)	Base version is free. Pro version is free for educators and students.	Easel (Inventables)	Limited — essentially 2D.
VCarve (Vectric)	Comes with Shopbot. Vectrix supports other machines as well, including X-Carve.	Fusion 360 (Autodesk)	Cloud based. Subscription. Free for educators and students.	Fusion 360 (Autodesk)	2D CAD. 3D CAM if solid model is imported.
BobCAD		BobCAD		BobCAD	
Draftsight (Dassault)	Individual version is free.	Rhino3D		RhinoCAM	
AutoCAD	Free for students and educators. Different versions for different applications. LT version is less expensive.			VCarve (Vectric)	2.5D for VCarve models. 3D for imported solid models.

Table 1. *Some CAD and CAM software used by luthiers.*