# A New Paradigm for Woodworking with NC Machines

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**ABSTRACT**

We present a paradigm that makes the flexibility of NC machining available to the non-technical woodworker. In this context, general-purpose CAD software and manufacturing systems are not appropriate due to prohibitive complexity and cost. We propose a machine architecture and suite of software tools that together offer a cost-effective and simple way of realizing art in wood. Designs can be tested in a 3D simulation before being realized. As a proof-of-concept of the new paradigm, we show a prototype NC milling lathe, a design tool for the special case of Islamic star patterns, and a decorative piece designed and cut using the system.

**Keywords:** NC machining, lathe, ornamental design, art.

## 1. INTRODUCTION

Woodworking is a hobby shared by millions of North Americans, as evidenced by the circulations of popular woodworking magazines [1]. Experienced amateurs and semi-professionals are constantly working on furniture building, cabinetry, relief carving, chip carving, sculpture, and other traditional and modern woodworking techniques.

Numerically Controlled (NC) routers and other computer-controlled machines have found extensive applications both in engineering and large-scale industrial woodworking. These machines have the ability to carve an infinite variety of shapes repeatedly and accurately. The same machines could potentially be of great benefit to the hobbyist, and yet their adoption in this context is nearly non-existent. We see four primary reasons for the lack of use:

1. Current computer-aided design (CAD) software is inappropriate for the design of artistic and ornamental objects. Although existing CAD software could in theory be used to construct just about anymodel, a casual user will be unable to select the tools they need from the overwhelming array of features available. Each specific ornamental style begs for its own tightly focused set of tools that guide the user in constructing objects of that style. In Section 2, we develop the idea of small, domain-specific CAD tools, and demonstrate a prototype for the domain of Islamic star patterns. Our tools are internet-based, making it easy for the hobbyist to experiment with different styles and collaborate with others.

2. The cost of NC routers is high: typical machines can run into the thousands or tens of thousands of dollars. We discuss our simpler, lower-cost NC lathe design in Section 3.

3. Once an object has been designed, it still needs to be converted into a toolpath to manufacture it on an NC machine. This step typically requires the use of yet another expensive and complicated piece of software. The complexity comes from the strict precision and speed requirements of engineering applications. By design, our hardware greatly reduces the degrees of freedom in toolpaths. Moreover, our focused software tools each embed customized toolpath generation algorithms targeted to the ornamental style and the machine.

4. Finally, there is the fundamental issue that not all woodworkers *want* sophisticated technology to play a role in their work. We respect and admire the dedication of those woodworkers

> who favour traditional tools because of the satisfaction and intimacy inherent in the craft. The work presented here is aimed at those who are willing to experiment with the latest technology, with the possible benefits of greater power, flexibility, and expressiveness. At the same time, we recognize that a machine cannot produce a piece that is entirely finished. We expect and endorse the necessity of careful human detail work in turning a machined piece into a work of art.

The goal of this paper is to propose a new paradigm for the integration of NC machining into casual woodworking. We address the specific hardware and software issues mentioned above. We also discuss our prototype machine and show a sample object manufactured with it.

## 2. DESIGN TOOLS

Instead of a single, general-purpose CAD system, we propose a suite of individual tools, each tailored to one particular decorative application. Tools might be provided, for example, for designing Celtic knots, or low-relief floral patterns, or geometric chip carvings. Because each tool is deliberately limited in the range of designs it can create, we can reduce the user interface to only those features that are meaningful in one decorative context. These streamlined interfaces present the casual user with the right balance between expressiveness and guidance.

We are rapidly approaching a time where we can assume basic computer literacy and familiarity with the internet from our woodworking audience. It seems natural, therefore, to harness the power of the web as a medium for our software. The tools could be run directly over the internet (as Java applets, for example). Higher-level tools would permit the output of other tools to be combined, layered, and so on. Another tool would provide a 3D simulation of the cutting process, so that the appearance of the manufactured piece can be previewed before cutting.

Another advantage of these domain-specific tools is that for each one we can develop an optimized toolpath and embed the generation of that toolpath into the software. When each tool is responsible for its own toolpath generation, we avoid the need for costly CAM software.

### 2.1 Example: Isalmic Star Patterns

As a proof-of-concept in a specific ornamental domain, we turn to Islamic star patterns [5]. These patterns can be found decorating household objects and buildings in parts of Europe, Africa, and Asia.

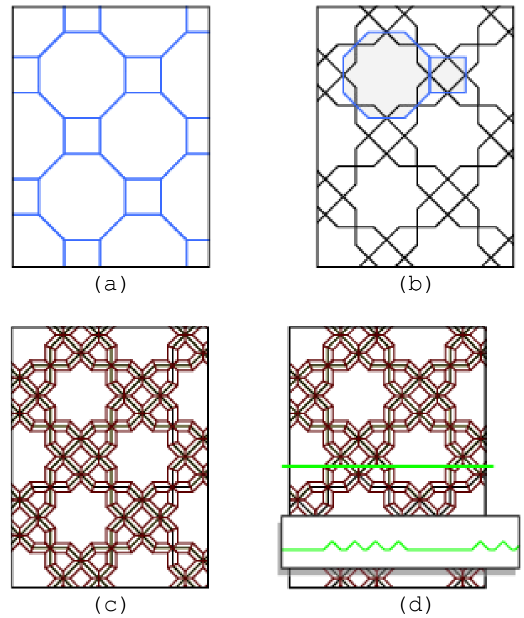


Fig. 1. A star pattern constructed using the method of Kaplan and Salesin. A tiling of the plane by octagons and squares is given in (a). In (b), simple motifs are copied into the tiles to yield a star pattern. In (c), this pattern is expanded in a beveled design that is used to guide the production of a toolpath in (d).

To produce star patterns we adapt the earlier work of Kaplan and Salesin [3]. Their technique is illustrated in Figure 1. They begin with a tiling of the plane where many tiles are regular polygons. With each tile shape is associated a ``motif,'' a small planar map representing a fragment of a star pattern. When suitably-chosen motifs are copied into the tiles in a tiling and linked to form a single planar map, the result is a design in the style of traditional star patterns. Kaplan and Salesin define a large class of applicable tilings, provide a library of traditional motifs for those tile shapes that are regular polygons, and describe an ``inference algorithm'' that invents motifs for any remaining irregular tile shapes.

Kaplan and Salesin's star pattern design tool, Taprats, is available on the web as a Java applet [4]. We augment Taprats with a module to turn the abstract planar maps into simple three-dimensional toolpaths. We refer to the planar map produced by Taprats as the ``base map.'' A sample base map is shown in Figure 1(b). It may be regarded as an undirected graph $G=(V,E)$ where each vertex $v_i$ has two-dimensional position $(x_i, y_i)$.

We may now imagine a star pattern being realized as a wooden lattice by sweeping a diamond-shaped profile along every edge in $E$. When viewed from above, this lattice might look like the diagram in Figure 1(c). This diagram can itself be represented by a new planar map that we call the ``beveled map." Every edge of the base map is present in the beveled map, flanked by two trapezoids. The beveled map can be constructed directly from the star pattern by offsetting every face in the base map by some user-selected width $w$ towards its interior and connecting corresponding vertices in the old and new copies of the face. (The question of the maximum legal value for $w$, as dictated by the geometry of the pattern, is an interesting one that we do not address in the present work.) We also store a $z$ value for every vertex in the beveled map; if we wish to cut a piece $h$ units thick and with a cutting depth $d$, we store a $z$ value of $h$ in all vertices taken from the base map and $h$-$d$ in all new vertices.

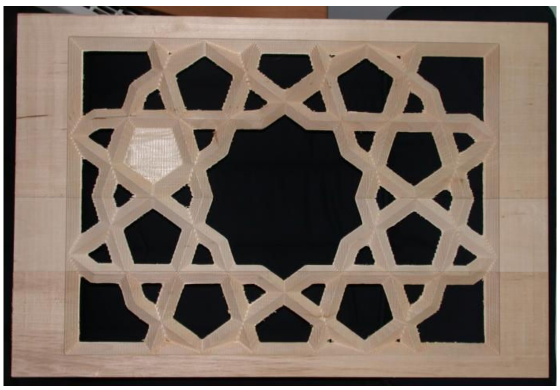

Fig. 2. A sample star pattern cut with a traditional 3-axis NC milling machine using the technique discussed in Section 2.1.

It is now straightforward to obtain a sequence of tool positions along any line intersecting the beveled pattern. We intersect the line with all edges of the beveled map and sort the intersections along the line. The result is a piecewise linear path like the one inset in Figure 1(d) that can either be emitted directly or sampled regularly depending upon the cutting method. As a test of this approach, we concatenated a sequence of evenly-spaced parallel paths in boustrophedonic (zig-zag) order and cut a star pattern on a traditional 3-axis NC milling machine. The resulting piece is shown in Figure 2.

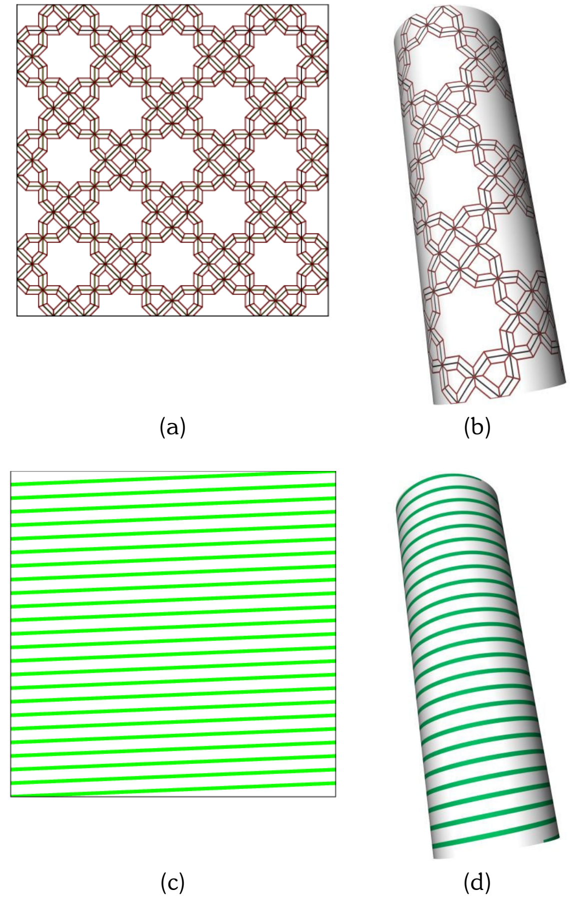


Fig. 3. Mapping a star pattern onto a cylinder. The pattern is shown in the plane in (a), and mapped onto a cylinder in (b). In (c) and (d), we show the analogous mapping for the toolpath.

It is also easy to map this process to a lathe; cutting depth is simply mapped to radial displacement from the lathe's centre of rotation. The star pattern is elaborated over an axis-aligned rectangular region, where $x$ and $y$ will be mapped respectively to the circumference and rotational axis of the finished piece. Our lathe's helical toolpath (described in the next section) corresponds to a sequence of tilted parallel lines in this rectangle, and we can produce a final toolpath in a manner analogous to the planar case described above. One important note is that we want the cylindrical pattern we produce to be seamless; this can easily be accomplished by ensuring that the tiling used to create the pattern is periodic, and that it is oriented so that an integral number of repeats occur along the $x$ direction of the bounding rectangle. The process of wrapping a star pattern and toolpath around a cylinder is illustrated in Figure 3.

## 3. NEW MACHINE ARCHITECTURE

Our proposed paradigm takes advantage of the tradeoff between flexibility of movement and simplicity of controller design. A traditional NC controller can move a tool along any path built up of linear segments. The projection of this path is called its footprint; there is no limit to the shapes of footprints on commercial NC machines. Our proposed tradeoff limits the shape of the toolpath footprint by mechanically linking two of the three axes of an NC machine. This link forces the tool to follow a fixed trajectory. Furthermore, in the new paradigm the machine controller does not control the movement along this path. The movement is controlled either by the user by manually turning a handle or by other means such as a DC motor. The controller must manage only one axis of motion in coordination with and response to the movement of the axes under user control.

While this approach leads to toolpaths that are not optimal, it is certainly adequate for the purposes of woodworking. Furthermore, the controller becomes simple enough to run on any personal computer.

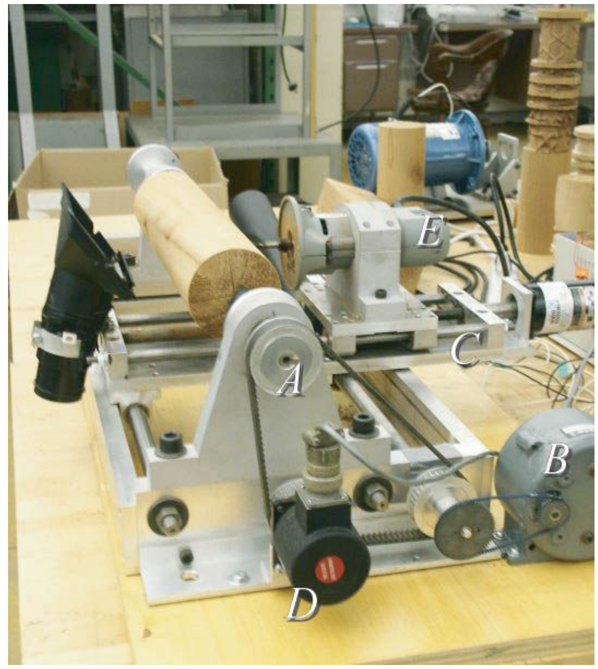


Fig. 4. Our prototype milling lathe. Labeled in the lathe photograph are the spindle (A), a DC motor (B) driving the tool carriage (C), the encoder (D), and the router (E).

### 3.1 Machine Design

A prototype of our machine design is shown in Figure 4 as an example of the new architecture. This design is a modification of a milling lathe (a lathe in which the tool has been replaced with a spindle). In this machine the object is mounted in between the chuck (labeled A in the figure) and the tailstock. A rotary handle or a DC motor (B) controls the movement of the chuck manually. This manual movement is coupled to the linear travel of the tool carriage (C) along the chuck axis. Furthermore, the rotation is coupled to an encoder (D), which is directly connected to the computer via the parallel port. The computer can read the encoder and determine the true location of the tool carriage and the part.

The manual rotation of the part and the simultaneous linear movement of the tool carriage result in a helical footprint for the toolpath. The encoder helps the computer determine the exact location of the tool along the footprint. Having determined the tool location, the controller interpolates a new radial position for the tool from a user-supplied toolpath containing a sequence of radial displacements. The new tool position is than converted into the rotation of the stepper motor and the number of steps required to achieve the motion. The steps are communicated to the motor directly through the parallel port, as described by Manos [6]. As a result, the router (E) moves radially into the part. This process of moving the tool is done at least twenty times per second.

Fig. 5. Sample piece cut with our lathe.

### 3.2 Machine Controller

The main task of the proposed controller is to synchronize the depth of the tool to the movement of the other axes, which are controlled by the user. A simple software controller running on any modern personal computer can provide this limited functionality [2]. The personal computer will not require any hardware modifications and will only run the controller interface software for the NC machine. The proposed architecture uses the computer's parallel or USB ports to communicate commands directly to the motors on the machine and to read the encoder.

The reduction in the functionality of the controller allows it to be much simpler than those used in traditional NC machines. In our machine, two of the tool axes follow a fixed path, reducing the number of stepper motors required to one. Our design therefore eliminates some of the most expensive components found in commercially available machines, reducing the overall cost dramatically.

### 3.3 Machine Implementation and Sample Result

The spindle in our prototype machine is a router running at 10,000 RPM. The pitch of the helical tool path generated on this machine is 1.5875mm. The machine is capable of holding parts up to 80mm in radius. The encoder on this machine (labeled B in Figure 4) is directly interfaced to the computer via the parallel port. This port has a latency of 1ms. The stepper motor is mounted on the tool carriage and moves the router radially into and out of the part. The Islamic star pattern shown in Figure 3(a) was machined from a cylinder of cedar using this milling lathe with a 12.5 mm diameter ball nosed cutter. The final machined object is shown in Figure 5, with a machining time of 2 hours. The cutting tool leaves behind a fine pattern of grooves and scallops that must be sanded by hand as part of a manual finishing process.

### 3.4. Machine Simulation

The proposed machine architecture integrates the tool-positioning algorithm within the machine controller. Thus, an external CAM package is not required. However, both the machine interface and the web-based tools require a machine simulator. This machine simulator processes the machine movements and produces a likeness of the finished object. The simulated machined object lets the user assess how well the different geometric patterns interact with one another. The assessment is done before wood is cut and can prevent waste.

To test the toolpath, we wrote a simulator for the prototype milling lathe. Our simulator is a variation on the height field (``mow the grass") method commonly used for 3-axis simulation. For the milling lathe, however, rather than storing a $z$-map over a discrete $xy$-grid, the height field emanates radially from the rotational axis of the lathe (Figure 6).

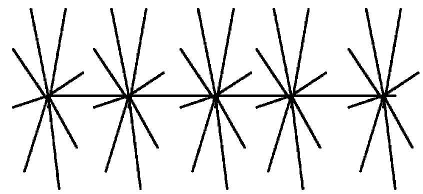

Fig. 6. A height field over a cylinder.

To simulate the cutting of the cylindrical stock by the tool, we compute a piecewise linear sampling of the grazing curve at each tool position [7], and sweep the grazing curves between adjacent tool positions. This computation gives us a set of polygons that we intersect with the radial height field. The tips of the height field are connected to form a triangular mesh, which we render in an OpenGL
renderer.

Fig. 7. A picture from the milling lathe simulator. The simulator is shown cutting the cylindrical star pattern pictured in Figure 4(b).

To simulate the lathe cutting the Islamic star pattern pictured in Figure 5, we used a cylindrical height field with 50 samples around the radial axis and 1300 samples along the linear axis. The toolpath used in the simulation was the same as the one used to machine the final part and had 38,590 tool positions. The simulation time was 18 minutes on a 866MHz Pentium III with an NVIDIA GeForce 4 Ti 4200 graphics card. Figure 7 shows the results of our simulation.

## 4. CONCLUSIONS

This paper presents a novel paradigm that makes the benefits of NC machining available to the woodworking hobbyist. The paradigm centres on the design of hardware and software that reflect the needs and abilities of the casual home user and not the CAD professional.

Because of its simplicity, our prototype lathe is not as versatile as a commercial NC machine and is limited to following a helical tool path around the part. The machine is slow in comparison to commercial models. Still, our design is intended for the hobby market and not industrial applications. In this market the number of pieces required is small and efficiency is not the ultimate goal. We believe that many hobbyists will be excited by the creative and practical potential of NC machining. Our paradigm can provide them with a simple, low-cost way to harness that potential and overcome the barriers that may have prevented them from adopting this technology in the past.

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