Design and modelling of a universal CNC machine

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Abstract. This paper proposes a method of designing an affordable, universal Computer Numerically Controlled (CNC) machine for the use by hobbyists and university laboratories. The machine combines the functions of a 3 to 4-axis milling machine and of a 3D printer. We discuss the major factors contributing to manufacturability and dimensional accuracy of the produced parts, and make several suggestions that aim to maximize the cost effectiveness of the machine’s design. A methodology is developed for optimizing the machine’s rigidity and dimensional accuracy by selecting the proper off-the-shelf components. A calculation that follows the proposed method starts when the required level of accuracy and the machining speed is specified; the result of such a calculation is the overall design of the CNC machine, a bill of materials, and the cost estimate. The design can be optimized for cost, weight, or other parameters. The model presently accounts for the forces generated by the cutting action, the acceleration of machine components, and the associated simple bending moments. The future work in this area relates to the improvement of the proposed method and mathematical model to account for the twisting moments, friction, and vibration.

1. Introduction
1.1 Motivation for designing a CNC machine
Research and development of robotic systems is an interdisciplinary endeavour that investigates the interplay of electronic and mechanical systems. Work in the field or robotics, particularily the development of new robots, relies on the ability to make prototypes of electronic, mechanical, and electromechanical devices. Today, circuit boards and electronic devices can be prototyped quickly, but the same is not always true for mechanisms. Mechanical parts come in all shapes and sizes. The machines that make those parts are equally varied: milling machines, lathes, laser cutters, plasma cutters, grinding and boring machines – each is an expensive, specialized tool for creating a specific class of geometric features. The robotics laboratories of most universities cannot afford to purchase all the manufacturing equipment necessary to make the sum of all mechanical parts that make up a robot. We therefore argue that there is a demand for an affordable, universal machine to act as a functional replacement of many other machines. Such a universal machine would allow robotics researchers and engineers to locally manufacture and quickly prototype of a wide variety of specialized, intricate parts.

1.2 The contribution of this work
This paper discusses the general principles of CNC machines and makes several suggestions for designing a universal CNC machine. In addition, a methodology is developed that allows the designer of a CNC machine to optimize the accuracy and the machining speed against cost and weight. The effect of various high-level design choices, such as changing the overall topology of the machine, or...
substituting leadscrews for timing belts, can be determined without having to re-model the entire machine in CAD. The mechanical loads that the machine is expected to encounter can also be estimated.

2. CNC machine theory

2.1 Main concerns of CNC machine mechanics
All CNC machines work on a similar principle: the machine places a tool of some kind in a sequence of positions defined by the program. The tool then changes the workpiece by either machining the material away, or adding new material. Positioning is done by moving the tool or the workpiece along one or more linear axes, or rotating them around a rotary axis. An assembly that allows positioning along a particular axis is called a “linear stage” or a “rotary stage” depending on the type of motion performed. The process of machining (cutting, grinding, drilling, etc) generates forces between the tool and the workpiece. These forces may cause the tool to deflect from the desired position. Deflection is the principal source of mechanical inaccuracy for CNC machines, and is the result of deformation of the machine’s rigid elements, as well as backlash in the machine’s joints. To mitigate this inaccuracy, the frame of the machine is made rigid, so that it may withstand the forces of cutting, acceleration, and of the weight due to gravity, all without deforming.

A CNC mill, a 3D printer, and a laser cutter are similar in that they all use a 3-axis orthogonal linear positioning system, but the loads these machines experience are different. A 3D printer’s positioning system deals with the forces of acceleration and weight of a relatively light extruder (an extruder is the part of the 3D printer that heats and extrudes various materials and adds them to the workpiece). The positioning system of a CNC mill, on the other hand, has to manage cutting forces in addition to the weight and acceleration of a spindle (which is, on average, heavier than an extruder). This requires more powerful motors and a more rigid frame.

Many 3D printing enthusiasts have attempted to convert their 3D printers into CNC mills by replacing the extruder with a spindle, but the weaker frame of the 3D printer resulted in such deflection that machining anything but the softest materials (styrofoam and balsa wood) proved to be impossible.

A machine that performs additive manufacturing (i.e. 3D printing) deposits material to places where the workpiece does not yet have any. On the other hand, a subtractive manufacturing machine removes material that should not be part of the workpiece. If the machine cannot access this excess material (for example, if the material is obstructed by the workpiece itself), the feature (a design-mandated area where material should be removed) cannot be machined. This problem is solved using multiple “setups”, i.e. by rotating and clamping the workpiece in a different orientation, so that previously inaccessible areas become accessible. Various types of features for subtractive manufacturing are typically made using different, specialized machines, yet nothing prevents combining several functions in a single machine [1].

2.2 Possibility of a universal CNC machine
If one had a CNC milling machine that was perfectly rigid, could position its tool to infinite precision, and used as many setups as necessary, one could manufacture any 3-dimensional part without cavities or caverns (a “cavity” is a fully enclosed empty volume; a “cavern” is a feature that is partially obstructed from the machine tool no matter the orientation). It stands to reason that parts typically made on a lathe, a planar cutting machine, or any other subtractive manufacturing machine could also be made on a CNC mill. The difference between a universal machine and a specialized one is in performance.

Mechanical parts with cavities can be made through 3D printing. While 3D printing can, in principle, produce parts of any geometry, it is typically slower and produces mechanically weaker parts than machining. The resolution of 3D printing is typically lower than what can be achieved with subtractive manufacturing – around 50 um for FDM printing, compared 5…20 um for milling. There is
an inverse relationship between the time to machine and time to print a given shape – if the part is large in volume, typically the volume of the stock material to remove is small, so machining would be faster than printing, and vice versa [8,10].

A CNC machine that combines the functions of a mill and a 3D printer would therefore be truly universal in the sense of the variety of possible geometries, with the caveat that the admissability of the manufactured parts for use in robotics depends in the required vs. available level of dimensional accuracy.

2.3 Difference between linear and rotary stages
In practice, a purely milling-oriented CNC machine would find it difficult to make accurate round parts. Such parts are typically made by turning (a term used for the process of machining a workpiece on a lathe). The reason for that is the difference between an orthogonal coordinate system and a polar one: since any CNC positioning system moves in discrete steps, a circle would form a staircase-like series of segments in orthogonal coordinates [2], but a smooth line in polar coordinates. As a result, a rotary positioning stage would permit better dimensional accuracy and surface finish for round parts.

3. Design suggestions

3.1 The topology should be based on expected loads

The topology of the CNC machine (the arrangement and order of the linear and rotary stages) determines the way forces are distributed around the machine. Designs where the tool has many degrees of freedom, such as figure 1 (b) and (c), leave the bed stationary, which means that majority of the weight of the workpiece is transferred directly to the base. Such a distribution of force has some
advantages when the workpiece is heavy relative to the tool – for example, the machine as a whole can be made lighter while maintaining the same level of accuracy. Designs where the table has many degrees of freedom, such as figure 1 (d), are useful in the opposite scenario, where the tool is heavy compared to the workpiece. Designs where multiple axes are stationary relative to the base, such as figure 1 (d) and (e), require a bigger, heavier base, but reduce the requirements for all other stages.

3.2 Tool change should take little time and effort
How can a single CNC machine be operated as either a mill, a lathe, or a 3D printer, when each of those types of machines require a different set of tools? The answer is: by changing the currently active tool. There are several mechanical and electromechanical means of changing between rotary bits of varying diameter, such as automated tool changers (ATC) built into some high-end spindles. However, such tools are prohibitively expensive for small laboratories and hobby-grade machines. An indexing turret can be used (an indexing turret rotates to bring the needed tool into place, while all the other tools stay attached to the turret), but the added weight would cause an unnecessary increase in rigidity requirements of the CNC machine. It may be possible to apply an inexpensive quick-change mechanism, as used for robotic end-effectors [3]. By far the cheapest solution, requiring the least design commitment, is to simply make the tool interchangeable through simple assembly operations, i.e. it should be possible to un-screw one tool and screw in another tool with minimal effort.

3.3 Using a detachable rotary axis
A rotary axis allows the CNC machine to manufacture round features with an improved accuracy. It also reduces the number of setups required to make a complex workpiece, as some setup changes can be replaced by a simple rotation of the part. The downside of a rotary axis is that it takes up valuable space within the workable volume. This downside can be mitigated if the rotary stage is made detachable. A detachable rotary stage, that can be mounted either horizontally or vertically, allows the user of the CNC machine to choose between one of three coordinate systems with every setup: the orthogonal coordinate system (using only the linear stages), the axial polar coordinate system (with the rotary stage mounted vertically), or the tangential polar coordinate system (with the rotary stage mounted horizontally).

3.4 Separating the alignment and support functions of linear rails
Linear rails with good accuracy and a smooth, level surface are expensive. The cost of the CNC machine can be reduced if the load-bearing capacity of a linear stage comes not from the rail, but from a cheaper structural beam that supports it. Figure 2 shows two examples of a linear stage assembly. The linear stage in figure 2 (a) uses round shafts for the slide rails. Bigger shafts could support greater
loads, but they would also be more expensive. The other way to solve this problem is to use shafts supports. Shaft supports take form of a beam that supports the round shaft along their entire length, increasing the load capacity for a comparatively smaller increase is cost. Figure 2 (b) shows a linear stage that uses a sliding contact dovetail slide. While such a slide has an unparraleled load capacity, it is also heavy and requires constant lubrication to operate.

3.5 Using a cheap, bulk material for the base of the machine
Concrete, granite, and granite epoxy are popular materials for machine bases, as they are very cheap per kilogram and per unit of stiffness. In addition, they are better at damping vibration than metal beams.

3.6 Using a conveyor belt for an “infinite Z axis”
Several 3D printing enthusiasts have demonstrated a novel idea of using a conveyor belt in place of a bed, which makes the build volume effectively infinite in at least one direction. While such a modification may make setups difficult, it opens up some niche applications that would be difficult to perform otherwise.

4. Methodology of structure optimization

4.1 Data preparation and trend extraction
4.1.1 Component catalogue. The first step of the proposed method of the CNC machine structure optimization is to make a catalogue of available off-the-shelf components from which the CNC machine would be made. The cost, mass, mechanical properties and performance of the components should be noted.

4.1.2 Calculating speeds and feeds. In machining terminology, the term “speeds and feeds” refers to the process parameters of milling and turning. These parameters include: the feed rate (velocity of the tool center relative to the workpiece), rotation speed, tangential velocity (velocity of the point on the mill bit that contacts the workpiece), chip load (maximum thickness of the chip that is shaved off by a single flute (cutting edge) of the tool), width of cut (width of the cut cross-section) and depth of cut (height of the cut cross-section).

For every mill bit (endmill, face mill cutter, engraving bit, chamfer cutter and the like) there is a manufacturer-recommended chip load and tangential velocity. These are experimentally measured parameters that result in the highest material removal rate (MRR) for a given tool bit. Exceeding these parameters may result in rapid decrease of tool life and breaking of the tool.

Table 1. Formulas used for the “speeds and feeds” calculation [4]

| Formula                                | Description                        |
|----------------------------------------|------------------------------------|
| \( \omega = \frac{v_t}{R} \)          | Rotation speed \( \omega \)        |
| \( FPR = FPT \times N \)               | Feed rate \( FPR \)                |
| \( FR = f \times FPR \)                | Rotation speed \( f \)             |
| \( AoC = DoC \times WoC \)             | Tangential velocity \( AoC \)      |
| \( MRR = AoC \times FR \)              | Maximum chip load \( MRR \)        |
| \( \tau = \frac{P_{spindle}}{\omega} \)| Spindle power \( P_{spindle} \)     |
| \( P_{linear} = F_{linear} \times FR \)| Linear power \( P_{linear} \)      |
| \( R = D / 2 \)                        | Rotation speed \( \omega \)        |
| \( f = \omega / 2 \pi \)              | Rotational frequency \( f \)       |
| \( DoC_{max} = D \)                    | Maximum chip load \( DoC_{max} \)  |
| \( WoC_{max} = L \)                    | Maximum width of cut \( WoC_{max} \)|
| \( P_{spindle} = E \times MRR \)       | Spindle power \( P_{spindle} \)    |
| \( F_{linear} = \tau / R \)            | Linear force \( F_{linear} \)     |

Here \( \omega \) is rotation speed or angular velocity \((\text{rad/s})\), \( f \) is the rotation frequency \((\text{Hz})\), \( v_t \) is tangential velocity \((\text{m/s})\), \( D \) is a tool bit diameter \((\text{m})\), \( R \) is the tool bit radius \((\text{m})\), \( FPR \) is the feed \((\text{m})\), \( FPT \) is the
feed per tooth (m), N is the number of flutes or cutting edges the tool bit has, AoC is area of the cut cross-section (m²), DoC is the depth of cut (m), WoC is the width of cut (m), L is the length of the tool bit, MRR is the material removal rate (m³/s), \( P_{spindle} \) is the power output by the spindle-motor, E is the specific cutting power – a reference value derived experimentally, taken to be 6.83 J/m³, \( \tau \) is the spindle torque (N*m), \( F_{linear} \) is the linear (tangential) cutting force (N), \( P_{linear} \) is the power due to the cutting force acting at the given feed rate, or power at the linear stage motor (W).

### 4.1.3 Calculating beam stiffness

For beams, the area moment of inertia is calculated from the known beam cross-section:

\[
I_x = \int_A y^2 \, dx \, dy \quad \quad \quad I_y = \int_A x^2 \, dx \, dy
\]

Here \( I_x \) is the object’s second moment of area about an arbitrary axis X passing through the center of mass of the body, assuming that the axes X and Y are orthogonal. \( I_y \) is then the second moment of area about the axis Y. \( I_x \) and \( I_y \) have units of (m⁴).

Once we have calculated \( I_x \) and \( I_y \) for every beam to be considered, we can determine the ratio of force acting on a beam (F, N) to the deflection (\( dw, m \)) caused by that force. The formula for maximum deflection in a beam varies depending on the beam’s support condition, such that the deflection experienced by a cantilevered beam is 16 times greater than the deflection experienced by a beam supported on both sides.

#### Table 2. Formulas used for the stiffness calculation [5]

|                        | beam supported on both sides | beam fixed on one end and free on the other (cantilevered) |
|------------------------|-----------------------------|------------------------------------------------------------|
| \( F_x/dw_x \)        | \( \frac{48 \, E \, I_x}{L^3} \) | \( \frac{3 \, E \, I_x}{L^3} \)                           |
| \( F_y/dw_y \)        | \( \frac{48 \, E \, I_y}{L^3} \) | \( \frac{3 \, E \, I_y}{L^3} \)                           |
| \( F_z/dw_z \)        | \( SE / L \)                 |                                                            |

Here \( L \) is the length of the beam (m), \( F \) is the force acting on the beam (N), \( E \) is the Young’s modulus of the beam’s material (Pa) and \( dw \) is the deflection of the beam from its original dimensions (m).

The resulting ratios determine the stiffness of the beam along each axis. Here, \( Z \) is the axis along the length of beam, while \( X \) and \( Y \) are perpendicular to the beam. If the axes are chosen in such a way that beam size \( x \) > size \( y \), then \( F_x/dw_x \) becomes the stiffness of the “strong side” of the beam while \( F_y/dw_y \) becomes the stiffness of the “weak side” of the beam, which simplifies subsequent sorting and selection of the best beam for a given application.

### 4.1.4 Extracting trends

In this method, the catalogue of components is analyzed to find correlations between various properties, from which estimation formulas can be derived. These formulas reduce the dimensionality of the combinatorial optimization problem, making it tractible. Interesting correlations to consider are those between the MRR and the spindle and linear stage motor parameters required to achieve it. On the other hand, a brute force computer search of the best among all possible combinations may yield a more accurate result, if the number of components to consider is small.
4.2 Stage decomposition
The machine’s topology is split into stages, where every stage can be estimated as a set of beams experiencing simple bending moments, as seen in figure 3:

![Figure 3](image)

**Figure 3.** Stage decomposition diagram for the selected CNC machine topology. Each stage is represented by a rectangle with a pictogram illustrating the type of bending moments experienced by the beam.

4.3 Slide and linkage split
A linear stage is composed of a slide, carriage, linkage and a motor, as seen in figure 2. When selecting the beams to handle the forces experienced by the stage, we shall assume that the slide rails handle only the forces perpendicular to the beam direction, and the linkage (belt or a leadscrew) handles only the force parallel to the beam direction. The motor would then be chosen according to the feed rate and the force along the linkage.

4.4 Beam bundle method

![Figure 4](image)

**Figure 4.** Area moments of inertia in the X and Y axis for various beam cross sections. All cross sections have the area of 100 mm$^2$. Gray dot marks the data point, the black outline shows the corresponding shape.

For the following calculations, we introduce the concept of a beam bundle. A beam bundle is an abstract beam, made from one or more elementary beams joined together, where an elementary beam is simply a single off-the-shelf structural beam element. The deflection of a beam bundle can be calculated as the the deflections of a single beam when it experiences a force equal to the total force divided by the number of beams in a bundle. Note that two beams are not equivalent to the single beam with a doubled cross-section, as the Euler-Bernoulli theory of beam bending assumes that “plane sections remain plane”, an assumption which is violated if we treat a bundle of beams as a single
beam. As an aside, this also explains why stranded wire is more floppy than a solid-core wire, even though their cross section is similar. The effective second moment of area for the beam bundle, as calculated backwards from the resulting deflection, is shown in figure 4.

Every element in a linear stage is modelled as a beam bundle. The composition of the beam bundle depends on the type of application (e.g. the beams that act as slides in a linear stage have requirements on surface finish and geometric accuracy). From all beams appropriate to a given application, we select the one that would result in a lightest and cheapest beam bundle, if the beam bundle contains as many copies of this beam as necessary to support the requested load.

4.5 Flow of data between stages

Figure 3 shows how, in accordance with Newton’s third law, the forces generated by cutting affect both the bed and the spindle stages. Each successive stage has to contend with the same forces as the previous stage, in addition to the forces required to support and to accelerate the previous stage. This typically means that higher stages should prefer lighter beams over cheaper ones, to reduce the load requirements on the lower stages.

4.6 Model limitations

The mathematical model [6,7,9] used by this method of structure optimization overlooks several factors that may negatively affect the performance of a CNC machine. The treatment of these factors is a subject of future work in developing the methodology. The model does not include twisting and shear forces on the beams, friction between components, vibration and resonance within the machine. Estimation of the expected machining time would also be a valuable measure of machine performance. In the interests of brevity, the structure and dimensions of the machine base are not discussed in this paper.

5. Results

A variety of commercial available machine components were considered: 15 spindles (5 high speed rotary hand tools, 3 handheld routers, 7 bare spindle-motors), 22 linear stage motors (14 stepper motors and 8 BLDC motors), 74 types of structural beams (aluminum, steel and cast iron rods and profiles), and 6 types of linkages (1 rubber belt, 1 fiber-reinforced neoprene timing belt, 4 sizes of steel leadscrews).

A set of correlations have been found in part properties, from which the following empirical formulas were derived:

\[
F_{linear} = C_f l \times MRR
\]
\[
V_{linear} = C_v l \times MRR
\]
\[
P_{linear} = C_{pl} l \times MRR
\]
\[
P_{spindle} = C_{ps} l \times MRR
\]
\[
M_{spindle} = C_{ms} l \times P_{spindle}
\]
\[
M_{motor} = C_{mm} l \times P_{motor}
\]
\[
CS_{motor} = C_{cm} l \times P_{motor}
\]

Where \(F_{linear}\) is the tangential cutting force generated (N), \(V_{linear}\) – optimal feed rate (mm/s), \(P_{linear}\) – required linear stage motor power (W), \(P_{spindle}\) is the required spindle power (W), \(M_{spindle}\) is the mass of the spindle (kg), \(MRR\) is the material removal rate, \(M_{motor}\) is the motor mass, \(P_{motor}\) is the motor power and \(CS_{motor}\) is the motor cost. Some of the values were different for high and low chip load conditions.

The cost of machine components was partially based on their retail price in Russia, their retail price in US, and in some cases on the resale price in online marketplaces such as amazon, ebay, aliexpress and alibaba. An accurate price estimate for higher-end components could not be made, as the
distributors tend not to reveal the price outright but instead have the potential buyer request a quotation, which may indicate that the price is either negotiable or non-disclosable.

| Table 3. Observed coefficients of linear dependence |
|---------------------------------------------------|
| high chip load | low chip load |
| $C_0$ (N s mm$^{-4}$) | 0.0572 | 0.3035 |
| $C_d$ (m mm$^{-4}$) | 0.0023 | 0.047 |
| $C_p$ (W s mm$^{-4}$) | 0.002 | 0.013 |
| $C_p$ (W s mm$^{-4}$) | 0.683 |
| $C_m$ (kg s mm$^{-4}$) | 0.0028 |
| $C_{mm}$ (kg Watt$^{-1}$) | 0.1069 |
| $C_{cm}$ (USD Watt$^{-1}$) | 2.85 |

Nevertheless, a general rating can be made:

| Table 4. General price comparison of various machine components |
|---------------------------------------------------------------|
| Beams | Spindles and motors |
| Less expensive | ( where bundle stiffness = const ) |
| concrete plate | low power stepper motors |
| granite epoxy plate | low power BLDC motors |
| granite plate | low power high-speed rotary tools |
| cast iron bar | high power stepper motors |
| square tube profile (rolled) | high power BLDC motors |
| corner profile (rolled) | high power high-speed rotary tools |
| round steel shaft | low power hand routers |
| T-slotted aluminum extrusion | high power hand routers |
| V-slotted aluminum extrusion | low power spindle-motors |
| supported round steel shaft | high-power spindle-motors |
| More expensive | |
| linear motion guide rail | high-power spindle-motors with automatic tool changer (ATC) |

As a starting point for the structure optimization, we specified the desired CNC machine to have a working area of 300 mm by 200 mm by 200 mm, accuracy of 0.4 mm, material removal rate (MRR) of 100 mm$^3$s$^{-1}$, and acceleration of 0.2g. The machine topology and its stage decomposition are as shown in figure 3. The results of the calculation are as follows:

| Table 5 (a). Results of structure optimization |
|-----------------------------------------------|
| $P_{spindle}$ | 6.83 W |
| $M_{spindle}$ | 0.191 kg |
| $F_{linear}$ | 5.72 N |
| $V_{linear}$ | 0.23 mm/s |
| $P_{linear}$ | 0.2 W |
| $M_{linear}$ | 0.04 kg |
| First stage from spindle | |
| Axis | Y-axis as a beam supported on both sides |
| Rail type | Two 20x40 mm T-slotted aluminum extrusion profiles. |
| Supports | none |
| Linkage | A 10 mm leadscrew. |
| Motor | Nema 17, 2.5 W stepper motor |
| Second stage from spindle | |
| Axis | Z-axis as a cantilevered beam |
| Rail type | Two 20x40 mm T-slotted aluminum extrusion profiles. |
Table 5 (b).

| Supports   | none       |
| Linkage    | A 10 mm leadscrew. |
| Motor      | Nema 17, 2.5 W stepper motor |

First stage from bed
- Axis: Bed reinforcement as a beam supported on both sides
- Rail type: Two 20x40 mm T-slotted aluminum extrusion profiles.
- Supports: none
- Linkage: A 10 mm leadscrew.
- Motor: Nema 17, 2.5 W stepper motor

Second stage from bed
- Axis: X-axis as a beam supported laying directly on the base (no bending moment)
- Rail type: Two 20x40 mm T-slotted aluminum extrusion profiles.
- Supports: none
- Linkage: A 10 mm leadscrew.
- Motor: Nema 17, 2.5 W stepper motor

Total weight: 2.69 kg, not counting the base.
Total cost: $73 USD, not counting the electronics and the spindle.

6. Discussion of future work
This study may be expanded in several ways: First, by improving the method so that the parameters outlined in section 4.6 Model limitations are modelled; Second, by creating a computer program that automates the optimization process; And third, by comparing the results of the calculation with a CAD simulation to find the expected tool deflection / positioning error, and a CAM simulation to evaluate the expected machining time.

7. Conclusion
We have established that there is demand for an affordable, universal CNC machine that could do the work of a wide variety of expensive, specialized machines. A reasonable starting point for the design of such a machine is to structure it as a CNC mill with a replacible tool and a detachable rotary stage, possibly with a concrete base. The structure of the machine and the composition of its sub-assemblies can be optimized through the method of stage decomposition and beam bundle optimization. The method, when applied to real-world data, yields plausible results. The method can be improved in the future by considering shearing and twisting loads, friction and vibration, as well as by incorporating computer modelling techniques.

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