Design & Fabrication of Scale Model Turning Machine

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Introduction

Since Pakistan is a relatively young nation, it faces a dearth in industrial automation aids such as Computer Numerically Controlled (CNC) machines while the rest of the world advances. Due to high capital costs and the need for sufficient expertise, very few engineering setups in the country can afford to procure, operate and maintain such hi-tech machines. Thus we took it upon ourselves to develop design principles and methodologies that any workshop owner could use to retrofit existing manual machines and turn them into fully functional CNC machines or could develop a fully functional CNC turning machine as a well.

We managed to design and fabricate a small-scale CNC Turning machine to establish and validate our methodologies. Our key design principles were functionality, simplicity, scalability, customizability, ease of development and use and low cost so that smaller engineering setups can save up significantly on capital costs when retrofitting or building their own CNC machines using our methodologies.

The resulting machine has a landed cost of manufacture of about one-eleventh of the total cost of an equivalent machine purchased from abroad and imported into Pakistan. The mechanical structure was built using recycled steel and aluminum while more sensitive mechanical components were sourced from the second-hand market such as ball screws, bearings etc.

This strategy allowed us to use very high-tech parts at a cost significantly lower than their retail value. Use of ball screws coupled with stepper motors for movement of our tables resulted in a highly accurate and precise movement with 0.125 mm linear movement when using single-stepping. This figure can be improved even further by using micro-stepping (up to 0.00125 mm), a feature which was also integrate into our motors as well as microcontroller setup.
The overall result is a machine with significantly lower capital and running costs that many smaller engineering setups and workshops can easily build and use for their daily operations.

Our proposed solution consists of developing design principles and methodologies that any local engineering setup could use to either fabricate their own or retrofit existing manual machines to CNC ones. These were validated via fabrication of a small-scale CNC Turning Machine demonstration prototype.

- Mechanical Aspects – Fully developed design procedures for designing and selecting machine structures including guideways, lead screws, couplings, motors, cutting tools, etc.
- Electrical Aspects – Fully developed design procedures for designing and selecting electrical systems such as motors, control and power circuitry, sensors, microcontrollers, etc.
- Computer Sciences Aspects – Fully Developed design procedures for designing and selecting Human Computer Interface (HCI), I/O devices, G&M code Interpreter programming, microcontroller programming and interfacing, etc.

For the purposes of our paper, we decided to use a demonstrate-through-practice approach. We will describe the method that we used to design our own demonstration prototype and in the process, we will lay down the techniques that other may use to develop similar machines of various scales and complexities.

Mechanical Design

Mechanical Design is the most vital part of this research. There were a lot of constraints when decisions were made regarding lead screws, cutting force calculations, box volume, etc.

Orthogonal Cutting Model is chosen because it is less complex than the Oblique Cutting Model. Some assumptions were made before choosing Orthogonal Cutting Model:

- The tool is perfectly sharp
- The shearing surface is a plane extending upward from the cutting edge.
- The chip does not flow to either side
- Continuous chip, no built-up-edge

In Orthogonal Cutting Model, the radial component of force is ignored which is denoted as 'F_r'. Other two forces as shown in Fig 2.1 taken in consideration are:

- F_t – Tangential Force
- F_a – Axial Force

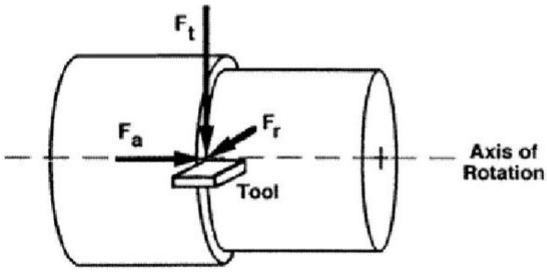

Fig. 2.1: Free Body Diagram

Many material properties were reviewed from handbooks before opting for the final choice of Aluminum and Wood. Aluminum was chosen as the worst case and wood was chosen as the best-case material which can be machined by the turning machine. CNC turning Machine which can machine aluminum and wood can be fabricated at a low cost.

The box volume was calculated by specifying the diameter (swing-over bed) and length of the work part (center-to-center distance) being used in the machine.

- Diameter Range (swing-over bed) = (1.5 - 4) in
- Length Range (center-to-center distance) = (1.5 – 4) in
- Box Volume = (2.65 - 50.27) in^3

Then, Eq. 2.1 was used to calculate the RPM of the AC Motor, where, SFM for aluminum alloys = 1000 SFM (Surface Feet per Minute):

$$\text{Spindle RPM} = \frac{(\text{SFM} \times 12)}{(3.14 \times \text{D})} \rightarrow \text{(Eq. 2.1) [1]}$$

The operation of the CNC Turning Machine is only limited to finishing operations, so the ranges for depth and feed are given below. These values have been extracted from ASM Machining Handbook.

- Depth: (0.025 - 0.01) in [2]
- Feed: (0.002 - 0.006) in [2]

The concept of Specific Energy has been used to calculate the cutting forces acting on the work part. As the tool will wear out with operation, Worn-Out Tool Factor was incorporated in the calculations to get closer to the real conditions.

- Specific Energy for Aluminum Alloys = 120000 (in-lb. /in^3) [1]
- Worn- Out Tool Factor = 1.10 [1]
- Taking product, Modified Specific Energy for Aluminum Alloys = 132000 (in-lb. /in^3)

Then Eq. (2.2) was used to calculate the cutting force, F_c

$$Fc = E \times CF \times d \times f \rightarrow \text{(Eq. 2.2) [1]}$$

Fig. 2.2. [1] extracted from Groover's Textbook was used to get the value of correction factor mentioned in Eq. 2.2.

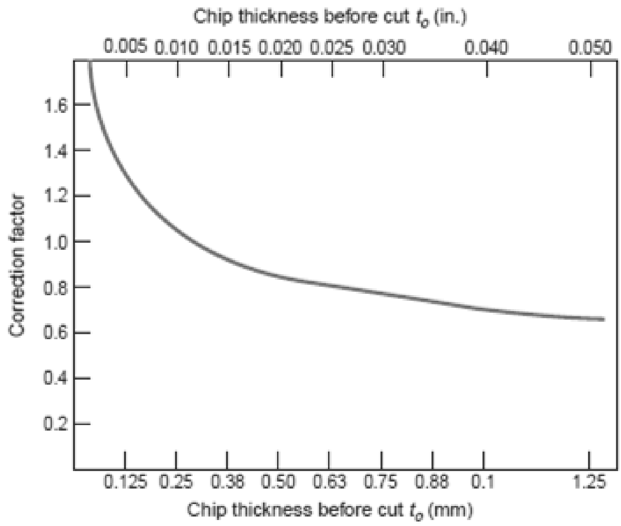

Fig. 2.2: Correction factor for unit horsepower and specific energy when values of chip thickness before the cut t_0 are different from 0.25 mm (0.010 in).

In the orthogonal cutting model, chip thickness before cut t_0 is referred as feed of the turning operation. The graph above shows the correction factor to be applied for various feed operations.

A value of feed was fixed in the calculation, and changed the depth in the range specified above to get different values of cutting forces. Then in the next iteration, the value of feed was changed and repeated the same process for different depths. By changing values of feeds, maximum and minimum cutting forces were determined.

- Minimum Cutting Force (F_c): 4.75 lb.
- Maximum Cutting Force (F_c): 25.34 lb.

To get the actual power of the spindle motor, efficiency of drive train was included in the calculations.

- Efficiency of Drive Train = 0.80

Eq. 2.3 was used to calculate power (P), where, SFM of Aluminum Alloys = 1000:

$$P = \frac{(Fc \times SFM)}{(0.80)} \rightarrow \text{(Eq. 2.3) [1]}$$

To get the power in Horsepower, we used Eq. 2.4.

$$HP = \frac{P}{33000} \rightarrow \text{(Eq. 2.4) [1]}$$

After using Eq. 2.4 over all the range, maximum and minimum power was calculated.

- Max Power = 0.96 hp
- Min Power = 0.18 hp

Merchant equation was used to calculate thrust force F_t. To calculate the friction angle (β), Eq. 2.5 was used where Friction Coefficient (μ) = 0.61 (for Aluminum and HSS Cutting tool):

$\mu = \tan \beta \rightarrow$ (Eq. 2.5) [1]

The Eq. 2.6 [11] given below was used to calculate Shear plane angle (φ), illustrated in Fig. 2.3:

$$\varphi = 45° + \frac{\alpha}{2} - \frac{\beta}{2} \rightarrow \text{(Eq. 2.6) [1]}$$

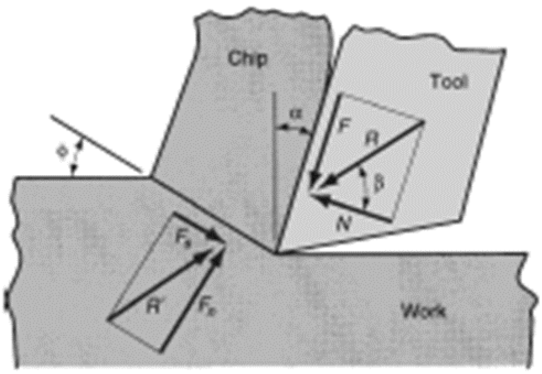

Fig. 2.3: Forces acting on a chip in the Orthogonal Cutting Model.

The Shear plane angle (φ) is further used in the merchant equation to get the value of F_t. There are *some assumptions that need to be considered before using merchant equation*:

- Shear Strength of the work material is a constant
- Shear Strength is unaffected by Strain Rate
- Shear Strength is unaffected by temperature

Then, the Merchant Equation, Eq. 2.7, was used to get calculate F_t, where Shear Stress for Al 2011 T4 = 221 MPa:

$$\tau = \frac{\sin \varphi \text{ x } [(Fc \text{ x } \cos \varphi) - (Ft \text{ x } \sin \varphi)]}{to \times w} \rightarrow \text{(Eq. 2.7) [1]}$$

Aluminum have many grades available in the world but the Aluminum Alloy chosen for machining was: 2011 T3/T8 [2]. It was chosen because it has a good machinability rating: A. Secondly, it can be easily procured from local markets in Pakistan.

The tool properties mentioned below are extracted from ASM Machining Handbook. The tool with these properties can perform the finishing operation efficiently on the Aluminum Alloy mentioned above.

- Back rake angle: 20° [2]
- Side rake angle: 20° [2]
- End relief angle: 10° [2]
- Side relief angle: 10° [2]
- End cutting edge angle: 50° [2]
- Side cutting edge: 10° [2]
- Nose radius: 5.1mm (0.20 in) [2]

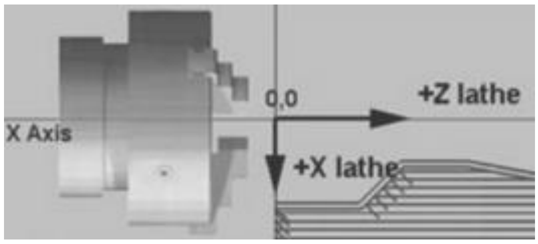

Fig. 2. 4: Top view of Lathe machine with axes' relation to the chuck visible.

After getting the maximum Cutting Force (F_c) and Thrust force (F_t), power calculations for lead screws in x-axis and z-axis were done. The procedure to calculate lead screw forces is discussed below.

Firstly, market survey was performed and found out what kind of lead screws and in what dimensions are available. The Table 2.1 [3]. shows the dimensions in which lead screws are manufactured an available in market.

Ball screw were selected due to its various advantages over trapezoidal threaded or ACME thread lead screws, some of which are:

- High efficiency; ball screws have an efficiency around 90% as compared to 25-30% of ACME thread lead screws.

- Longer lifespan due to lack of sliding friction between threads and nut.
- No need of regular lubrication.

Nominal Major Diameter d mm	Coarse-Pitch Series: Pitch p mm	Coarse-Pitch Series: Tensile-Stress Area A_t mm²	Coarse-Pitch Series: Minor-Diameter Area A_r mm²	Fine-Pitch Series: Pitch p mm	Fine-Pitch Series: Tensile-Stress Area A_t mm²	Fine-Pitch Series: Minor-Diameter Area A_r mm²
1.6	0.35	1.27	1.07			
2	0.40	2.07	1.79			
2.5	0.45	3.39	2.98			
3	0.5	5.03	4.47			
3.5	0.6	6.78	6.00			
4	0.7	8.78	7.75			
5	0.8	14.2	12.7			
6	1	20.1	17.9			
8	1.25	36.6	32.8	1	39.2	36.0
10	1.5	58.0	52.3	1.25	61.2	56.3
12	1.75	84.3	76.3	1.25	92.1	86.0
14	2	115	104	1.5	125	116
16	2	157	144	1.5	167	157
20	2.5	245	225	1.5	272	259
24	3	353	324	2	384	365
30	3.5	561	519	2	621	596
36	4	817	759	2	915	884
42	4.5	1120	1050	2	1260	1230
48	5	1470	1380	2	1670	1630

Table 2.1: Table showing lead screw parameters.

Using the nominal major diameter (d) and pitch (p) of screw given in Table 2.1, following calculations were made:

- Nominal minor diameter (d_r)

$$dr = d - p \rightarrow \text{(Eq. 2.8) [3]}$$

- Mean diameter (d_m)

$$dm = d - \frac{p}{2} \rightarrow \text{(Eq. 2.9) [3]}$$

- Collar diameter (d_c)

$$dc = 1.25 \times dm \rightarrow \text{(Eq. 2.10) [3]}$$

To calculate power required for the motor to move power screw, Torque and RPMs at which power screw is to rotate are calculated. Therefore, torque is calculated and then rotational speed of power screw.

Eq. 2.10 is obtained by resolving all the forces that act on the threads of power screw which is shown in Fig. 2.6.

$$T = \frac{(F \times dm)}{2} \times \frac{l + (\pi \times f \times dm)}{(\pi \times dm) - (f \times l)} \rightarrow \text{(Eq. 2.11) [3]}$$

Table 2.2 [3] gives the values the friction co-efficient for different cases.

Screw Material	Nut Material: Steel	Nut Material: Brass	Nut Material: Bronze	Nut Material: Cast Iron
Steel, dry	0.15–0.25	0.15–0.23	0.15–0.19	0.15–0.25
Steel, machine oil	0.11–0.17	0.10–0.16	0.10–0.15	0.11–0.17
Bronze	0.08–0.12	0.04–0.06	—	0.06-0.09

Table 2-2: Table showing the friction co-efficients for a leadscrews of various materials with various types of nuts.

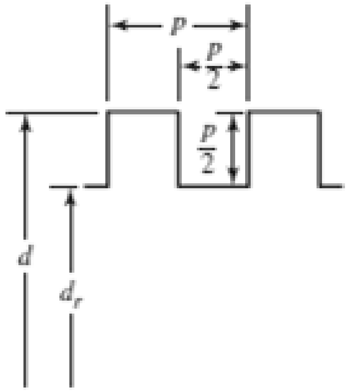

Fig. 2.5: Lead Screw Parameters

Apart from the friction of the lead screws, the place where the lead screw itself takes support from also has a friction as the lead screw will move and also have a high value of thrust (axial load) on it. Due to this a thrust bearing or a collar is added between the lead screw and the casing. This also includes friction and must be included to get an appropriate required power. Torque (T_c) required to overcome collar fiction is given by Eq. 2.12:

$$Tc = \frac{(F \times fc \times dc)}{2} \rightarrow \text{(Eq. 2.12) [3]}$$

Mean Diameter of collar (d_c) can be calculated by Eq. 2.13:

$$dc = \frac{dm + (1.5 \text{ x } dm)}{2} \rightarrow \text{ (Eq. 2.13) [3]}$$

Force (F) is composed of vector sum of all the forces acting in the direction of power screw. For instance, in x-direction,

$$F = Fc + [f \text{ x } (w + Ft)] \rightarrow \text{ (Eq. 2.14) [3]}$$

So, Total required torque will be calculated using the Eq. 2.15 below

$$T = \left[\frac{(F \text{ x } dm)}{2} \times \frac{(l + \pi \text{ x } f \text{ x } dm)}{(\pi \text{ x } dm - f \text{ x } l)}\right] + \frac{(F \text{ x } fc \text{ x } dc)}{2} \rightarrow \text{ (Eq. 2.15) [3]}$$

This torque is calculated for both power screws in x and z direction.

The revolutions per second of the lead screw motor 'ω' can be determined by dividing the maximum feed over the distance travelled by the lead screw in one rotation. Distance travelled by the lead screw in one rotation is equal to pitch of the lead screw, so

$$\omega = \frac{(\text{Max Feed})}{\text{Lead}} \rightarrow \text{ (Eq. 2.16) [3]}$$

Where Lead is simply equal to pitch times the number of starts (It has only one independent thread therefore screw has only one start).

Then, Power (P) is a simple product of above calculated Torque (T) and Rotational speed (ω) of power screw.

$$P = T \times \omega \rightarrow \text{ (Eq. 2.17) [3]}$$

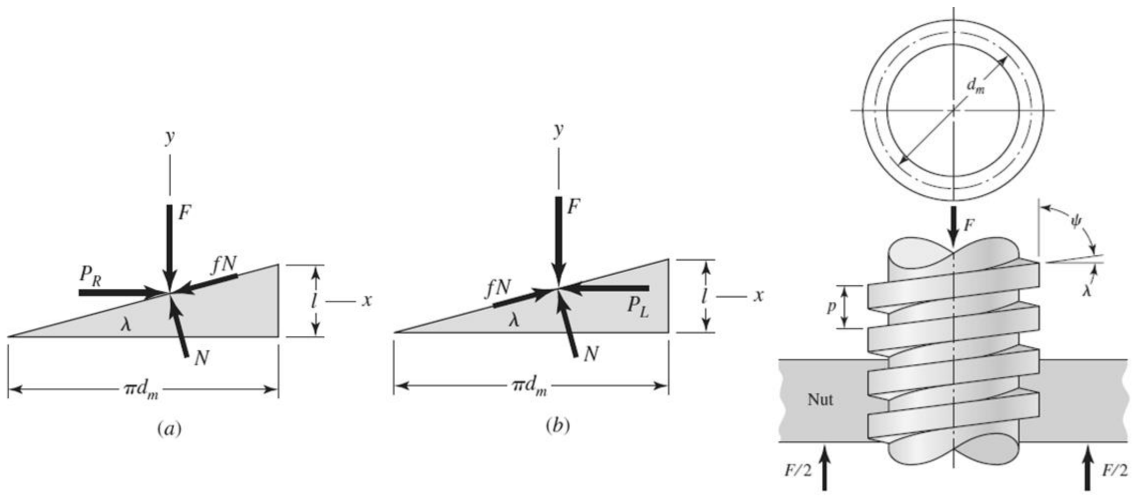

Fig. 2.6: Detailed Free Body Diagram of the Forces acting on a leadscrew.

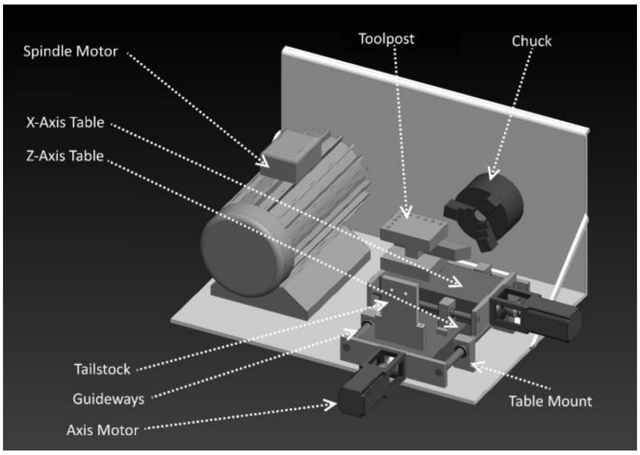

Fig 2-9: Dimetric View of our final CAD model with labels.

Fig 3-8: Machine under fully functioning conditions with all electronics installed.

Electronic & Computer Science Aspects

Keeping our key design principles in mind, we had to propose a set of techniques that make the job of building a CNC machine a reasonably practicable task. Considering our key design principles as stated earlier, we chose a balance between off-the-shelf components and development from scratch.

Some major considerations for the electronic and computer science aspects of a CNC machine are listed below:

- Develop a suitable microcontroller-based setup to control machine processes.
- Assess use of sensors and their feedback for system regulation and control.
- Select and procure suitable motors for each machine process.
- Develop or procure a motor driver circuit.
- Design and fabricate, or procure and integrate a voltage regulating power supply.
- Develop suitable Human Computer Interface (HCI).
- Design interpreter for converting G & M codes into commands suitable for processing by the microcontroller.

The fact that these considerations were set on a broader scope without specifying restrictions is due to the fact that we intended to leave room for adapting our electronic architecture design to the availability of material and devices locally and keeping in mind the relative cost of indigenous design and development and/or fabrication versus procurement and integration of materials, devices and code.

The component-wise selection/design process is highlighted below.

Machine Aspect	Specification Selected	Possible Alternates	Explanation
Control System	Open-Loop	Closed Loop	We chose an open-loop system as it was sufficient in helping our machine achieve its desired level of accuracy (i.e. table axis movement with an error less than +/- 0.25 mm and spindle RPM with error less than +/- 50 RPM); plus it reduced our costs significantly.
Motor (Spindle)	AC Induction Motor (Used Siemens; 2 HP Power Output (1.5 kW); 3-Phase 440-volt AC (RMS) Input; Up to 2850 RPM)	DC In-runner Motor	We need a motor that could deliver smooth, high-speed and high-power operation. The noise and vibration levels were low due to the high quality brand-name that the motor came with, i.e. Siemens. Since it was also sourced

			locally and found in used form, it was relatively inexpensive.
Spindle Motor Power and Control	Variable Frequency Drive (Used General Electric; Single Phase 220-volt AC Input; 3-Phase 440-volt AC Output; Frequency Range from 40 Hz to 80 Hz; Variable Speeds from zero to 2850 RPM)	-	Since we needed a way to control the angular speed of our spindle motor as well as make it compatible with the widely available mains power sources in the country. The VFD allows the speed of the motor to be varied between zero and 2850 RPM which easily contains the range of speeds that we require for machining our selected materials.
Motor (Axes)	Stepper Motor (24V NEMA 23 Bi-Polar DC; Rated at 24 Volt, 2.2 Ampere, 1.4 N-m Torque; 1.8 degrees per step)	1. DC Brushless Motor 2. DC Servo Motor	Stepper motors turned out to be the best choice due the amount of control and precise movement they provide to the user and the fact that they can infinitely turn in both directions puts them above servo motors. Our motors were sourced locally and since they were bought used, they were extremely economical. Combined with our 5-mm pitch ball screws attached to their shaft, these motors give the linear axis movement an accuracy of 0.025 mm when run on single-stepping mode and with no-slip since ours is an open-loop control system.
DC Power Supply	Mean Well Corporation (AC Input 220 V (RMS); 24V-DC Output; Auto-Switching with shunt and voltage fluctuation protection)		Using mains AC power, this unit supplies a constant maximum 23.95 volt DC current at its output terminals regardless of input power fluctuations. It has surge protection as well as a circuit breaker with built-in bullet fuses. The current output is variable and can be brought down to 12V if necessary.
Microcontroller	STM-32F4	1. Arduino 2. PIC-24 3. Raspberry Pi 4. AVR Atmega 5. BeagleBone Black	STM-32FA is an industrial grade controller having capability of up-scaling
Feedback Sensors	Axis Limit Switches	1. Shaft Encoder 2. Tachometer	Most suitable option with good reliability
Programming Language & IDE (Human-Computer Interface)	Visual Basic .NET 2015 running on Microsoft Visual Studio 2015 with .NET Framework 4.6.1	1. Java 2. Python	Machine level languages & allow more access to hardware for better controlling their parameters
Programming Language & IDE (Microcontroller)	C/C++ running on Atollic TruSTUDIO		
Command Set	ISO 6983-1:2009 (G00, G01, G02, G03, G70, G71, G90, G91, M04, M05)	-	Most of the above mentioned codes were fairly easy to implement while the Linear and Circular Interpolation codes required some work to be done. The algorithm was developed by us and the general objective was to develop a code that generates incremental waypoints for tool on intended interpolation path. The outcome of this activity was an Incremental Movement Table Displacement Array that once graphed on an appropriate set of axes, shows the tool path in two dimensions. This array will be used to synchronize the table axes motors to produce

			interpolated curves that are highly accurate. This code makes part of the HCI-cum-G&M code interpreter that we developed.
Microcomputer and I/O Devices	-	-	A desktop microcomputer with an Intel Core 2 Duo Processor, and a DB-25 Parallel Port was used along with a QWERTY keyboard and an optical mouse. The port allowed the software to send commands to the microcontroller.

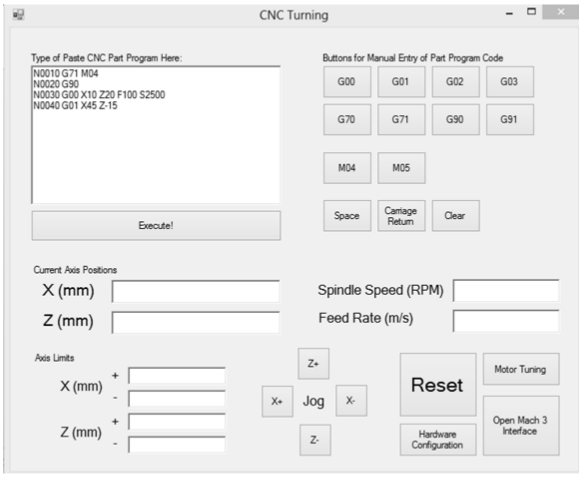

Fig 4-5: Screenshot of the front-end HCI that we designed ourselves on Microsoft Visual Basic .NET 2015.

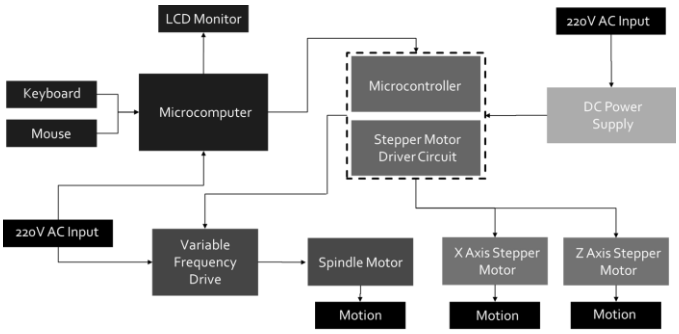

Fig 4-6: Schematic showing the complete electronic architecture of our machine.

Conclusion

We were able to develop design principles and methodologies that any local engineering setup could use to either fabricate their own or retrofit existing machines to CNC ones. Mechanical, Electrical and Computer Science aspects were clearly focused when designing principles and methodologies.

Secondly, our small scale model was successfully fabricated under PKR 175,000 (approx. USD 1,700) which is quite economical as compared to machines imported from other countries. Moreover, the small scale model was able to machine precise and accurate parts which is the foremost demand of the industry these days. Since this was a first prototype, it cost more and thus we expect retail versions to cost less than PKR 80,000 (approx. USD 800).

This small scale model can be scaled up to industrial level machines easily using the design principles mentioned in this paper.

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