The Wall-Mill

The Design of a Flexible Machine for the In-Situ
Architectural Machining of Surfaces

by

Tiffany Yang

Submitted to the Department of Mechanical Engineering in
Partial Fulfillment of the Requirements for the Degree of

Bachelor of Science

at the

MASSACHUSETTS INSTITUTE OF TECHNOLOGY

June 2006

Signature of Author: ______________________
Department of Mechanical Engineering
May 27, 2006

Certified by: ______________________
Alexander Slocum
Professor of Mechanical Engineering
Thesis Supervisor

Accepted by: ______________________
John H. Lienhard V
Professor of Mechanical Engineering
Chairman, Undergraduate Thesis Committee

The Wall-Mill

The Design of a Flexible Machine for the In-Situ
Architectural Machining of Surfaces

by

Tiffany Yang

Submitted to the Department of Mechanical Engineering
On May 12, 2006, in partial fulfillment of the
Requirements for the degree of
Bachelor of Science

Abstract

Water-like wave patterns on surfaces are seen in the walls of the Glaphyros Apartment in Paris, France and in the Frankfurt Nightclub in Frankfurt, Germany (designed by Mark Goulthorpe). These 3-D surfaces were created by first constructing molds which is an extremely time-consuming and inefficient process. It is also difficult to transport a large mold from the machine shop where it was created to the building site where the panel will be installed. Additionally, the non-modularity of molds requires that a new one be created for a different design. It would be much simpler and efficient if the mold is replaced with a portable apparatus that can machine the surface directly. The main concept is a vertical milling machine appropriately named the Wall-Mill. The goal of this thesis project is to design and construct a prototype of the Wall-Mill.

Thesis Advisor: Alexander Slocum
Title: Professor of Mechanical Engineering

Acknowledgments

This project would not have gone from design to implementation without the generous help of Mark Belanger, Edgerton Shop Manager and Instructor. The Wall-Mill would still be in pieces if it were not for his expertise.

I would also like to thank Derrick Tan, Gregory Scholl and Ben Zelnick. Derrick played an integral part in designing the carriage of the Wall-Mill. His V-shaped design was implemented. Greg machined all the test cars to test the mathematical theories, some of which he helped analyze. Both Derrick and Greg's input in the initial stages of the design was invaluable as well as Ben's input in the last stages of the design especially the y-actuation of the Wall-Mill.

Many thanks to Steve, Joe and the two Bobs from Pappalardo for kicking me out of the lab for 2.007 but more importantly, helping with the construction of the Wall-Mill whenever they can.

I would also like to thank Tsubaki for their kind donation of curved roller chains to this project. The Wall-Mill was designed around it.

Last but definitely not least I would like to thank Professor Slocum for his infinite patience, advice and supervision with this thesis. I know I gave him many grey hairs (or lack of).

Contents

1 Introduction

Even in protruding curved walls of Simmons Hall (designed by *Steven Hall*) and the Ray and Maria Stata Center (designed by *Frank Gehry*) in Cambridge, MA, the interior walls are still smooth and flat as in Figure 1. Contrary to this typical approach there has been a recent interest in walls with 3-D forms including the Glaphyros Apartment in Paris, France (Figure 2) and in a Frankfurt Nightclub in Frankfurt, Germany both designed by architect Mark Goulthorpe. The three-dimensional protrusions in these abstract walls resemble water flow and wave patterns providing a soothing effect that "washes away the stress of life."

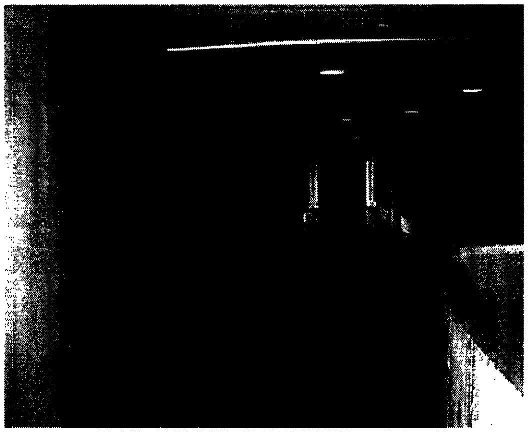

Figure 1: Smooth and flat walls of Simmons Hall, MIT

Each wave-like patterned panel was created by constructing a mold in a 3-axis CNC machine first and then using an appropriate manufacturing method with the mold to produce the final 3-D panel as seen in these buildings.

As with many molds, it is very time consuming to create one and the larger the mold is in size the more time it takes. Another problem with the mold's fairly large size is the difficulty in transport from the machine shop where it was created to the building site where the panel will be installed. An innate problem with any mold is that it is not modular. Each mold is unique and the only way to produce a different pattern for the wall panel is to go through the entire tedious process of creating a new mold.

Figure 2: Wave-like panel in Glaphyros Apartment in Paris, France

In response to this problem this paper present a design for the Wall-Mill, a portable apparatus that would machine flat or curved surfaces (walls, panels) directly. The surfaces would be constructed of soft materials including drywall and wood. Besides aesthetic walls and panels, these surfaces can be adapted for better acoustics such as auditorium walls or highway sound barriers. Additionally, the cost of the apparatus must be cheaper than the current method. This thesis examines the design of such an apparatus and the construction of an alpha prototype. The next section provides a general overview of the design as well as the analysis that led to the final design. The actual implementation of the design, i.e. the construction and assembly is described in section 3. Section 4 comments on the overall Wall-Mill and section 5 conclude with future work.

2 Design Requirements and Selection

Four main considerations for the Wall-Mill when deciding on a strategy and design:

- Ability to machine curved and flat surfaces
- 3-axis machining capability
- Portability
- Cost-effectiveness

The selected strategy was a vertical milling machine appropriately named the Wall-Mill. The basic idea is to have a long linear guide for the y-axis (up and down) travel with a linear actuator mounted on it for the z-axis travel (in and out). A spindle is mounted on the linear actuator to hold the tool for machining (see Figure 3). The linear guide would be supported by a guide rail nailed to the floor and a guide rail nailed to the ceiling.

While the design requirements allowed the y- and z- axis motions of the Wall-Mill to follow conventional actuation, the x- motion (travel along the surface) had to be designed for this particular application. An FRRDPARC chart (Table 1) was constructed to analyze different possible designs for the x-axis motion as well as the overall frame.

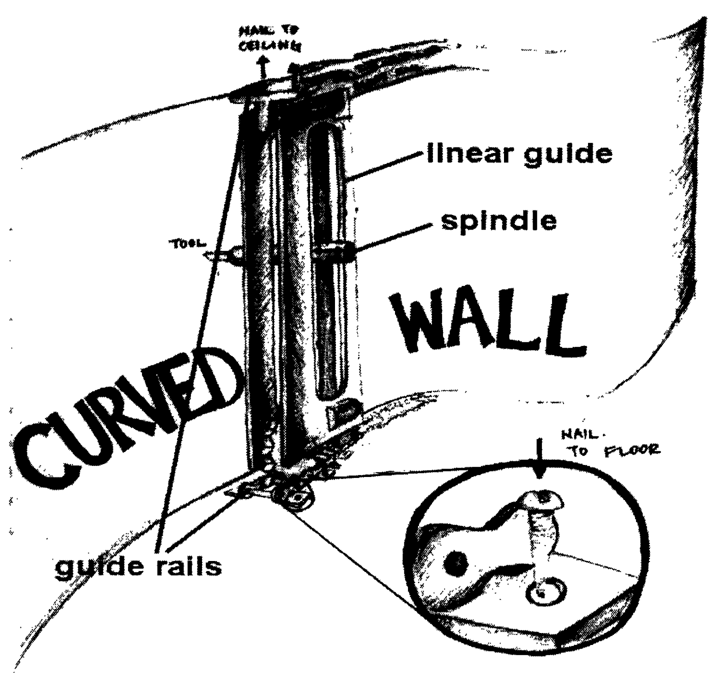

Figure 3: Rough sketch of preliminary design

2.1 FRRDPARC Chart

Functional Requirements	Possible Design Parameters	* Analysis	Risk	Countermeasures
Low Friction	Rolling (wheel, sprocket)			
Long Distance	Wheel		Position control not accurate enough	sprocket & chain
Position Control	Digital Encoder			
Curves (modular)	Tube • Bend in place • Bend using tool	Soft material or low section I (pipe, I-beam)	Stress too high, kinks	Segmented sections, sprocket and chain only
Sturdy	Constraint using ceiling and floor			
Curves (modular)	Roller chain	Noise from chain links	Bumpy	Round rail to guide and use only chain to drive and position sensor

Table 1: FRRDPARC chart used to analyze possible design parameters for x-axis motion of Wall-Mill

2.2 FRRDPARC Analysis*

The two functional requirements (both were potential design parameters for the frame) that needed further analysis were the (1) radius of the pipe bending in elastic region and (2) the noise generated from sprockets traveling on roller chains.

(1) Mathematical Analysis of Feasibility of Pipe Bending Design

For this analysis, the goal was to calculate if the minimum radius of curvature of a pipe or I-beam is small enough to be used as a guide for the Wall-Mill. The radius of curvature will highly depend on moment of inertia of each cross-section.

Mathematical Theory

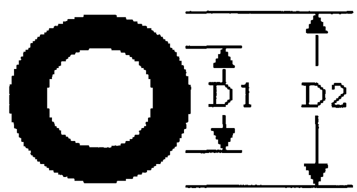

Figure 4: The cross-section of a pipe.

In Figure 4, if:

d_i = the inner diameter of a hollow pipe
d_o = the outer diameter of a hollow pipe

then the moment of inertia of a pipe is:

$$I = \int r^2\, dA \quad (1)$$

$$I = [\pi\, (d_o^4 - d_i^4]/64 \quad (2)$$

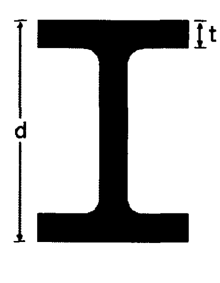

Figure 5: The cross-section of an I-beam.

In Figure 5, the moment of inertia of an I-beam is:

$$I = (2tw^3+dt^3)/6w$$

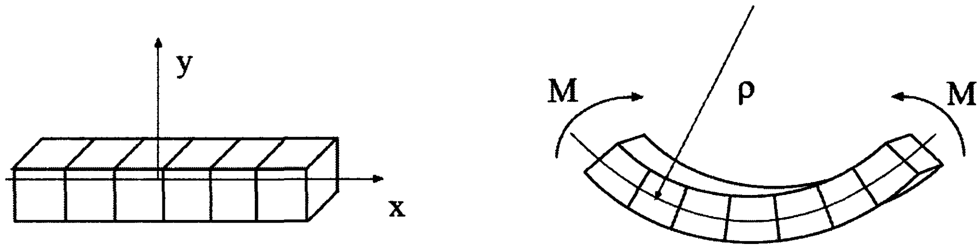

Figure 6: Beam bending. The radius of curvature is illustrated.

In Figure 6, if:

ρ = the radius of curvature (from the center of curvature to the neutral axis)
$d\Theta$ = the incremental change in angle

then from simple geometry:

$$\rho * d\Theta = ds \qquad (3)$$

$$1/\rho = d\Theta / ds \qquad (4)$$

And assuming that this will be a small deflection so that ds approximate equals dx:

$$1/\rho = d\Theta / dx \qquad (5)$$

An excel model was generated from the equations above using pipes and I-beams of different diameters, thickness and materials. From the table, none of the modeled shapes is small enough to be used as an x-axis actuator. For example, a copper tubing of 0.3" thickness with an outer diameter of 1.2" has a radius of curvature greater 75". Hence it appears that it is not feasible to elastically bend and secure a pipe to act as a guide rail. A countermeasure is needed, ad can be found in the se of special roller chain

(2) Vertical Motion and Sprocket Analysis

This analysis was to determine if the sprocket and roller chain can be used for actuation in the design of the Wall-Mill. In particular, is the noise i.e. vertical motion from the sprocket traveling over the rollers of the chain less than 0.1 mm. It was important to know that the Wall-Mill would be able to machine a wall as smooth and precise as possible in order to be comparable to the mold method. The maximum vertical motion as a function of sprocket dimensions was modeled in Excel. This was to test which sprocket size and the number of teeth to see if any is acceptable for the application.

Mathematical Theory

As a sprocket is pushed along a roller chain, the path will look like a series of semi-circles. But the maximum disturbance will be when the sprocket is traveling over one of the rollers i.e. the top of a semi-circle.

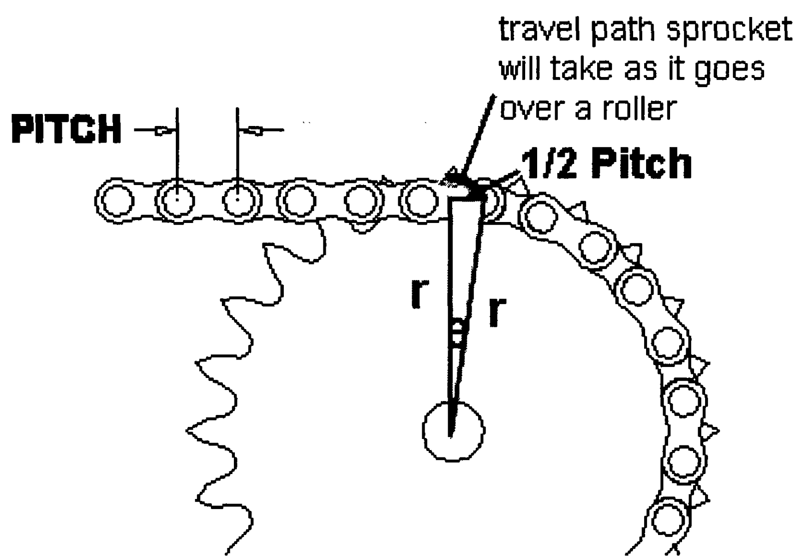

Figure 7: Illustration of a sprocket engaged in a roller chain. The geometry used for determining the maximum vertical motion is drawn out.

Using simple geometry, as seen in Figure 7 above, if:

n = number of teeth on a sprocket
r = sprocket radius
θ = angle between teeth
P = sprocket pitch

then:

$$\theta = \pi/n \quad (6)$$
$$P = 2*r\,(\sin\theta) \quad (7)$$
$$\text{Maximum vertical motion} = r\,(1-\cos\theta) \quad (8)$$

Equation (7) determines **r**, which is then plugged into equation (8) to solve for the maximum vertical motion. The graph below (Figure 8) was generated from the equations and used to visualize how the vertical motion varied with different sprocket sizes and teeth number. The orange line demarcated the 0.1mm tolerance and everything below that line was acceptable for the Wall-Mill.

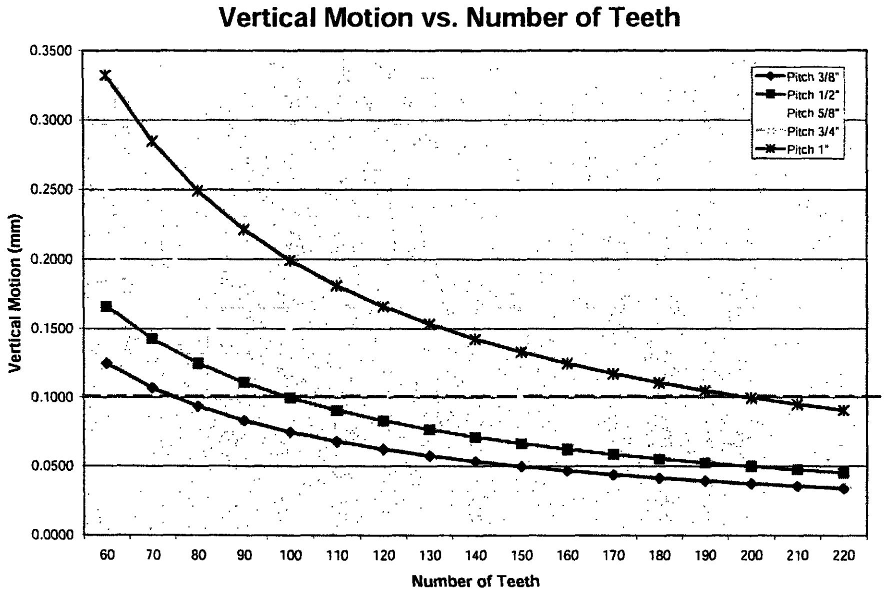

Figure 8: Disturbance as a function of number of teeth on a sprocket and pitch size. The smaller the pitch and the more number of teeth, the less the noise is.

Bench-Level Testing

To verify the theory behind the spreadsheet a simple car was constructed (Figure 9) to test the accuracy of the spreadsheet.

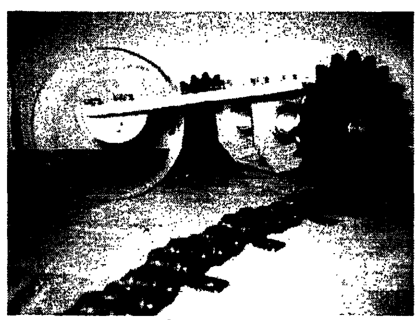

Figure 9: test car to verify mathematical prediction of the vertical motion of a sprocket as it travels on a roller chain.

A dial indicator was placed on top of the test car to measure the changes in vertical motion as it traveled along the roller chain (ANSI 40). Table 2 is the results of 10 runs of the test car. The excel model predicts the vertical motion for an ANSI 40 chain with 20 teeth to be less than 0.5mm. Since the average vertical disturbance of the test runs is 0.53mm, the excel model is fairly close. Thus, the use of the sprocket and chain was used in the design.

Run Number	Vertical Motion (mm)
1	0.49
2	0.53
3	0.49
4	0.47
5	0.55
6	0.56
7	0.54
8	0.54
9	0.49
10	0.51
Average:	0.52

Table 2: Results from different trials of the test car. The average vertical noise of the test runs is close to the mathematically predicted value and thus verifying it.

2.2 Design Refinement

Since the analysis concluded that the roller chain and sprocket is a better option than bending a pipe, both the top and bottom of the Wall-Mill was designed to be guided by sprockets. The general design of the Wall-Mill remained the same with a linear guide in the center attached to two sprockets on the bottom and two sprockets on the top. But the roller chain and sprocket concept was refined to further minimize the vertical motion. Section 2.2.1 describes and analyzes the improved design and section 2.2.2 analyzes a potential problem with the improved design.

2.2.1 Half-Pitch Offset Design

The central idea to the improved design is for two sprockets to be spaced (n + 0.5) pitches apart so that there will be half a pitch offset. The half-pitch offset provides minimal movement in the center because one sprocket will be traveling over a roller and the other sprocket will be in the valley between two rollers (Figure 10). This way the middle of the carriage where the machine tool will be located has as little disturbance as possible.

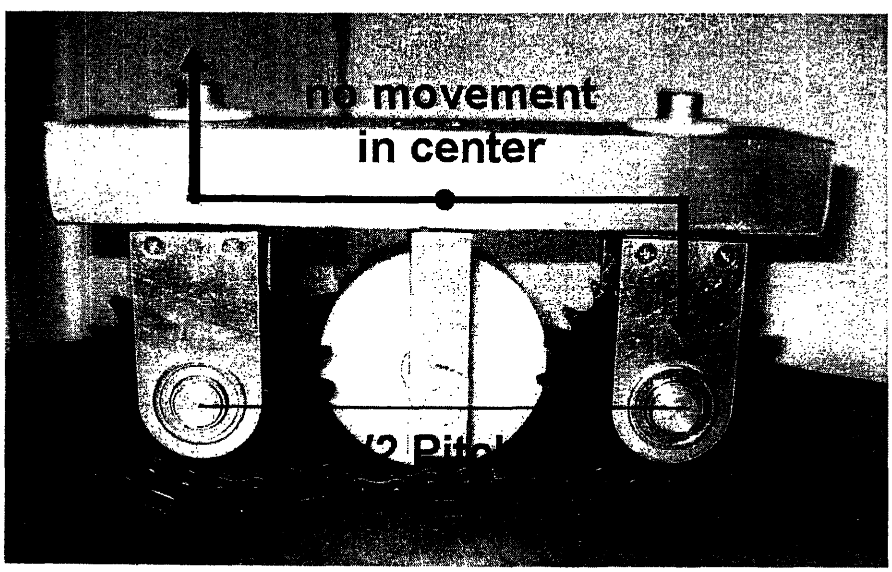

Figure 10: Test car to examine feasibility of refinement of sprocket and chain concept. The sprockets are half a pitch out of phase so that there is minimal movement in the center.

Mathematical Theory

As seen earlier, a sprocket travels along a series of semi-circular path as it rolls over the chain. Thus the path it takes can be modeled as the circumference of a semi-circle.

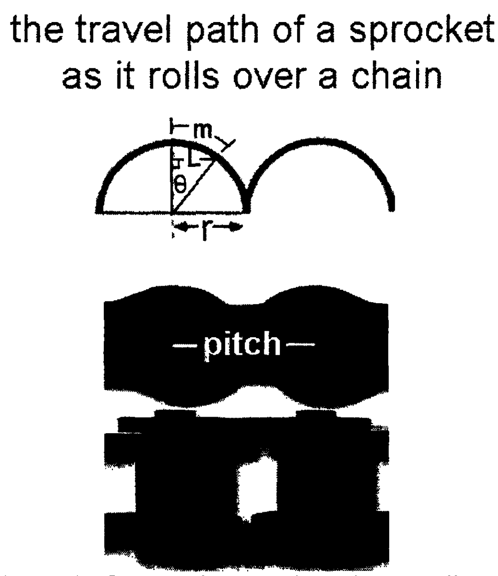

Figure 11: The semi-circular path of a sprocket traveling along a roller chain. The geometry of the path for analysis is shown.

In Figure 11, if:

r = the radius of the circle
L = half the chord length of the circle
θ = the angle between the two drawn radii
m = the circumference of the circle between the two points

and by properties of a right triangle:

$$\sin \theta = L/r \qquad (9)$$
$$\theta = \sin^{-1}(L/r) \qquad (10)$$

then the semi-circular travel path of a sprocket traveling over a roller chain is:

$$m = r\theta \qquad (11)$$
$$m = r^{*}\sin^{-1}(L/r) \qquad (12)$$

This equation was used to model the sprocket and chain offset concept in Excel to predict the movement of the center distance between the two sprockets. In the resulting graph (Figure 12), the first sprocket will follow the purple path and the second sprocket will follow the blue path. Thus the center distance between the two sprockets will have a vertical motion following the light blue path.

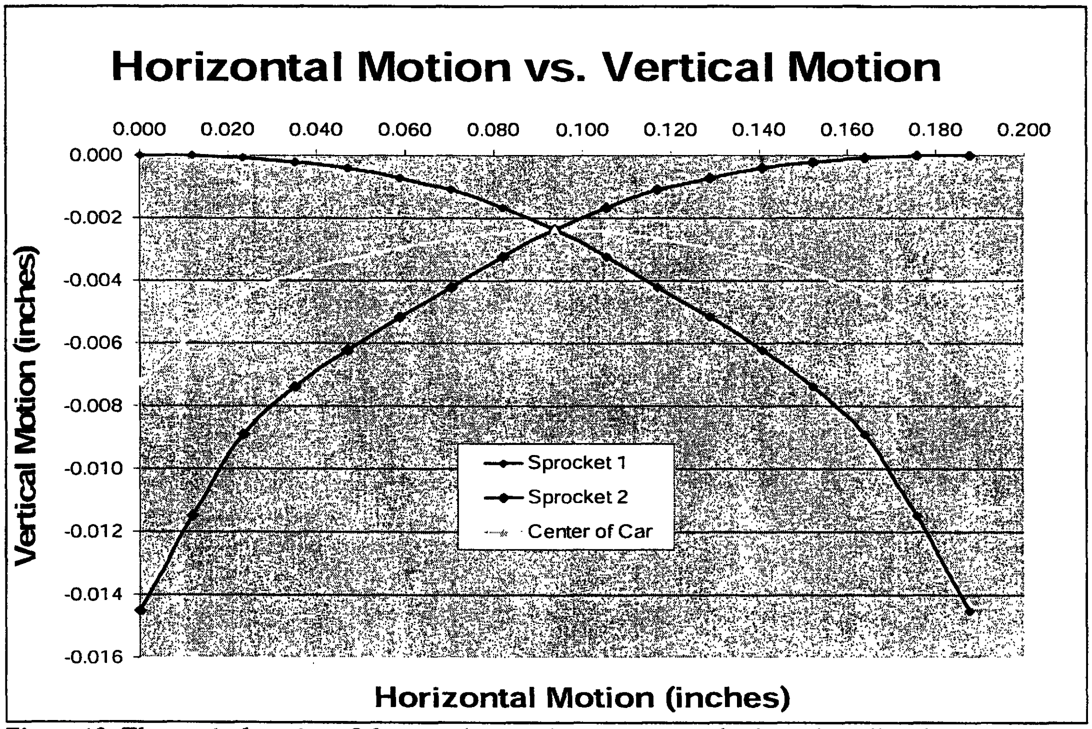

Figure 12: The vertical motion of the sprockets as the test car travels along the roller chain. The center of the test car which is the addition of sprocket one and sprocket two shows that the vertical motion in the center is at a minimal when the sprockets are

Bench-Level Testing

Since the mathematical model predicted a maximum vertical motion of less than 0.005mm for the center point between the two sprockets, another simple test car was built to test the theory. A dial indicator was placed in the center to measure the vertical motion as the car traveled along the roller chain. The tested values were similar to the predicted values and thus the design was implemented for the Wall-Mill.

2.2.2 Half-Pitch Offset Concern

When the sprockets make a curve their offsets are no longer half-pitch apart. With each curve, the offset will either increase or decrease. A concern is that eventually the offset increase or decrease will add up enough so the sprockets will be in phase. The analysis of this concern was to ask if the difference between the arc length and the chord length equals half the pitch of the sprocket (see Figure 5). In mathematical terms (based on the previous analysis of the design):

$$2m - 2L = \tfrac{1}{2}\text{ Pitch} \qquad (13)$$

- If the difference between the lengths of the arc and chord (2m-2L) equals half the pitch, then the half-pitch offset will completely be eliminated and the sprockets will be in-phase.
- If the difference is greater or smaller to half the pitch then the sprockets will still be out-of-phase but not half-pitch out-of-phase.
- If the difference is zero than the sprockets are traveling on a linear path and will retain the half-pitch offset.

There are many considerations that will determine how much the offset will change including the distance between the sprockets and the radius of curvature. The smaller the radius of curvature, the greater the offset will be eliminated. The worst case scenario is if the offset was completely eliminated and the two sprockets are in-phase. Since the minimum radius of curvature is a property of the roller chain, an Excel sheet was created to analyze the worst case scenario.

Table 3: Analyzes the variation in distances between the two sprockets initially set at half-pitch offset as they go around a curve.

ANSI	Pitch	n*	distance btw. sprockets	min. radius of curvature	cord length	curve offset	> 1/2 pitch?	1/2 pitch
	[inches]		[inches]	[inches]	[inches]			
35	0.375	**19**	7.3125	**10**	7.4861	**0.1736**	**No**	0.1875
40	0.500	**19**	9.7500	**14**	9.9586	**0.2086**	**No**	0.2500
50	0.625	**19**	12.1875	**16**	12.5032	**0.3157**	**Yes**	0.3125
60	0.750	**19**	14.6250	**20**	14.9722	**0.3472**	**No**	0.3750
80	1.000	**19**	19.5000	**24**	20.0806	**0.5806**	**Yes**	0.5000

** n = number of pitches a part between the sprockets. Distance between sprockets = (n*0.5)*P, where P is the pitch.*

For an ANSI 50 chain, the minimum radius of curvature is 16" (see Table 3). So if two ANSI 50 sprockets were placed 12.1875 inches (with a half-pitch out-of-phase) apart and traveling on a 16" curved roller chain, the two sprockets would become in-phase after they travel around the curve which is the worst case scenario. However the first sprocket and chain analysis showed that the vertical noise would be acceptable. Thus the worst case scenario is if the improved half-pitch offset design is eliminated and the sprockets perform like the first bench-level experiment.

2.3 Solidworks and Design Explanations

In the following sections, the design of the Wall-Mill is shown using Solidworks and explained. The first section is the overall design and the following sections details how the design requirements, as stated earlier, are fulfilled.

2.3.1 Overall Design and Description

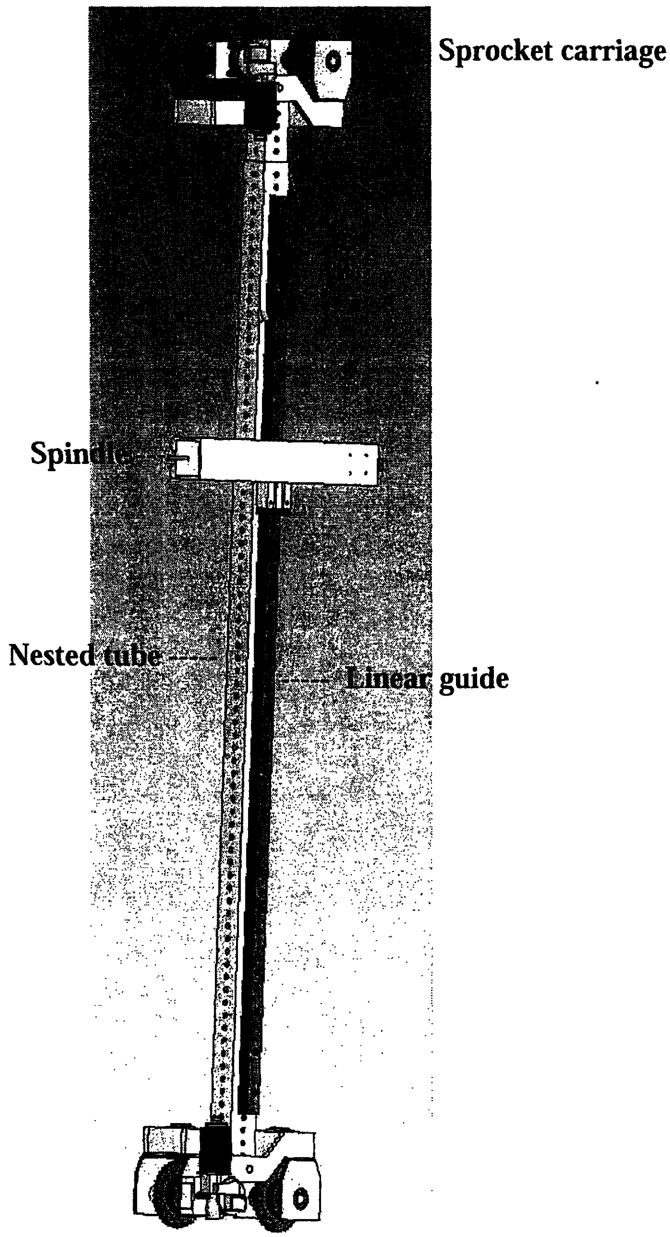

Figure 13: Solidmodel of overall Wall-Mill

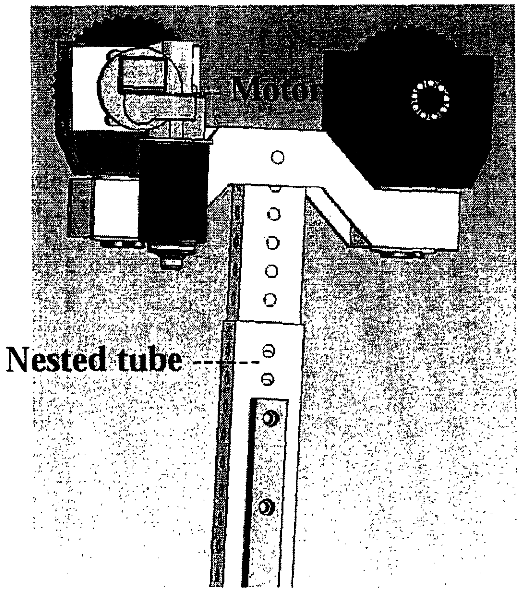

Figure 14: Top of Wall-Mill. Sprocket carriage attached to nested tube by a pin.

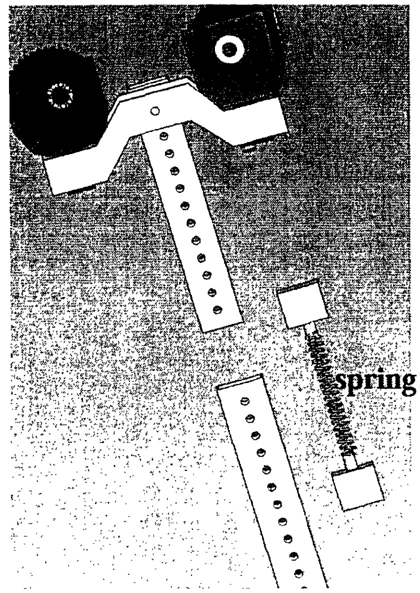

Figure 15: Tensioning system of exposed. The internal spring pushes the Wall-Mill against the ceiling and floor.

- The overall frame of the Wall-Mill is a perforated nested tube (an inner tube that telescopes out from an outer tube) sandwiched between two sprocket carriages.
- An internal spring (see Figure 14) tensions the nested tubes against the ceiling and floor to stabilize the Wall-Mill. The spring also dampens any bumps acting like a suspension.
- A linear guide is mounted on the nested tube. On the carriage of the linear guide sits a linear actuator. The linear actuator holds a router which machines the wall.
- The nested tubes are attached to the sprocket carriages by a pin so that the tubes can rotate according to the pitch-offset design. Both sprocket carriages are identical.
- Inside the sprocket carriages are constant force springs to align the sprockets when they rotate from traveling along the curved roller chains.
- The path of the Wall-Mill will be determined by the roller chains attached to the ceiling and floor.

2.3.2 Ability to machine curved and flat surfaces (Modularity)

Since it is the surfaces to be machined that are variable, the Wall-Mill design allows the surfaces to determine the path the Wall-Mill will take. Unlike conventional roller chains (Figure 16),

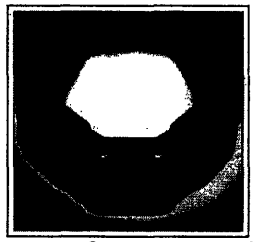

Figure 16: The curvature of a conventional roller chain.

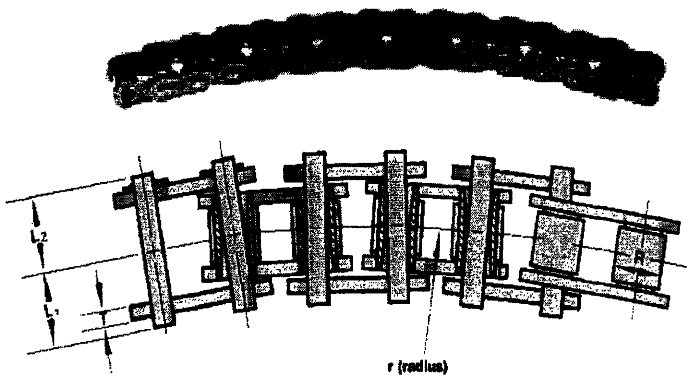

Figure 17: Tsubaki's special curved roller chain.

Tsubaki's special roller chain (Figure 17) has the ability to flex in an additional direction which allows it to align along a curving wall. When the roller chains are aligned according to the surface, they are then nailed to the floor/ceiling. This becomes the track that the Wall-Mill will take. Thus, the Wall-Mill can machine a curved or flat surface as it follows the path laid out by the roller chains.

2.3.3 3-Axis Machining Capability

X-Axis

The x-axis is the direction along the travel path of the Wall-Mill as determined by the roller chains and the surface. This motion is controlled by two driven sprockets, one in the top sprocket carriage and one in the bottom.

Z-Axis

The z-axis is the direction into and out of the surface and determines the depth of cut of the Wall-Mill. This motion is controlled by a linear actuator which is mounted on the linear guide.

Y-Axis
The y-axis is the direction along the nested tube and linear guide. It is the up and down motion of the Wall-Mill. This is controlled by a sprocket driven by the motor behind the linear actuator. The sprocket rides on a vertical roller chain attached off of the nested tube.

2.3.4 Portability (Assembly)

There are only seven loose pieces when the Wall-Mill is dissembled:

1. top sprocket carriage
2. bottom sprocket carriage
3. linear guide mounted on nested tube
4. linear actuator with spindle
5. top roller chain
6. bottom roller chain
7. vertical roller chain

3 Implementation

[pictures of final assembly will be inserted here]

3.1 Parts Selection

3.1.1 Spindle Selection and Calculations

The spindle is RYOBI's 1-1/2 hp router (Model R162-1K) bought off the self. Since the router is meant to cut wood, the power and speed is definitely sufficient for the Wall-Mill. The stall torque and an approximate cutting force can be calculated from RYOBI's specifications.

Specifications of Router:
ω = no load speed = 25000 rpm
P = power =1.5 hp

At maximum power, the operating torque is at half the stall torque ($\tau = \frac{1}{2}\tau s$) and the operating speed is at half the no-load speed ($\omega = \frac{1}{2}\omega_n$). In other words,

$$\tau = P*63025/\omega \qquad (14)$$

$$\tau = (1.5*63025)/12500$$

$$\tau = 7.56 \text{ in-lbs.}$$

and thus the stall torque (τs) is 15.12in-lbs.

The cutting force depends on the tool diameter which is unknown at this time but for approximation purposes the collet size (¼" diameter) will suffice.

$$F = \tau / r \quad (15)$$

- Approximate operating force = 60.48 lbs
- Approximate maximum force (stall motor) = 121 lbs.

3.1.2 Motor Selection

The Wall-Mill is using three Ford windshield wiper motors which were used for MIT's Design and Manufacturing I class. Though not as compact as other motors, it has the necessary torque and speed ratio to drive the Wall-Mill.

Requirements for Wall-Mill to operate:
F = translational force (60.48 lbs)
r = radius of sprocket (2.16")

$$\tau = F*r \quad (16)$$
$$\tau = (60.48 \text{ lbs})*(2.16")$$
$$= 131 \text{ in-lb total}$$

Since there are two motors driving the Wall-Mill, each motor needs to be able to provide a torque of 65 in-lbs. Each motor is able to provide the necessary torque as Table 2 shows.

Ford Motor Company Windshield Wiper Motor		
No Load Low Speed @ 13.8 volts	50 rpm	
Stall Torque	14 N-m	123.9 in-lbf

Table 4: Ford Motor Company windshield wiper motor specifications Connected clockwise (black and white).

3.1.3 Sprocket and Roller Chain Selection

The sprocket size selection was limited by the sizes Tsubaki had available since Tsubaki is the only known manufacturer of these special curved chains. Tsubaki only manufactured these chains in ANSI sizes 35, 40, 50, 60 and 80 (see Table 5). However, the maximum allowable load for ANSI 35 is 210lbs. which is not robust enough for this application. The predicted weight of the Wall-Mill was approximately 200lbs. And from the previous analysis, the noise is minimal with more teeth and smaller the pitch. Thus, RS50CU was chosen.

Table 5: Specifications of Tsubaki's curved roller chain.

U.S. TSUBAKI Chain No.	Average Tensile Strength lbs.	Maximum Allowable Load lbs.	Approx. Weight lbs./ft.
RS35CU▲	1,800	210	.22
RS40CU	3,480	420	.41
RS50CU	5,420	640	.68
RS60CU	7,830	900	.94
RS80CU	13,840	1,560	1.66

3.1.4 Other parts used

- TNK Linear Guide
- TNK Linear Actuator
- US Digital Corporation Encoder

4 Comments

The Wall-Mill design explicitly addresses each of the requirements in this paper so far except for one, cost-effectiveness which will be addressed in this section. The Wall-Mill cost approximately $1565 to build the alpha prototype excluding shipping charges which is definitely cost saving compared to the mold method. However there were many items (see Table 6) that were lying around i.e. free and used in the design. The cost of labor is also not tallied in the worksheet. If all the parts (linear actuator, bearings, electronics, etc) were counted towards the cost as well as machine time, then a rough estimate of the total cost is approximately $5000. Compared to the mold method, the Wall-Mill would still be more cost-effective.

Company	Item	Unit Price	Quantity	Total Cost
McMasters	Flanged Ball Bearings	4.06	4	16.24
McMasters	Spider Couplings (Hytrel Spider)	4.57	2	9.14
McMasters	Spider Couplings (Al. Coupling hub)	23.37	4	93.48
McMasters	Nested Tube (2" sq., 8ft. long)	44.08	1	44.08
McMasters	Nested Tube (1.75" sq, 4ft long)	21.62	1	21.62
McMasters	Sprockets (ANSI 50, 20 teeth, 5/8" bore)	22.11	4	88.44
Central Machine	Stock Material (Aluminum, Steel)	200.00	1	200.00
Home Depot	Spindle (Ryobi Router)	59.97	1	59.97
McMasters	Roller Chain	4.97/ft	10	49.70
McMasters	Compression Spring	14.80/pack	1	14.80
McMasters	Idler sprocket	18.87	2	37.74
McMasters	Constant Force Spring	5.08	2	10.16
Stock pile	Linear Guide	720	1	720

	Guide Blocks	150	1	150
Stock pile	Linear Actuator			
Stock pile	Motors			
Donated	Tsubaki Roller Chain			
	Electronics			
	Sensors			
			total	**1565.04**

Table 6: Bill of materials for the Wall-Mill.

5 Further Work

Since this is only an initial study on the design of the machine, there is a lot that can be done to carry the Wall-Mill further. The controls needs to be added to the Wall-Mill so that it can actually machine the wall and have all three-axis capability. The motors and digital encoders are already built into the frame work for the controls.

The alpha prototype addresses all four of the design requirements ability to machine curved and flat surfaces, 3-axis machining capability, portability and cost-effectiveness However, there are many improvements that can be made to each of these requirements.

- The sprocket and roller chain design of the y-axis motion can be improved with a linear actuator. This way the Wall-Mill has more precision and is more self-contained.
- The router needs to be replaced with a cordless spindle to allow for a longer x-axis travel.
- The entire machine needs to be driven from a battery or an AC power (long cord).
- Replace the router with an actual spindle to increase the z-axis reach.
- A more efficient method or tool needs to be created to align the roller chain along the surface and nail it to the ground.