Mechanical Design of a Desktop Milling Machine for Fabrication in an Introductory Machining Class

by

Johannes Schneider

Sc.B. Mechanical Engineering
Massachusetts Institute of Technology, 2010

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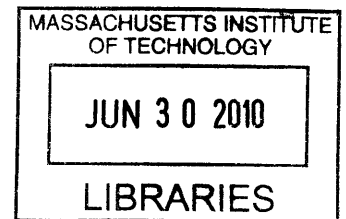Bachelor of Science in Mechanical Engineering

at the

Massachusetts Institute of Technology

June 2010

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ABSTRACT

The purpose of this research is the mechanical design of a miniature desktop milling machine for use as an alternative class project in MIT's introductory machining course 2.670. This research is important, because a well-designed introductory machining course has the potential of inspiring students early-on in their academic lives to learn about and become familiar with the principles of precision machine design. This thesis proposes a mill design that is simple enough to being built by inexperienced engineering students within the scope of a single semester introductory machining course and within a class budget of about $150 per student. The design that is proposed in this thesis is different to conventional desktop mill designs in that it is considerably more compact in size, thereby reducing material costs, machining time, and ease of storage. This thesis mainly focuses on the mechanical design aspects of the machine. It is structured in five sections: Machine Configurations, Cutting Analysis, Spindle Design, Stage Design, and a final segment covering frame design, vice design and final machine assembly.

Thesis Supervisor: Martin L. Culpepper
Title: Associate Professor of Mechanical Engineering

ACKNOWLEDGEMENTS

I would like to thank the Mechanical Engineering Faculty of MIT helping me with understanding life as an interesting design project.

Specifically, I would like to thank Professor Slocum for reminding me to always keep things simple. I would like to thank Professor Brisson for pushing me so hard in 2.006. Finally, I would like to thank Professor Culpepper for challenging me to face my fears head-on.

I would also like to thank my family and my friends for their support and care.

CONTENTS

FIGURES

TABLES

1 Introduction

The objective of this research is to develop a miniature desktop milling machine that may serve as a manufacturing project for an introductory manufacturing course. Figure 1-1 shows a picture of the final milling machine design (solid model), as well as a picture of the first machine prototype.
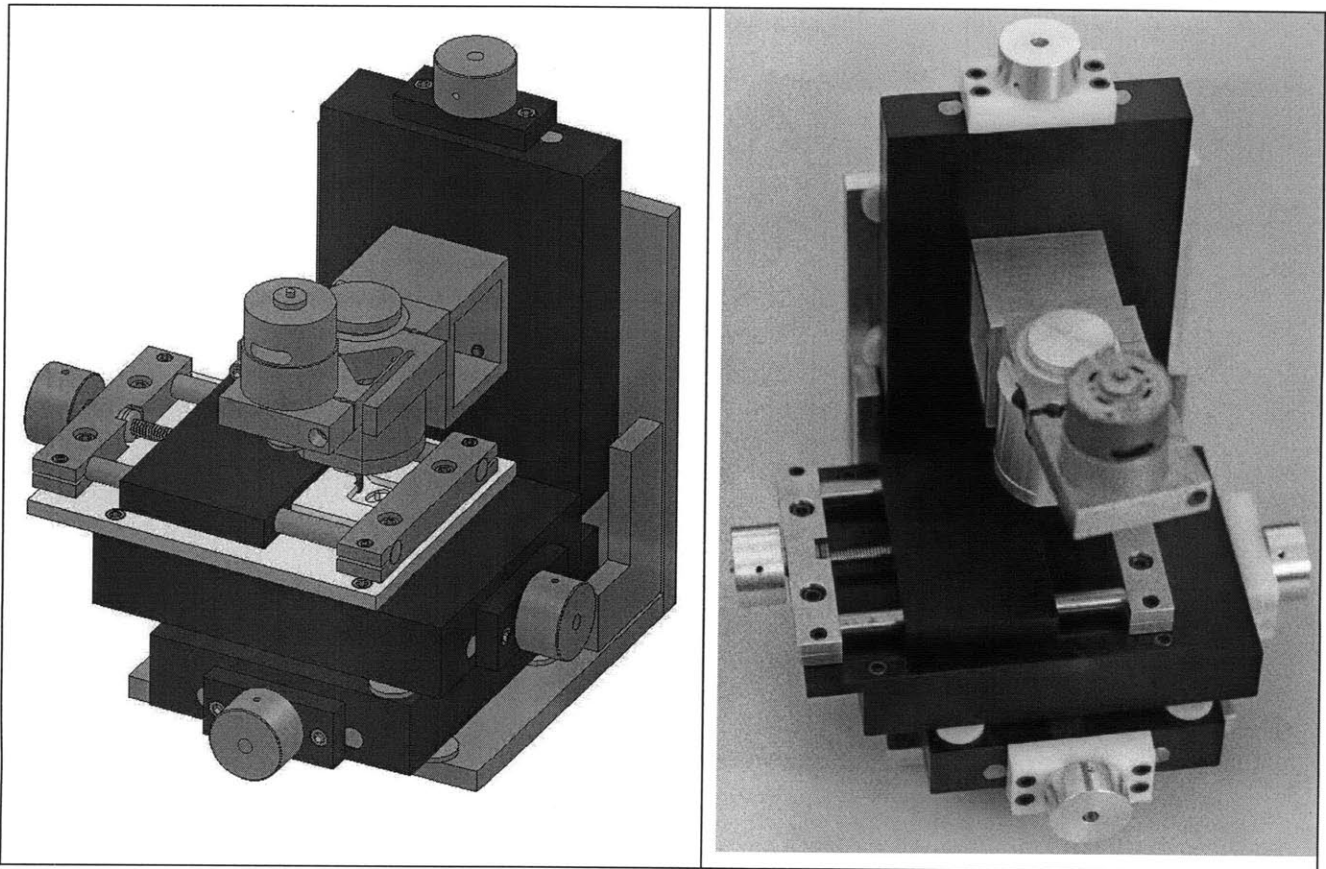

Figure 1-1: Desktop Mill Solid Model & Machine Prototype

1.1 Introductory Manufacturing Courses

Introductory manufacturing courses, such as 2.670 at MIT [1], are generally designed for students without previous machining experience to achieve any of the following teaching goals:

1.) Raise awareness for a wide range of commonly used manufacturing processes and machines.

2.) Provide students with a basic level of confidence towards machining

3.) Inspire students to be taking an active role in their learning by experimenting with and exploring manufacturing techniques and machines that were not included as part of the course.

The following is a list of machining tools, machining operations, and working materials that an introductory manufacturing course might intend on introducing its students to:

Machining Tools [2]: Mills, Lathes, Band Saws, Drill Presses, Wrenches, Pliers, Files

Machining Operations [3]: Milling (Manual & CNC), Drilling (Manual & CNC), Turning, Boring, Facing, Drilling, Taping, Threading, Counter Boring, Counter Sinking, Cutting to Size, Bending, Edge Finding, Setting Stops, Indicating

Working Materials: Steels (Carbon, Regular, Leaded, Stainless), Aluminum, Plastics (Delrin, ABS, PVC, Nylon, Polyethylene)

There are different approaches to teaching such an introductory manufacturing course. The course instructor could rely on mostly lecture-style teaching, the course could consist of a range of unrelated small projects that each cover different manufacturing techniques and machines, and the course could revolve about a single larger-scale manufacturing project [4] that is intended on covering a wide rage of manufacturing projects, machines and materials.

Each of these approaches has benefits and draw-backs. Lecture-style teaching is less resource intensive than the other two options, but relies on the students' independent efforts to seek out machining space to practice what they learned in class. Small projects are more flexible than large projects, and might likely require less material recourses than a single larger project. A single large project is likely the most resource intensive option of the three, but may also be the most rewarding one for both students and instructors since a larger-scale project may actually result in a useful machine that students can afterwards use for real-life tasks, and proudly share within their social networks, possibly inspiring others to learn about manufacturing as well.

This project targets the kind of introductory manufacturing course that is based on a single larger-scale manufacturing project and is looking for interesting, new ideas for such a project.

1.2 Project Selection: Miniature Desktop Milling Machine

Professor Martin Culpepper [5], Associate Professor of Mechanical Engineering at MIT, initially proposed the miniature desktop milling machine for use as a class project in MIT's introductory mechanical engineering machining course 2.670.

The educational goals for this desktop mill design may be summarized in three points:

1.) Helping students to get comfortable with using many of the machines that occupy space in any regular machine shop, by spending many supervised hours machining

2.) Encouraging students to learn about the inner workings the milling machine by building a scaled version fro scratch

3.) Providing students with a sense of accomplishment and a physical sign of their first achievements as rising engineers by allowing students to keep the machine after the class such that they could share their experiences with their friends and families.

Equipped with machining confidence, raised awareness for engineering details, and an understanding that machines aren't actually as scary are they might at first appear to be, students are likely prepared to take the next step on their journey of becoming real-life engineers.

1.3 Project Outline

The following points are sorted in chronological order.

1.) Concept Ideas

2.) Mechanical Design

3.) Prototype Development

4.) Prototype Testing

5.) Final Machine Design & Complete Machine Characterization

6.) Manufacturing Plan

7.) Production Runs

So far, points 1 and 2 have been fully achieved, and point 3 partially. Detailed documentation of these tasks is available to the public [6].

Present work focuses on providing a detailed overview of the Mechanical Design Process (Point 2) that went into proposed miniature desktop mill design.

1.4 Design Process: Axiomatic Design

The desktop mill proposed in this work is designed as a machining project for inexperienced machinists. As such, the overall machining complexity of the design should be kept at a minimum. This is exactly what axiomatic design [7] is trying to achieve, as summed up in its two axioms:

1. Independence Axiom

2. Least Information Axiom

A perfect axiomatic design is one in which all functional requirements are independent from another (1), and no redundant information is contained by the final design (2). In other words, axiomatic design calls for structured thinking and rethinking of every design step from first concepts to final design, making sure that no lines or shapes are unnecessarily placed or attempt to serve two or more functional requirements at once.

In practice, the axiomatic design process follows a hierarchic top-down approach in which the designer first considers a set of very broad functional requirements without which the machine could not possibly function. Then she comes up with a list of design parameters that each map onto exactly one of these functional requirements. Each of these design parameters then calls for new, more specific sets of functional requirements that can each be tackled with another set of design parameters, and so on and so forth. The quality of each set of functional requirements and design parameters is continually evaluated against the two axioms as previously stated, ideally resulting in an extremely simple, non-redundant (robust) design.

The miniature desktop mill design documented in this work attempts to follow axiomatic design principles in order to achieve functionality through simplicity.

1.5 Functional Requirements

The goal of this section is to outline a set of basic functional requirements that govern the desktop mill design process.

A 3-axis design is desirable over a 2-axis design since it provides the capability for machining 3-D features. The overall size and weight of the machine should be kept at a reasonable minimum since a portable design would allow students to easily share the results of their work with friends and family outside their home, as well as making it easier for these students to find storage space within their crammed dorm rooms. Finally, a small-scale, lightweight design would also help minimize machining time, and material costs. A roughly basketball-sized machine appears ideal since such a design is likely to fit into most book shelves as well as being relatively easy to carry. Considering a machine of roughly such size (~10" x 10" x 10") it seems reasonable to be aiming for a working volume that is linearly scaled by a factor of ~$1/5^{th}$ with respect to the rest of the machine (2" x 2" x 2"). If this working volume were positioned at the center of the machine, this would leave 4 inches in all directions for frame components, actuators, transmission elements and other components to be placed. With expected ~2" of linear range of motion, tool sizes between 1/16" and 1/8" seem most appropriate, corresponding to roughly 16 to 32 tool diameters of linear range of motion. For teaching purposes, a machine that is only capable of cutting plastics and wax but no metals would likely be acceptable, but a more ambitious and practical design should at least be capable of cutting both soft aluminums as well as plastics. Resolution of linear motion and cutting accuracy are not extremely important for a teaching tool, but an ambitious goal might aim for similar resolution and accuracy as can be found with most commercial machines, which is usually just around 0.001". Budget and machining time are both significant driving factors at all levels of the design process since these are what determine whether the proposed design can truly make a feasible alternative to existing machining projects. The budget estimate of $150 shown in Table

1.4.1 below is based on a rough estimate of how much a student might be willing to spend on the materials for building a miniature desktop milling machine. The other important measure for feasibility is overall required machining time per student including set-up times. Considering a course that requires 3 hours of lab per week over the course of a semester – a total of 12 weeks – and 50% efficiency due to machine availability and organizational issues, the required overall machining time should not exceed 20 hours. A summary of all these functional requirements is presented in Table 1-1.

Table 1-1:   Desktop Mill Functional Requirements and Design Parameters

Type	Functional Requirements	Design Parameters
Machine Type	3-Axis	Motion stages
Working Materials	Aluminums, Plastics	Spindle/ Stage actuation design
Rough Machine Size [in^3]	10 x 10 x 10	Component size
Budget per machine [$]	< 150	Component cost
Overall Machining Time [hr]	< 20	Part count/ Machining complexity
Cutting Volume [in^3]	2 x 2 x 2	Stage range of motion
Tool Sizes - Diameter [in]	1/16 - 1/8	Chuck selection/ design
Resolution [in]	< 0.001	Stage Transmission
Cutting Accuracy [in]	< 0.001	Everything

Comprehensive analysis of material cost, machining time, and cutting accuracy are not included in this thesis. For details on these points, please refer to: http://web.mit.edu/bubby/www/Sub/2ThU.html

The following chapter serves as a general overview of the design process that was involved in coming up with the machine design that is shown in Figure 1-1.

2 Mechanical Design

The desktop mill design process is presented in four parts:

1.)   Machine Configurations
2.)   Cutting Force Calculations
3.)   Spindle Design
4.)   Stage Design & Integration

Machine Configurations introduces the general layout of the entire machine. The second chapter on Cutting Forces outlines the analytical background required for FEA analysis, Motor selection, and possibly also for future stiffness analysis. The final two chapters on Spindle and Stage design detail a number of mayor design decisions that each contributed to the final mill design as it is shown in Figure 1-1. Each design configuration table throughout the work first shows the configuration that was chosen for the final design, followed by one to three other configurations that were less convincing yet appeared strong enough to potentially be reconsidered in future design iterations.

2.1 Machine Configurations

3-axis milling machines consist of a rotating tool (End Mill) and a piece of working material that can be brought in contact with one another as well as being moved in 3 orthogonal directions with respect to another. The assembly that holds the tool and rotary actuator is called "Spindle." Each assembly that linearly moves the spindle with respect to the part or vice versa is called "Stage." The structural components holding everything together within the structural loop is called "Frame." Per definition, a 3-Axis milling machine requires exactly one spindle, three stages, and one frame that may be arranged in four different ways with respect to another.
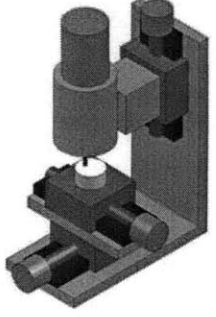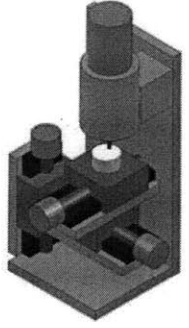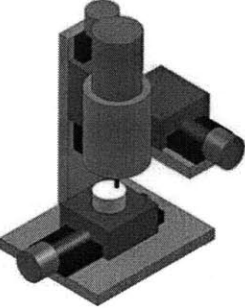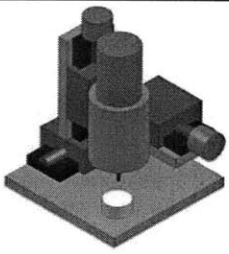
Symmetry	Frame Design	Machine Size	Interfaces		
+	+	O	+		
O	-	-	O		
O	+	+	O		
-	+	+	-		

Figure 2-1: Mill Stacking Order Configurations.

Structural Components are marked yellow (Frame & Spindle Connector), Linear Bearings blue,

Transmission Elements (Lead screws) pink, Bearing Frames orange, Actuation elements (Motors &

Hand wheels) turquoise, End Mills red, and work pieces white. Blue arrows mark degrees of freedom of

Spindles; red arrows mark degrees of freedom of Work Pieces.

2.2 Cutting Analysis

In order to be conservative, all components were designed for "rough" machining of aluminum using an 1/8" 2-fluted end mill. For this case cutting forces are not expected to exceed 50N. Required maximum spindle power is approximately 50W, corresponding to about 1/10 horse power spindle motor, assuming 70% efficiency in power transmission elements. Furthermore, based on orthogonal cutting theory and speed-feed ranges adapted from the Machinery's Handbook, for cutting alumina and plastics using 2-fluted 1/16" to 1/8" end mills and assuming a transmission ratio of 1:1, the motor should be capable of operating in a speed range of 6000 – 12000 RPM with corresponding maximum cutting torques of 0.05 – 0.01 Nm. All cutting force calculations, in much greater detail, are presented in the attached Cutting Analysis design spreadsheet.
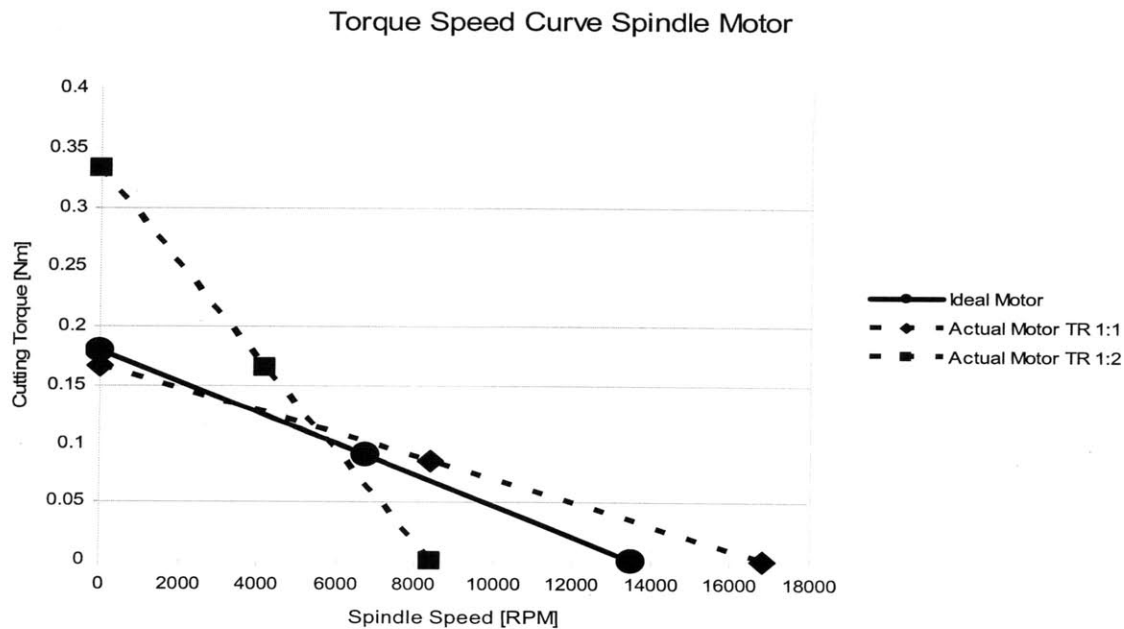
Figure 2-2: Spindle Motor Torque-Speed Curves
Ideal Spindle Motor vs. RS545 Motor[1] at transmission ratios of 1:1 and 2:1

[1] RS545 DC Motor. BaneBots Web Site. http://banebots.com/pc/MOTOR-BRUSH/M5-RS545-12

As can be seen in Figure 2-2, the ideal spindle motor, based on cutting analysis, and the one selected are extremely close at a direct transmission ratio (1:1). For the actual mill, a belt transmission was chosen in order to increase flexibility in terms of transmission ratios, as well as to avoid having to use expensive flexure couplings for directly connecting the spindle motor with the spindle shaft. The transmission bracket was chosen to be made from aluminum such that it could act as a heat sink to help with heat transfer from the motor.

Basic beam bending calculations show that 1/8" HSS End Mills are likely to fail if cutting forces significantly exceed 100N. This value is used for all following FEA analysis in order to assure that the tool breaks significantly before any other machine elements are expected to yield.

2.3 Spindle Design

This section presents the mechanical design of the spindle. Figure 2-3 shows a picture of the latest spindle solid model and a picture of the first spindle prototype.
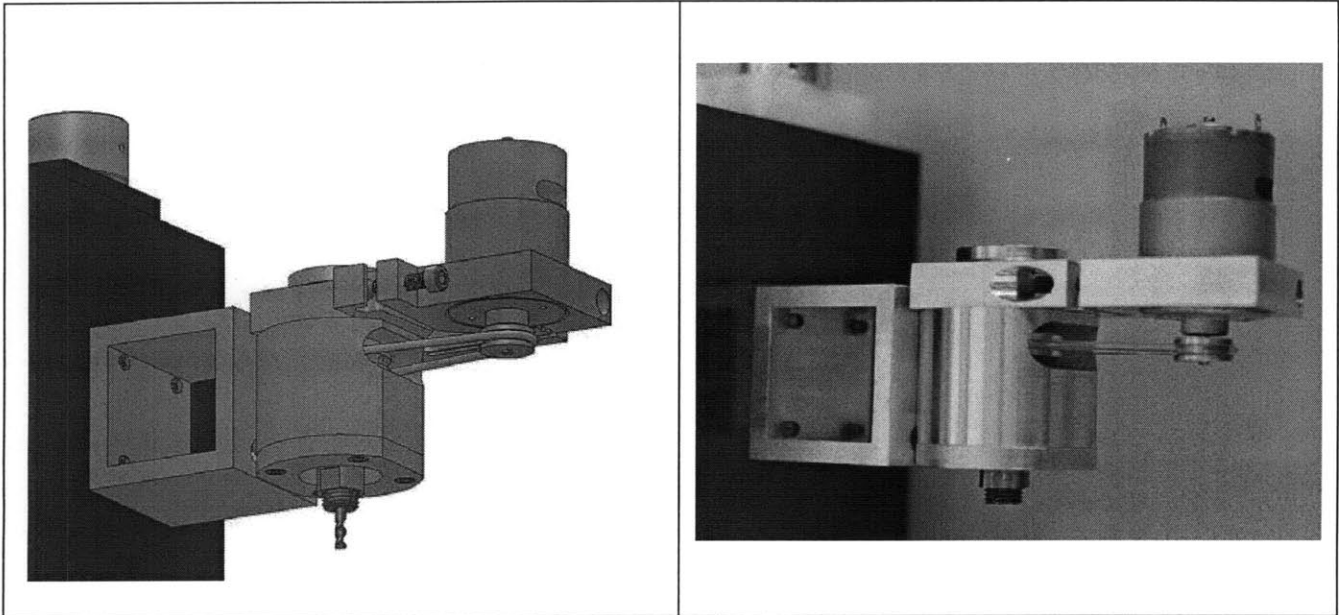
Figure 2-3: Spindle Solid Model & Prototype

The machine functional requirements as shown in Table 1-1 call for a spindle design that is capable of holding 1/16" to 1/8" diameter end mills, minimizes part count, cost, machining steps/ setups, and overall machine size. Further important design goals are the machine's ability to sustain cutting forces of up to 100N without damage (other than that the tool breaks), as well as to maximize overall machine stiffness in order to maximize cutting accuracy.

As was done for the case of machine configurations (Figure 2-1), each design decision is presented in the form of a basic Pugh chart, supported by pictures of solid models and, were appropriate, accompanied by results from FEA analysis.

Double Rowed Angular Contact Bearings were selected over pairs of radial ball bearings or pairs of tapered roller bearings which significantly reduced shaft length, as well cost when compared with tapered roller bearings for similarly small shaft radii. If bearing stiffness turns out to be of concern, it might be worth increasing the bearing spacing by considering one of the other two options presented in Figure 2-4.

A circular aluminum tube with 2" OD and 1" ID was chosen for housing stock, the housing connector was selected to be a 2" x 2" rectangular aluminum extrusion with 1/4" wall thickness. This choice allowed for a simple implementation of a kinematic coupling at the interface, both intended as a repeatable alignment feature during machine assembly, as well as to allow for the spindle to be quickly swapped with a 3D printing head (Figures 2-5 & 2-8)

A standard 1/8" Dermel collet was chosen as the center piece to the chuck design. A custom collet preload nut allows for the entire chuck to be located within the shaft, reducing the overall length of the shaft when compared to a shaft where the preload nut is located on the outside, as well as reducing the relative moment that the bearings experience under comparable loading conditions between the two designs (Figure 2-6).

FEA analysis was performed on the final shaft design in order to verify its strength characteristics and Factor of Safety under excessive loading (100N). For a summary of these results, please refer to Figure 2-7.

Frequency FEA analysis was performed on the Spindle Stage Connector in order to verify the first modes of resonance. If frequency turned out to be a serious problem with the current connector design, it might be worth considering a stiffer version of the housing connector, like the second configuration shown in Figure 2-8.

Belt drive was selected over direct drive to better optimize the operating speed range, as well as to avoid having to deal with alignment issues between motor and spindle shafts. Motor and transmission

Clamp were chosen to be facing forward, with the electrical leads pointing upwards. A "backward" facing configuration would likely have run into interference problems with the kinematic coupling. Having the belt run through the housing is preferable since this arrangement reduces the effective moment load on the bearings due to belt preload, moreover, in this arrangement, the motor leads run upwards, which is also preferable since it reduces the chance of the leads getting caught and ripping out. See Figure 2-10 for reference.

The Spindle Motor Transmission Clamp was optimized for maximum range of motion, including hard stops to avoid yield. A flat belt drive is preferable to a round belt drive since these are more efficient and provide higher holding torques. See Figures 2-12 and 2-13.
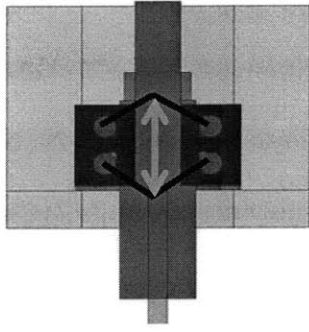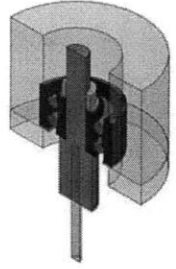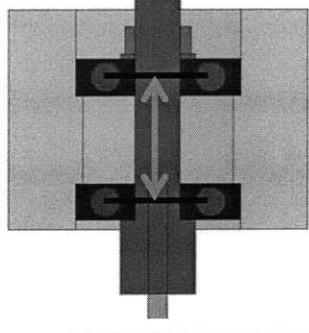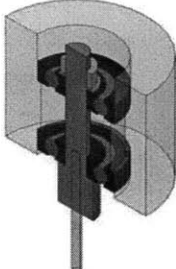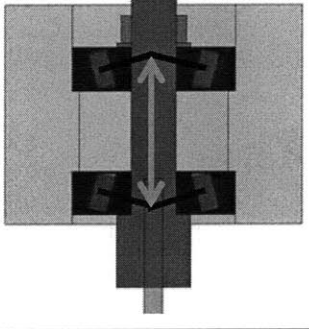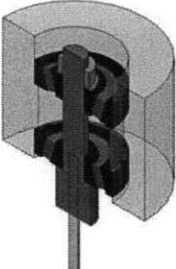
Moment Arm	Size	Cost	Preload Design		
-	+	+	+		
O	-	+	O		
+	-	-	O		

Figure 2-4: Spindle Bearing Configurations.

Green arrows mark the effective moment arms in each bearing configuration. Black lines mark bearing contact lines. Structural elements shown in yellow (Housing), Power transmission elements orange (Shaft & Chuck), Rolling contact surfaces blue (Bearing Races), Rolling contact elements pink (Rollers & Balls), Preload setting elements green (Disc Springs), Preload tuning elements turquoise (Nuts), End Mill red.
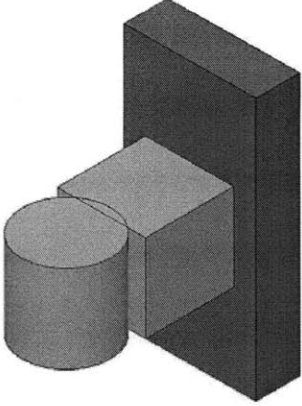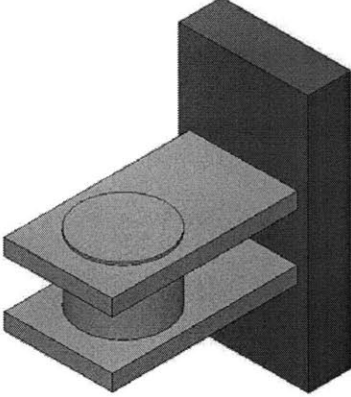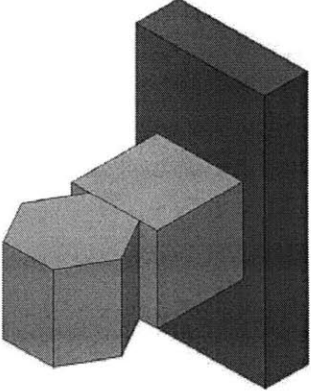
Modularity	Cost	Part Count	
+	+	+	
-	O	-	
+	-	+	

Figure 2-5: Spindle Stage Connector Configurations.

Structural Components (Spindle Housing, Spindle Stage Connector) marked in yellow, Bearing Block marked in orange.
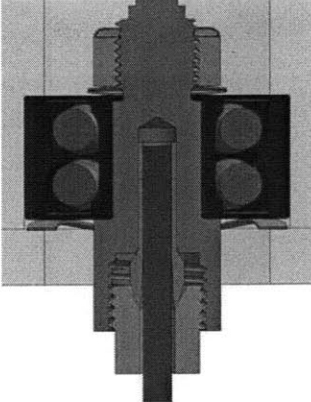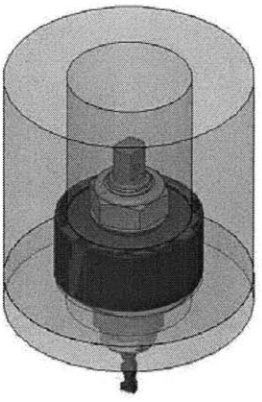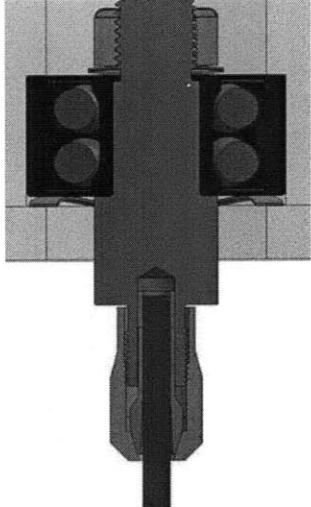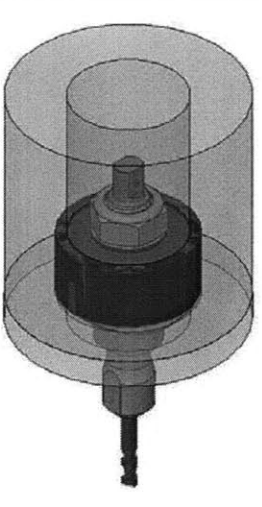
Stiffness	Size	Machining		
+	+	-		
-	-	O		

Figure 2-6: Spindle Chuck Configurations.

Structural Components marked in yellow (Housing & End Cap), Power Transmission Elements in orange (Shaft), Flexural Preload Elements in green (Disc Springs, Wave Washers, Collet), Preload Setting Elements in turquoise (Collet Preload & Lock Nut), Rolling Contact Surfaces blue (Bearing Races), and Rolling Contact Elements in pink (Bearing Balls).
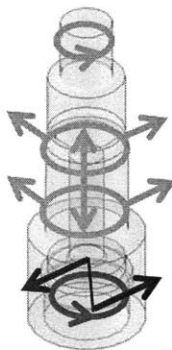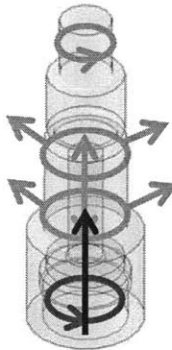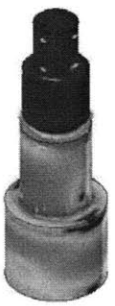
Spindle Shaft FEA – Cutting Force Couple & Torque							
	Max Cut XY (F=100N, T=0.1Nm)			Max Cut –Z (F=100N, T=0.1Nm)			
Forces, Moments & Fixtures	↻	Fixed Rot Z		↻	Fixed Rot Z		
	↔	Fixed Trans XY		↔	Fixed Trans XY		
	↕	Fixed Trans Z		↕	Fixed Trans Z		
	↙	500 N		↑	100 N		
	↻	0.1 Nm		↻	0.1 Nm		
Von Mises Stress [MPa]	Yield	220		Yield	220		
		83			19.5		
		62			14.5		
		42			9.5		
		20			4.8		
Factor Of Safety		75.5			77.5		
		51.5			55.5		
		27			33.5		
		2.66			11.5		

Figure 2-7: Spindle Shaft FEA.

Shaft material: 41L40 steel. Goal: Test for maximum spindle loading conditions: 100 N of cutting force for cuts in X, Y, and Z. Results: 83 MPa of maximum von Mises Stress in bending (Cuts in X & Y), and 19.5 MPa in compression (Cuts in Z), corresponding to factors of safety of 2.66 in bending and 11.5 in compression.
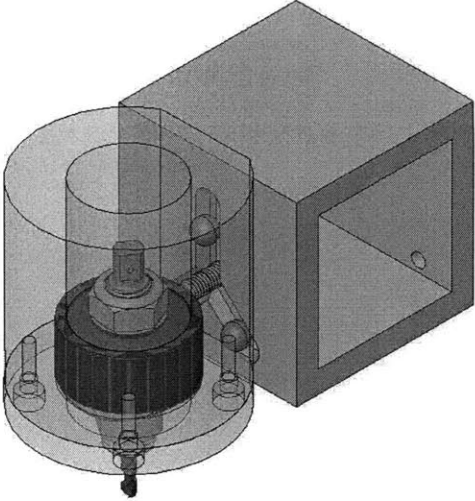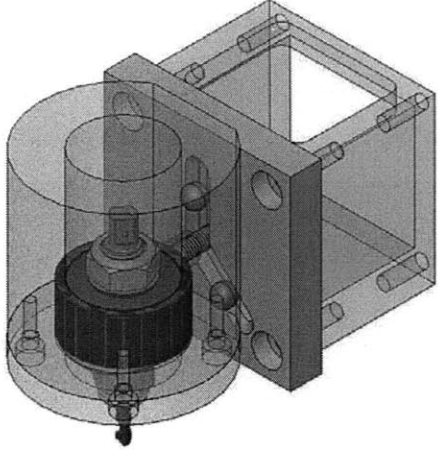
Part Count	Resonance	Stiffness	
+	O	O	
-	+	+	

Figure 2-8: Spindle Stage Connector Configurations.

Structural Components marked in yellow, Power Transmission Elements in orange (Spindle Shaft), Bearing in blue, Preload Elements in turquoise (Nuts, Chuck Preload, Kinematic Coupling Contact Faces, KC Preload Screw), Flexible Preload Elements & Balls in green, and End Mill in red.
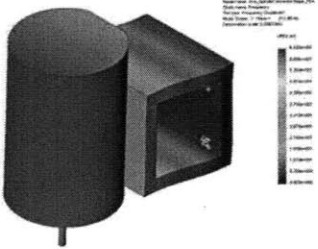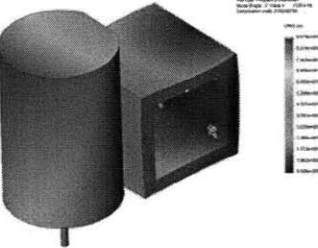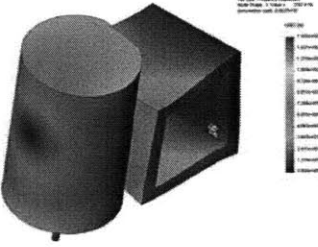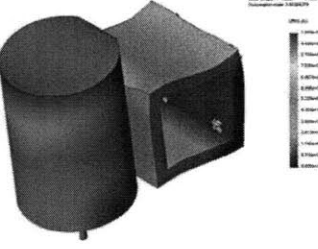
Spindle Connector FEA – Resonance –Housing modeled as Rigid Body			
Mode #	Modal Shape	Frequency [Hz]	Frequency [RPM]
1		812	48770
2		1328	79700
3		2768	166070
4		4107	246110

Figure 2-9: Spindle Stage Connector Frequency Analysis FEA.

First Mode at 48770 RPM.
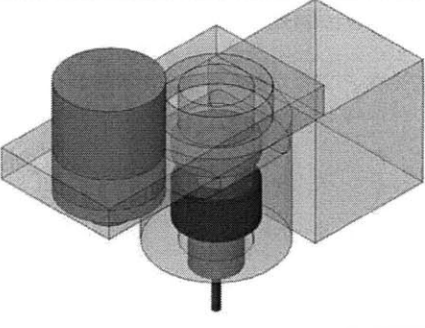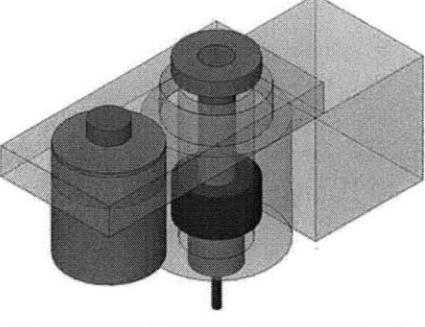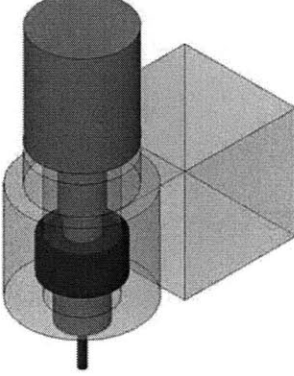
Machining	Transmission Ratio	Cost	Stiffness	
-	+	-	+	
O	+	-	-	
O	-	+	O	

Figure 2-10: Spindle Transmission Configurations.

Structural Elements marked in yellow (Housing, Motor Clamp, Spindle Stage Connector), Flexible Power Transmission green (Pulleys, Motor Coupling), Rigid Power Transmission Elements orange (Shaft, Chuck), Bearings blue, Motor turquoise, End Mill red.
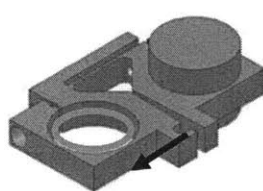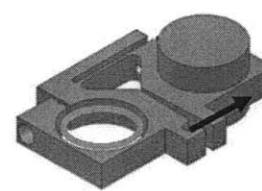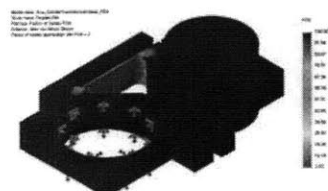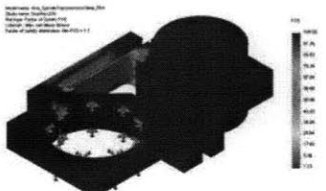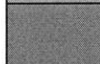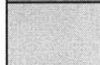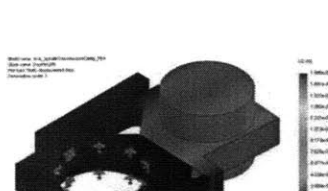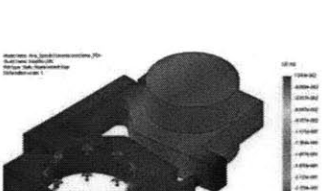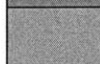
Spindle Transmission Clamp FEA – Range of Motion					
	Min. Flex Position			Max. Flex Position – Force 20N	
Forces & Fixtures	⬭	Fixed		⬭	Fixed	
	↙	20 N		↗	20 N	
Factor Of Safety		75.5			75.3	
		51			50.5	
		26.5			26	
		2.02			1.12	
Displacements [in]		0.185			0.015	
		0.138			-0.060	
		0.092			-0.136	
		0.045			-0.212	
		-0.002			-0.288	

Figure 2-11: Spindle Transmission Motor Clamp Range of Motion FEA.

Results: Overall change in belt length: 0.45 in; Factor of Safety about 2 and 1.1 at Extremes.
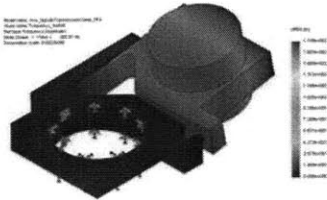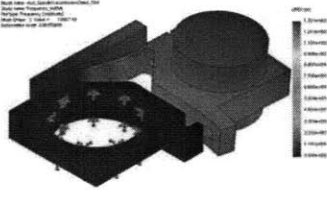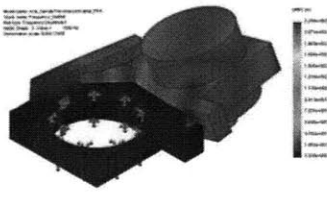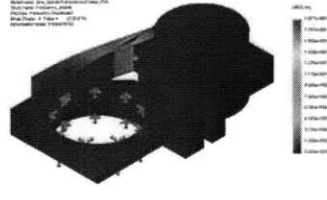
Spindle Transmission Clamp FEA – Resonance			
Mode #	**Modal Shape**	**Frequency [Hz]**	**Frequency [RPM]**
1		265	15930
2		1390	83380
3		1890	113400
4		3067	184030

Figure 2-12: Spindle Transmission Motor Clamp Frequency Analysis FEA.

First Mode at 15930 RPM.
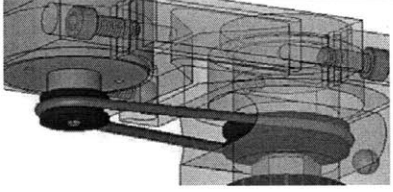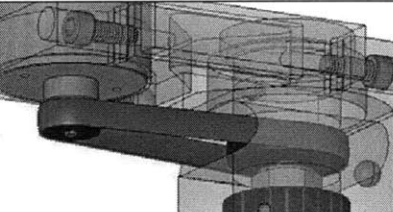
Efficiency	Holding Torque	
O	O	
+	+	

Figure 2-13: Spindle Pulley-Belt Configurations.
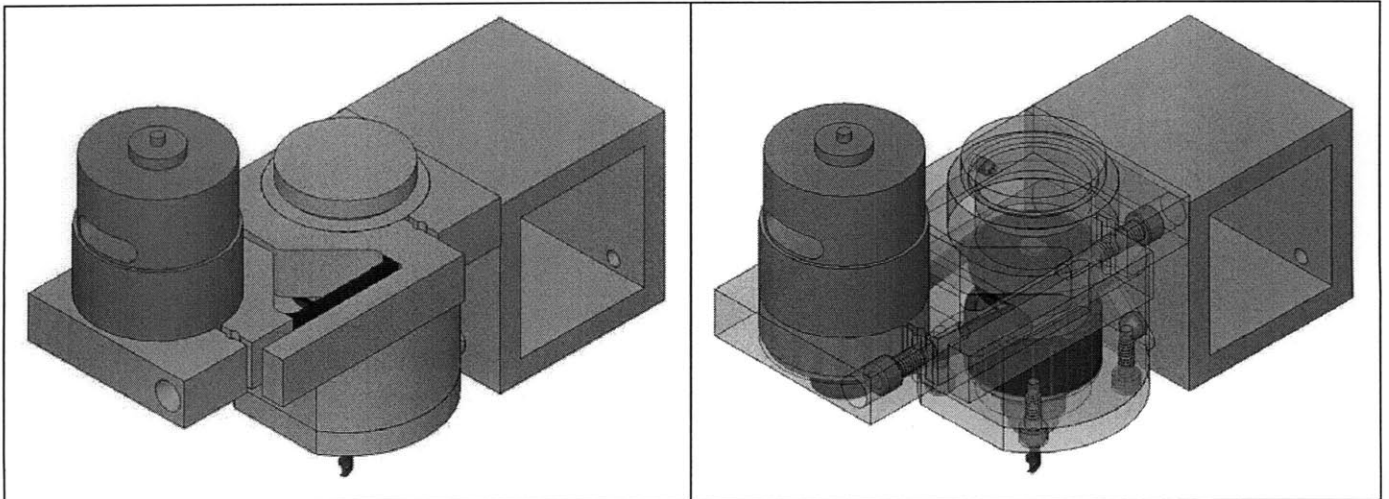
Figure 2-14: Spindle Assembly Solid Model.

Stage Design

This section presents the mechanical design of the motion stages. Figure 2-15 shows a picture of the latest motion stage model and a picture of the first motion stage prototype, including rail bushings and lead coupling.
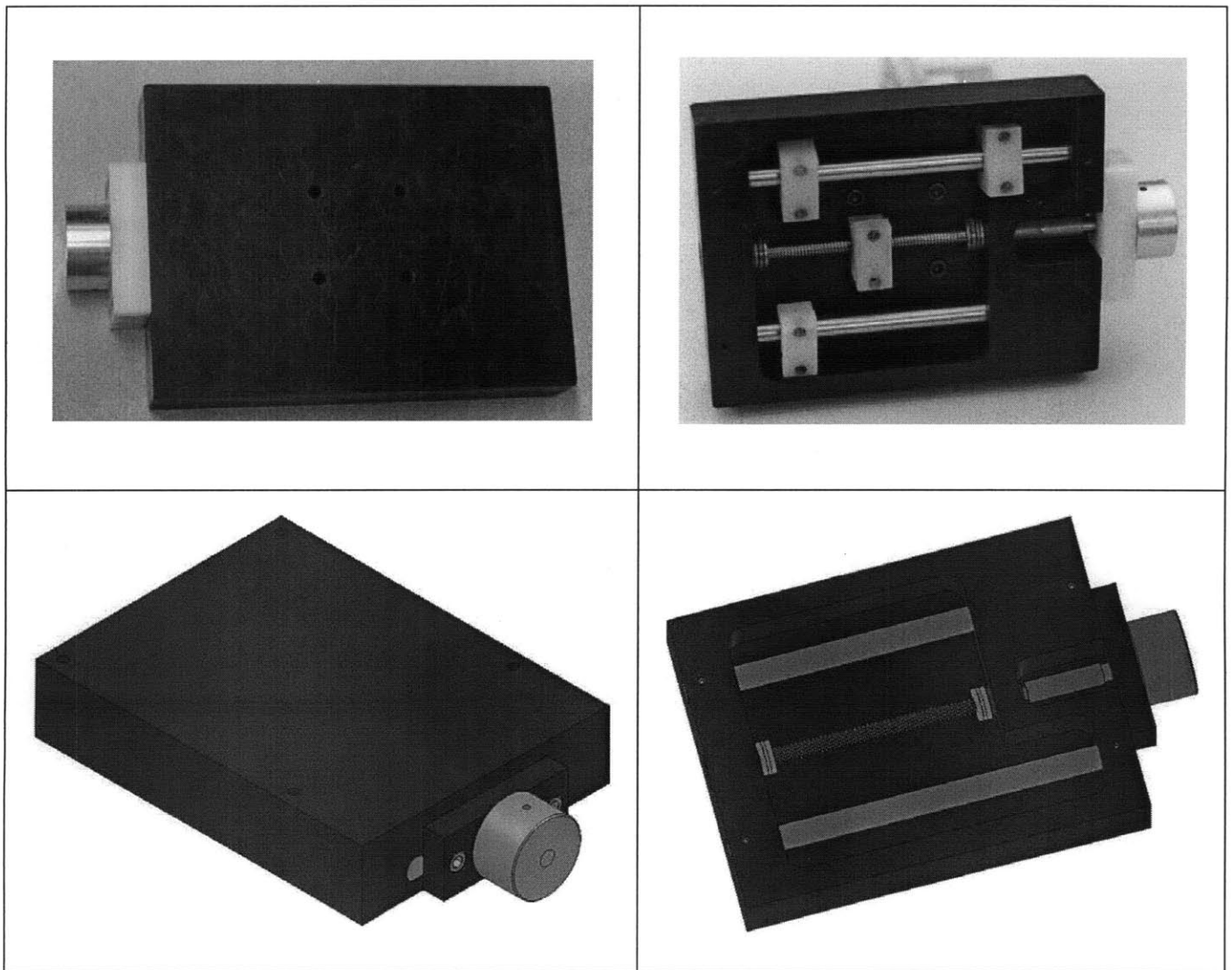
Figure 2-15: Stage Solid Model & Prototype.

Bushings on rails were selected as linear guides over a flexure-based design or commercial dove-tail guides. Flexure-based bearings either lack in range or in orthogonal stiffness or are much too large for the space constraints, as well as being fairly expensive to manufacture (Waterjet/ EDM). Commercial dove-tail guides provide high stiffness and are fairly easy to integrate but would take away from the students' learning experience since there would be no machining involved in the making of these guides. Bushing on rails, on the other hand, are neither limited in motion nor in size, as well as being fairly inexpensive and involves significant machining efforts (both in terms of quantity and quality) to make. Another advantage of rail/ bushing bearings is that it may be used in order to introduce students to the principles of exact constraint design (See Figure 2-16).

Linear actuation is achieved by a lead screw drive, rather than friction or capstan. Friction drive relies on the rolling contact interface between the drive roller and the motion stage. This requires either compliant rollers or precision machining. Furthermore, each roller would have to be preloaded to the contact surface in order to assure repeatable motion. Finally, the linear translation distance of the motion stage is inversely proportional to the square of the roller diameter. In other words, the smaller the roller diameter, the better the resolution of motion. Most commercially available rollers feature diameters of 1/2" or more, corresponding to a minimum transmission ratio of ~5/1000" per degree of wheel rotation. Assuming manual mode of operation, and a manual resolution of ~3 degrees of wheel rotation per step, at best, this corresponds to a linear resolution ~15/1000" per step, which is significantly larger than the design goal of 1/1000" per step. A similar case can be made for capstan drive. In order to assure repeatable motion, the cable must not slip, which requires appropriate tensioning. Based on the minimum bend radius of the smallest diameter commercially available steel cables (1/32"), the drive shaft diameter should not be less than 1/4", which corresponds to a linear resolution of ~5/1000"per step, still significantly higher than the design goal. A lead screw transmission, on the other can achieve much better linear resolution with less design effort. In order to achieve

repeatable motion, a lead screw transmission requires axial preload and an anti-backlash leadnut that is anchored to the surface with respect to which linear motion is to be achieved. In the case of the lead screw transmission, resolution of linear motion is determined by the pitch of the lead screw. In the case of current design, 1/4"-20 lead screw was selected, corresponding to 1/20" of travel per lead screw revolution, or, again assuming ~3 degrees of hand wheel rotation per step in the case of manual operation, a linear resolution of 0.5/1000" per step can be achieved, ~30X better than the best case scenario for the friction drive, and ~10X better than the best case scenario for the capstan drive. See Figure 2-17 for reference.

When considering stacking configurations for XY Stages, it is preferable to do so in such a way that each stage is nearly identical to another, thereby significantly reducing the number of unique parts, as well as the overall design complexity. Another consideration for selecting stage stacking orders concerns chip handling: It's preferable that the stages are configured in such a way that chips cannot easily accumulate in sharp corners or pockets, as well as being fairly easy to clean afterwards (See Figure 2-18).

The stage block forms the structural backbone of each motion stage and can either be machined from one piece or assembled from several pieces. Machining the stage block from one piece simplifies machining & assembly steps. Drawbacks are extremely tight machining tolerances, to minimize motion errors, as well as stiffness and material cost concerns. For example, if one chose to machine each stage block from a 1.25" thick ABS plate, its relatively thin center-section would be much weaker than if only the "thick" parts were to be machined from ABS, and the "thin" cover plates were to be machined from aluminum. It is important to keep this in mind when seeking to optimize the machine for stiffness. For reference see Figure 2-19.

Perfect constraint design demands careful bushing design: Three points define a plane. So in order to perfectly constrain a stage block mounted on two rails, no more than three bushing should be

used (Each bushing acting as an effective point constraint). Two bushings take away four degrees of freedom (2 translations & 2 rotations), the third bushing takes away the final rotation, only leaving one translation (in the feed direction). Ideally, this third bushing is infinitely stiff in the direction that is tangential to the arc that the stage rotation describes but has zero stiffness in all other directions. The final degree of freedom (in the feed driection) is then taken up by the lead screw coupling which ideally is infinitely stiff along the axial direction but has zero stiffness in all other directions. Obviously, neither zero, nor infinite stiffnesses are practically feasible, but it is possible to design flexures that are orders of magnitudes stiffer in one direction than in another. In accordance with this line of reasoning, two of the rail bushings are plain bushing blocks without any flexure features. The third bushing block and the lead coupling, on the other hand, feature flexures in order to achieve a "quasi-kinematic" overall stage design. For reference, see Figures 2-20 through 2-24.

The Hand Wheel Mounts and Stepper Motor Mounts are designed such that they can be interchanged simply by unscrewing two screws, and removing the shaft from the lead coupling. This allows for students to easily transform their manual miniature milling machine into a CNC miniature milling machine (See Figures 2-25 through 2-29).
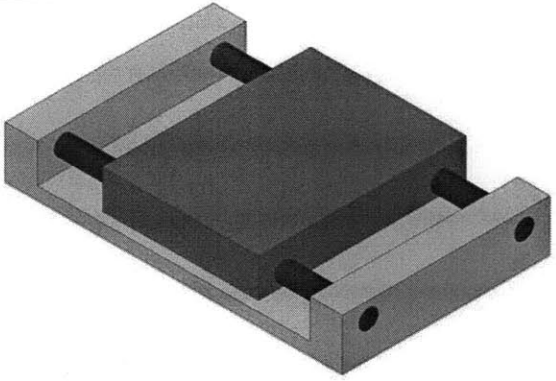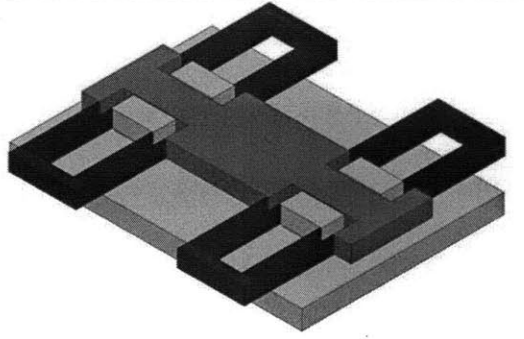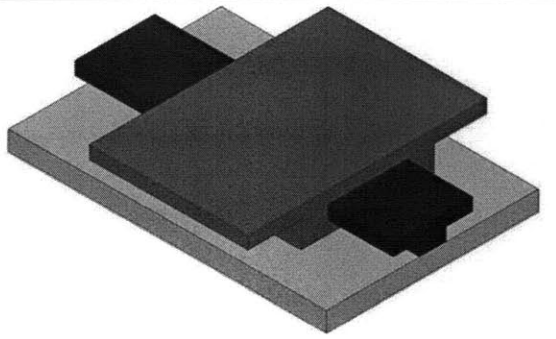
Range of Motion	Accuracy	Cost	
+	O	+	
-	+	-	
+	O	-	

Figure 2-16: Stage Linear Bearing Configurations.

Structural Elements marked in yellow, Stationary Bearing elements in blue (Rails, Flexures), and mobile bearing elements in pink.
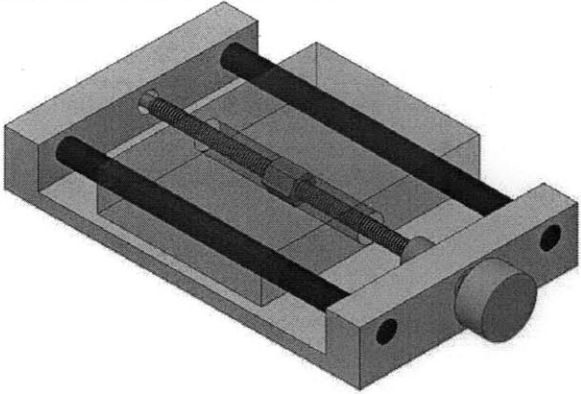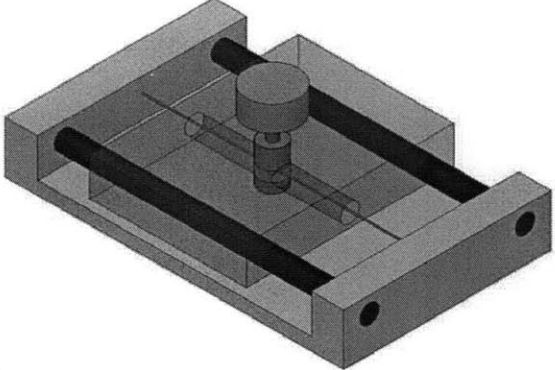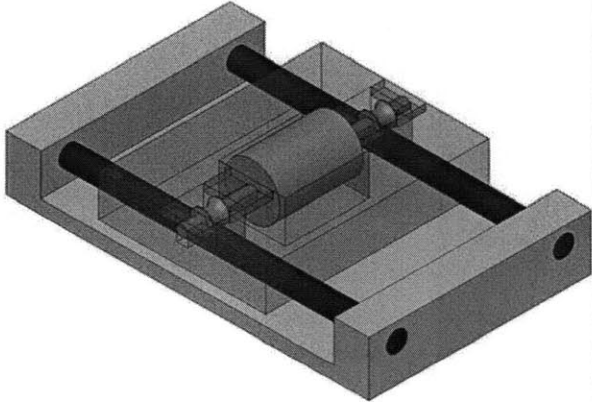
Transmission Ratio	Stiffness/ Backlash	Design Complexity	Cost/ Machining	
+	-	+	O	
-	+	-	O	
-	+	-	-	

Figure 2-17: Stage Transmission Configurations.

Structural Elements marked yellow, Fixed Bearing Elements blue, mobile Bearing Elements pink (transparent), Transmission Elements orange (Shafts, Lead Screw, Capstan Wire), Coupling Elements green (Lead Nut, Cable Pulley, Friction Rollers), Actuation Elements turquoise (Hand Wheels).
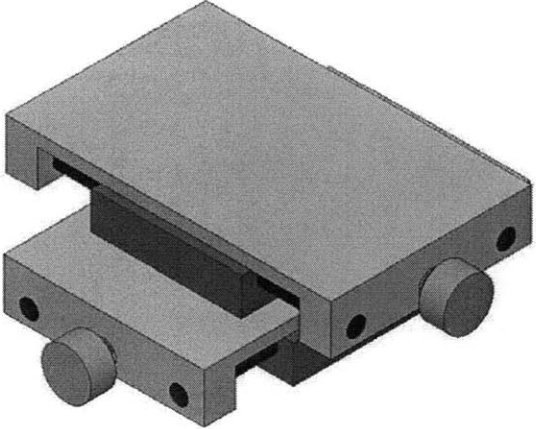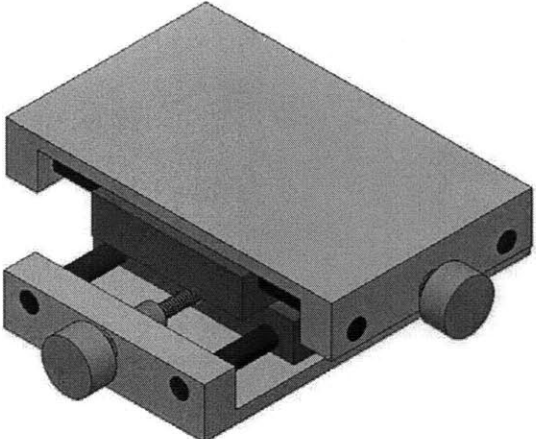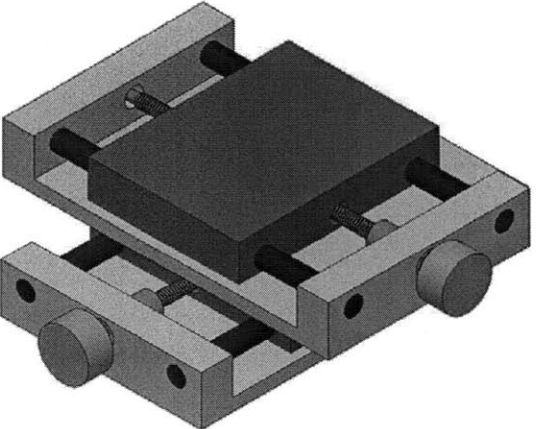
Protective Cover	Part Count	
+	O	
O	O	
-	-	

Figure 2-18: Stage Stacking Configurations.

Structural Elements marked in yellow, Fixed Bearing Elements blue, Mobile Bearing Elements pink,

Rigid Transmission Elements orange, Flexible Transmission Elements green, and Actuation Elements

turquoise.
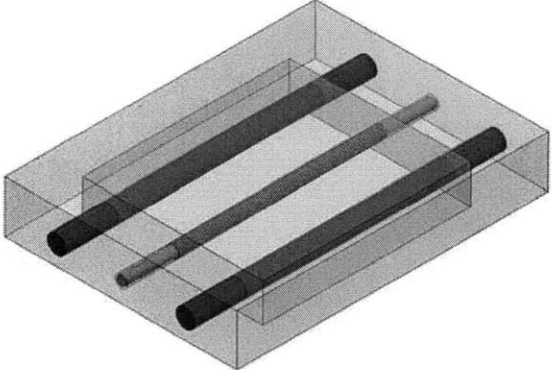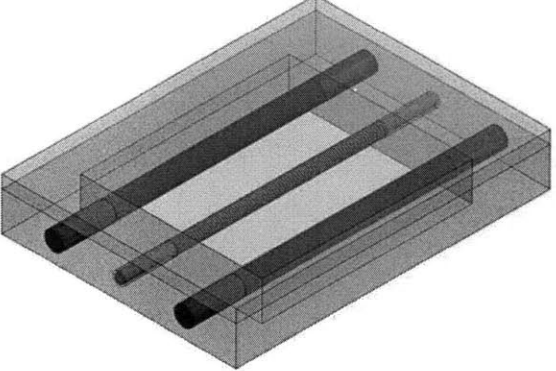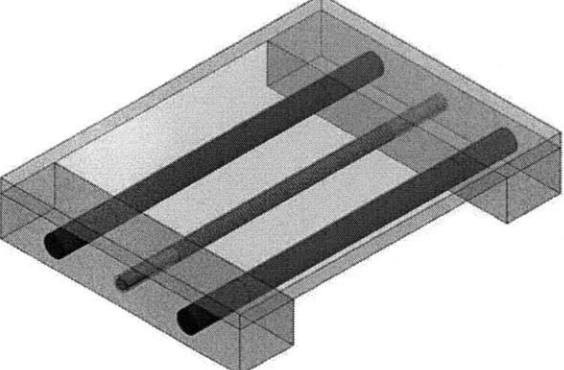
Stiffness	Part Count	Cost	
-	+	O	
+	O	-	
O	-	+	

Figure 2-19: Stage Block Configurations.

Top Stage Block Parts marked in yellow, Bottom Stage Block Parts green, Rails blue, and Lead Screws orange. To keep costs low, Stage Block Parts that interface with Rails/ Lead Screw are chosen to be plastic (ABS). In configurations 2 & 3, Top Stage Block Parts are chosen to be Aluminum for improved Frame Stiffness.
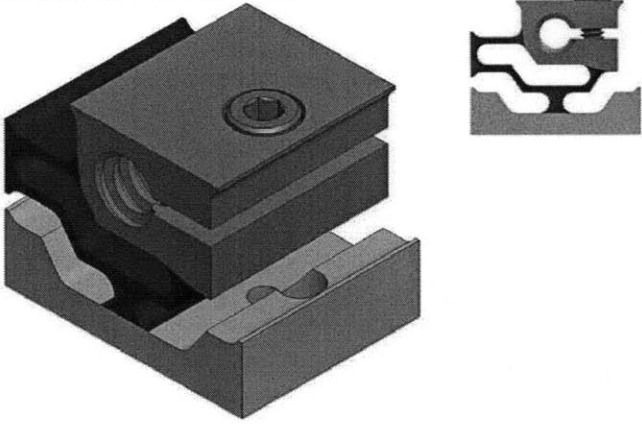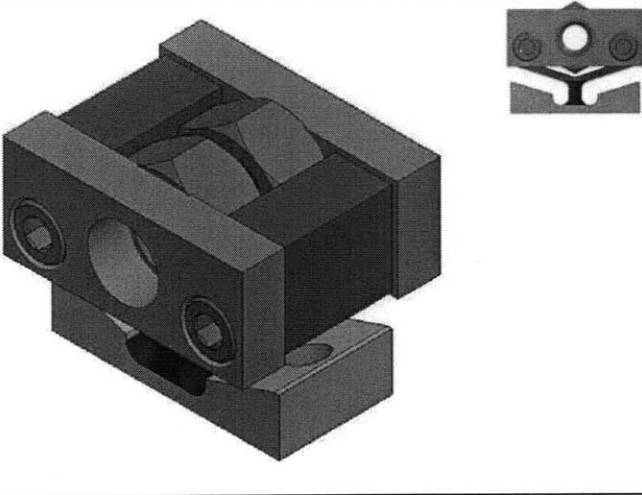
Vertical Stiffness	Lateral Stiffness	Part Count	
O	O	+	
+	O	-	

Figure 2-20: Stage Lead Flexure Configurations.

Mounts are marked in yellow, Flexural Elements in blue, Coupling Elements green, Preload Elements turquoise, Nut Frames pink, and Screws in orange. In Configuration 2, there is a wave spring washer clamped between both nuts to minimize Backlash.
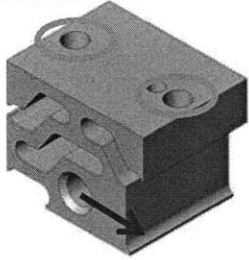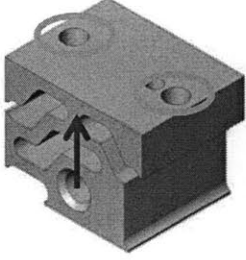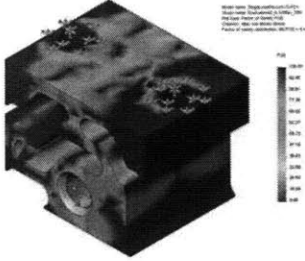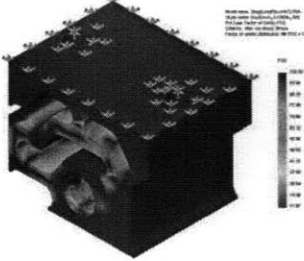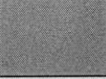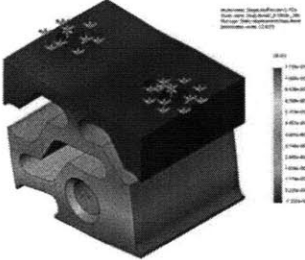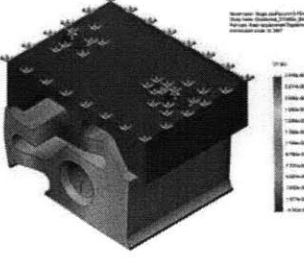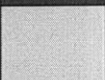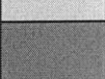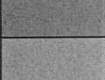
Lead Flexure FEA – Range of Motion					
	Max. Flex Position – Force 30N			Max. Flex Position – Force 30N		

Forces & Fixtures	◯	Fixed		◯	Fixed	
	↘	30 N		↑	30 N	

Factor Of Safety		77.5			78	
		55			56	
		32			34	
		9.45			12	

Displacements in direction of applied Force [in]		0.008			0.0025	
		0.006			0.0018	
		0.004			0.0012	
		0.002			0.0006	
		0.000			0.0000	

Figure 2-21: Stage Lead Flexure Range of Motion FEA.

Goal: Attain estimate for lateral & normal displacements of Coupling Cylinder at applied loading conditions of 30 N in each respective direction. Results: 6/1000 of lateral displacement & 2/1000 of normal displacement.
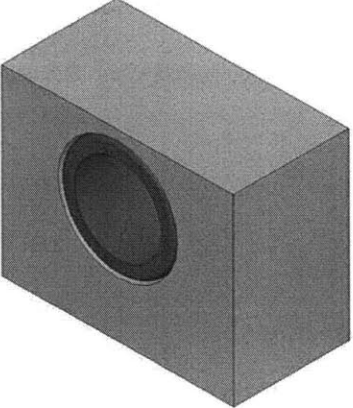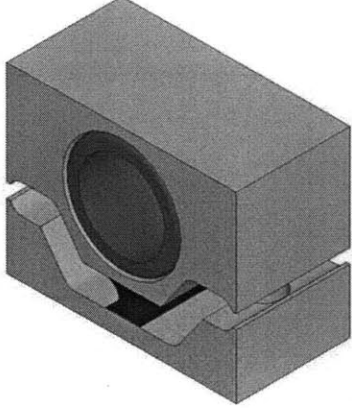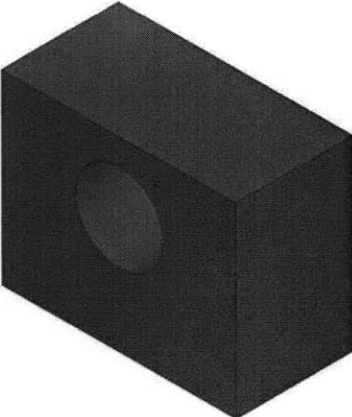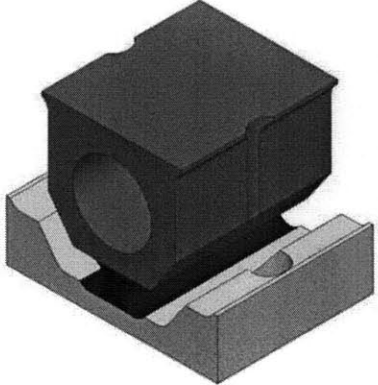
Stiffness	Part Count/ Assembly		
+	-		
O	+		

Figure 2-22: Stage Rail Bushing Configurations.

Structural Components marked in yellow, Bushing Elements pink, and Flexural Elements blue.
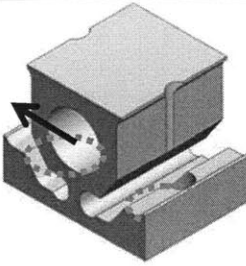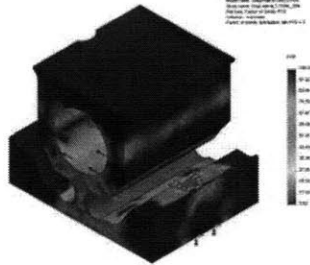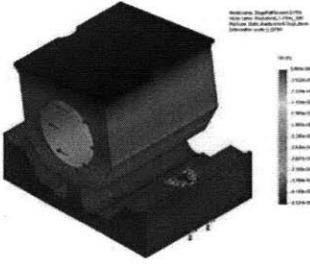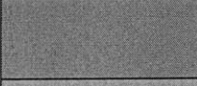
Rail Flexure FEA – Range of Motion			
	Max. Flex Position – Force 30N		
Forces & Fixtures	⬯	Fixed	
	↖	30 N	
Factor Of Safety		76	
		51.5	
		27	
		3.02	
Displacements Lateral [in]		0.000	
		0.011	
		0.022	
		0.034	
		0.045	

Figure 2-23: Stage Rail Bushing Flexure Range of Motion FEA.

Goal: Estimate Lateral Displacement of Bushing Cylinder at applied lateral loading condition of 30 N.

Results: 22/1000 in of lateral displacement at 30 N loading.
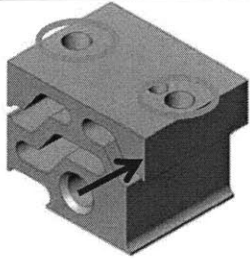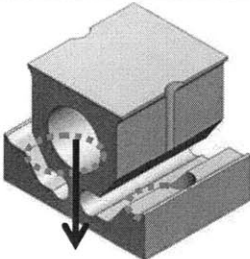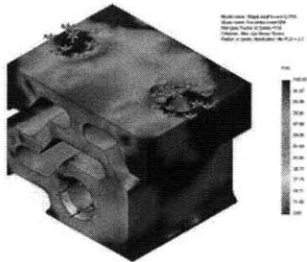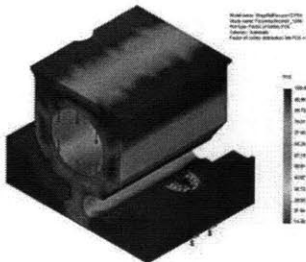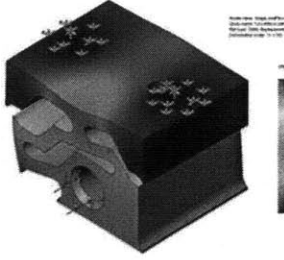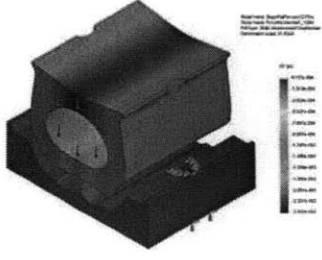
Lead & Rail Flexure FEA – Max. Force						
	Lead Flexure Max. Force Axial			Rail Flexure Max. Force Normal		
Forces & Fixtures	⬯	Fixed		⬯	Fixed	
	↗	100 N		↓	100 N	
Factor Of Safety		76			78.5	
		52			57	
		27.5			35.5	
		3.65			14.3	
Displacements Direction of applied Force [in]		0.0095			0.0000	
		0.0071			-0.0006	
		0.0048			-0.0012	
		0.0024			-0.0018	
		0.0000			-0.0024	

Figure 2-24: Stage Lead Flexure & Rail Bushing Flexure Max. Load FEA.

Goal: Estimate Axial Displacement of Lead Flexure Cylinder and Normal Displacement of Rail Flexure Cylinder at maximum cutting loads of 100 N respectively. Results: 8/1000 in Axial Displacement of Lead Coupling Cylinder, <1/1000 in displacement of Rail Flexure Cylinder.
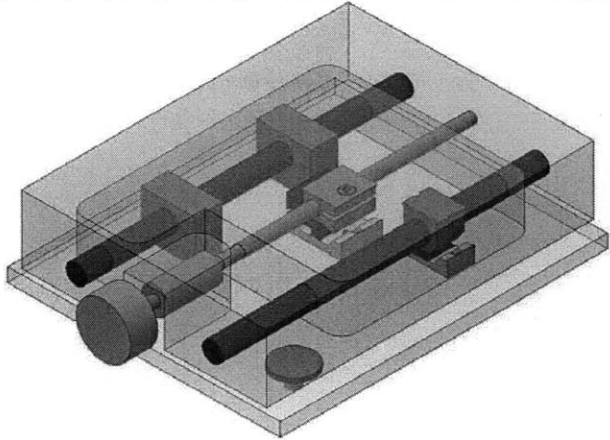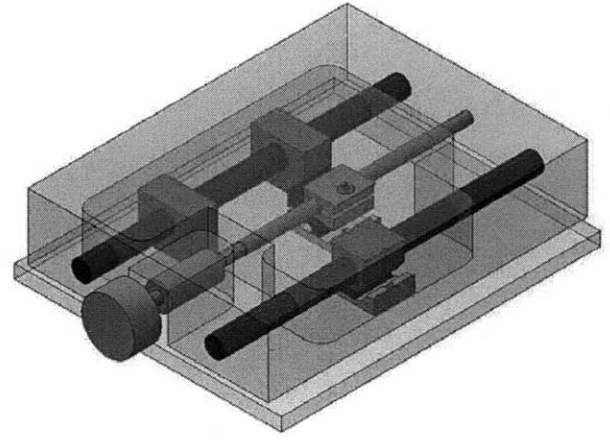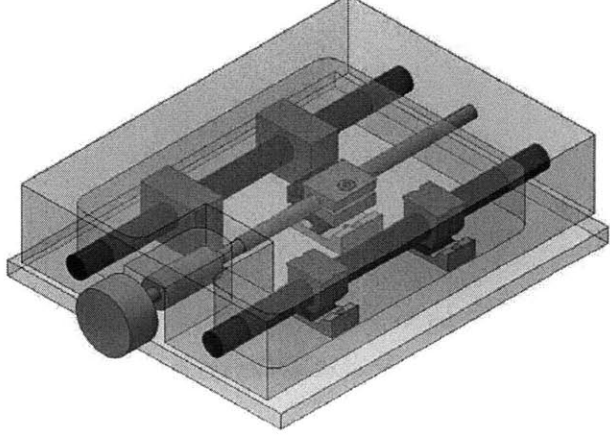
Stiffness	Perfect Constraint	Part Count	
O	O	O	
-	+	+	
+	-	-	

Figure 2-25: Stage Rail Bushing Flexure Configurations.

Structural Elements marked in yellow, Fixed Bearing Type Elements pink, Mobile Bearing Type Elements blue (Rails, Flexures), Flexible Power Transmission Elements green (Couplings), Rigid Power Transmission Elements orange (Lead Screws, Shafts), and Actuation Type Elements turquoise (Hand Wheels).

Stiffness	Cost/ Part Count/ Machining	Alignment Tolerances	
O	**+**	**+**	
+	**O**	**-**	
+	**-**	**-**	

Figure 2-26: Stage Lead Coupling Selection.

Configuration 1 is a HDPE Tube segment that is used as a shaft coupling, Configurations 2 & 3 are made from Aluminum.
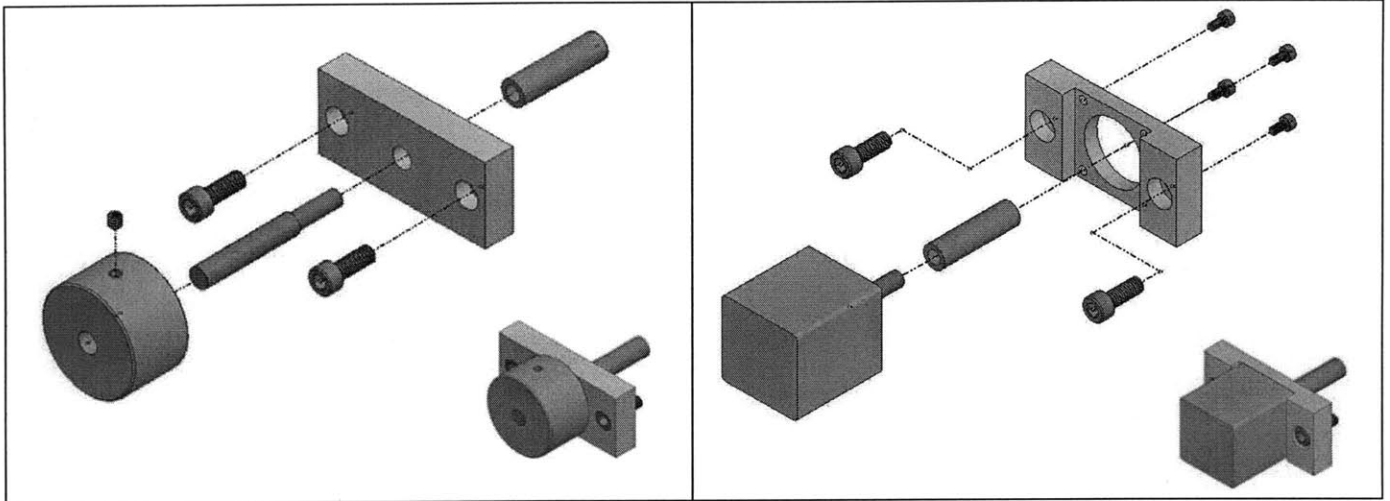
Figure 2-27: Stage Actuation Assemblies.

Configuration 1 shows Hand Wheel Mount Assembly, Configuration 2 shows Stepper Motor Mount Assembly.
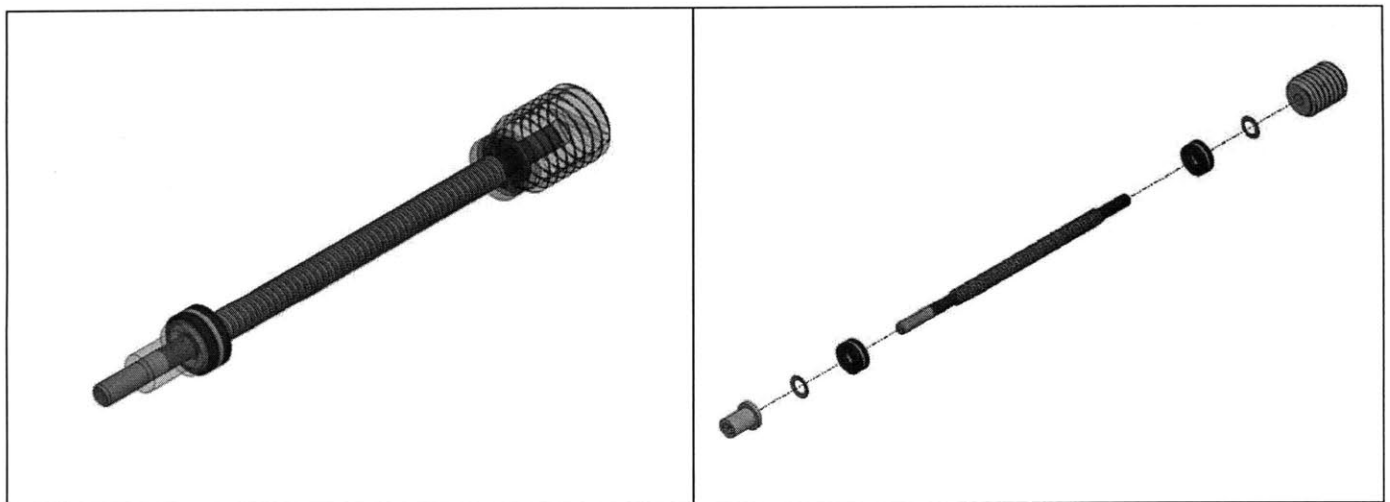
Figure 2-28: Stage Lead Screw Assembly.

BOM: Flanged Bronze Bushing, 2 Spring Washers, 2 Thrust Bearings, Lead Screw, Threaded Brass Preload Bushing.
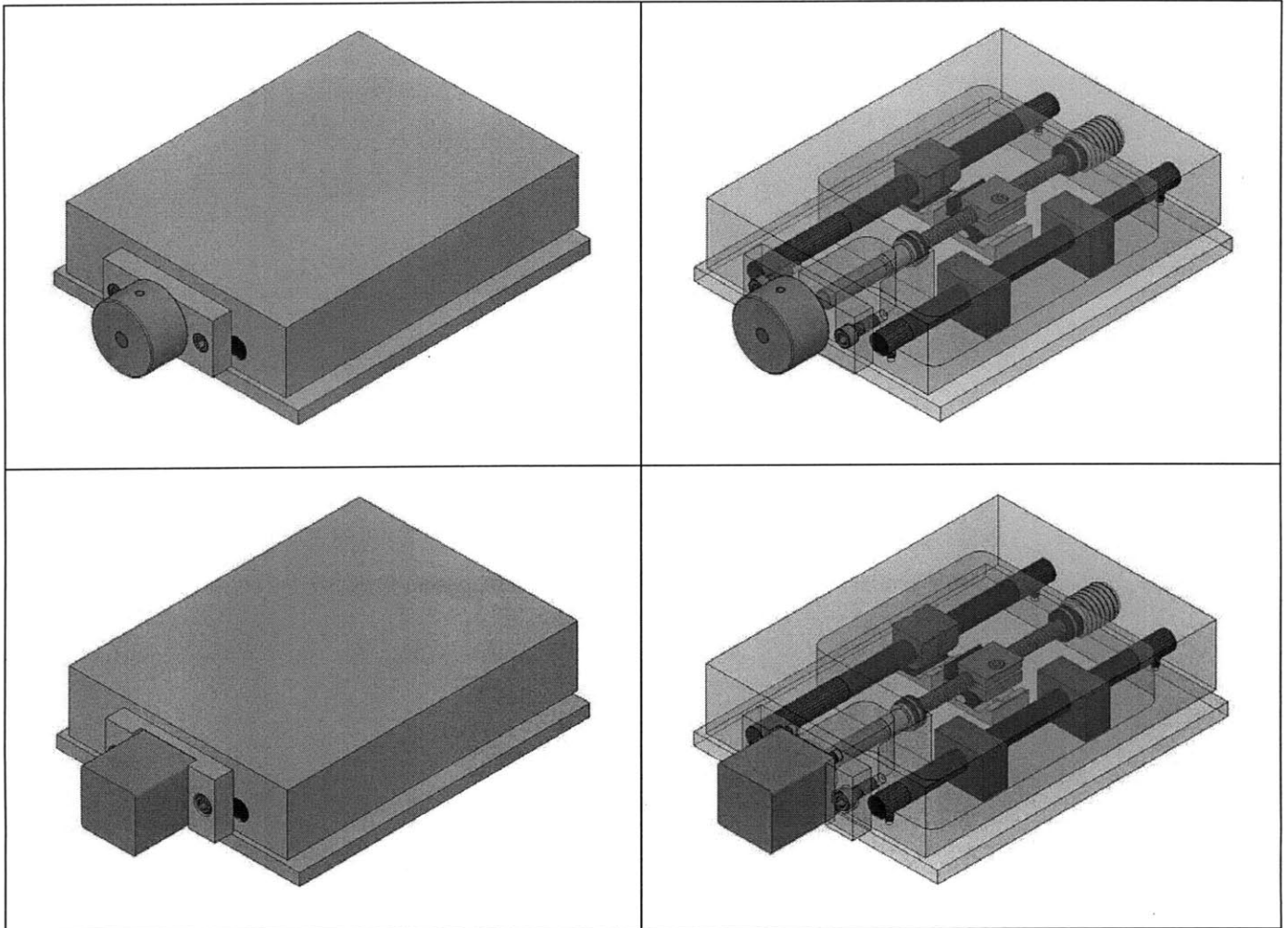
Figure 2-29: Stage Assembly Solid Models.

Structural Elements marked in yellow, Fixed Bearing Type Elements pink, Mobile Bearing Type Elements blue (Rails, Flexures, Thrust Bearing Discs), Flexible Power Transmission Elements green (Couplings, Spring Washers), Rigid Power Transmission Elements & Screws orange (Lead Screws, Shafts, other Screws), Actuation Type & Preload Elements turquoise (Hand Wheels, Stepper Motors, Flanged Bushing, Preload Bushing).

2.4 Frame Design, Vice Design, & Machine Integration

Functional Requirements for the Machine Frame:

1.) Rigid connection between three motion stages and spindle

2.) Lightweight, cost-effective, minimalist design

3.) Simplify & minimize Manufacturing Operations

Assembly in Figure 2-30 shows how three motion stages and frame interface to form the Base of the Miniature Desktop Milling Machine.
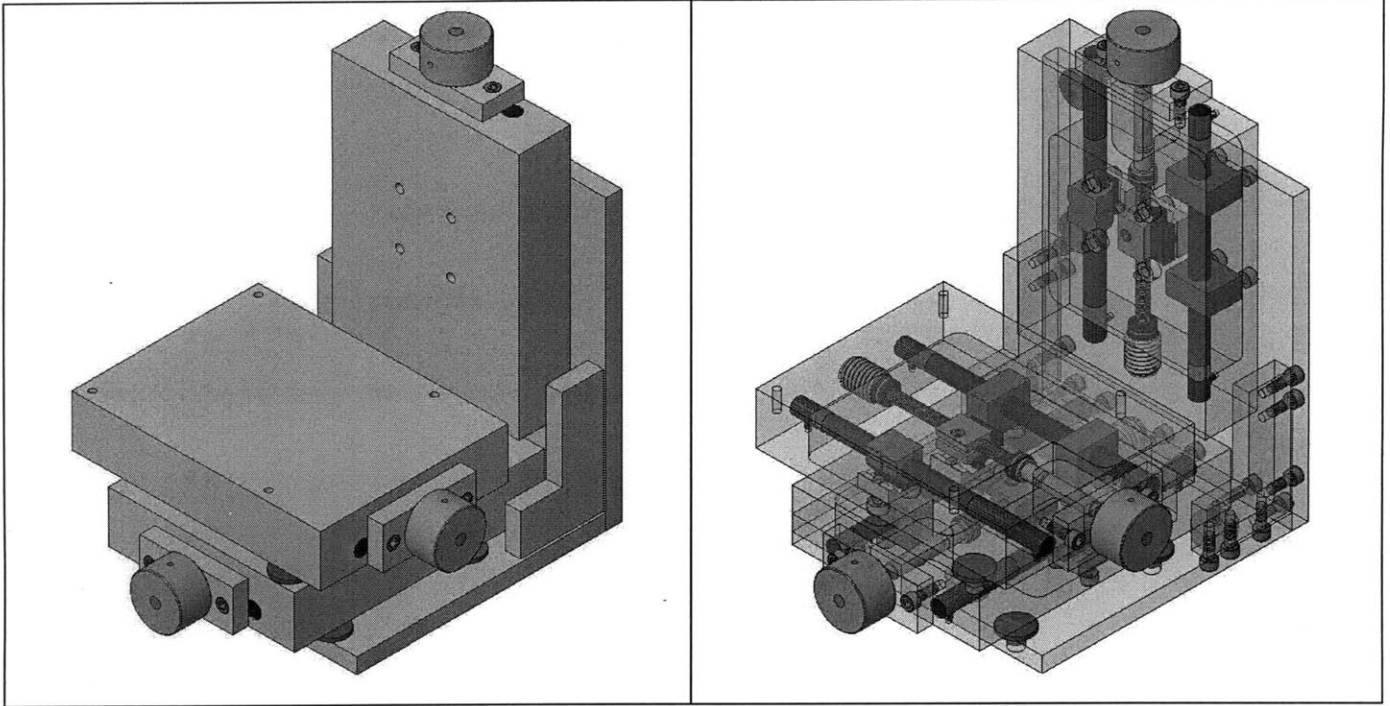
Figure 2-30: Frame & Stages Assembly Solid Model.

Color coding schemes carried over from previous models.

Functional Requirements for Vice:

    1.) Range of Motion: ~2in

    2.) Height: ~0.5in

    3.) Lightweight, cost-effective, minimalist design

    4.) Simplify & minimize Manufacturing Operations

Figure 2-31 shows how vice and spindle assemblies integrate into the base machine assembly shown in Figure 2-30, resulting in the final version of the desktop mill machine design as shown in Figure 1-1.
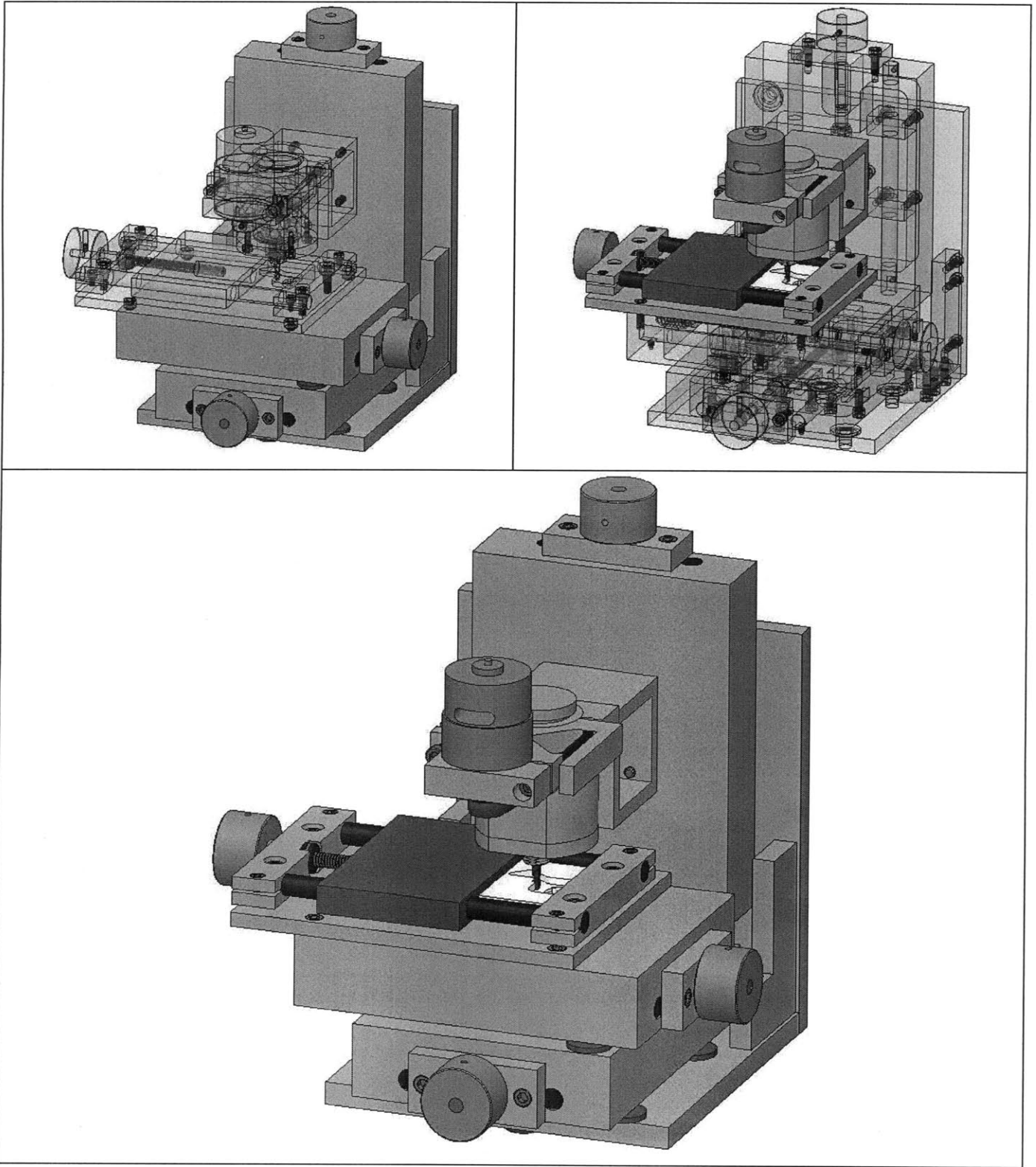
Figure 2-31: Mill Assembly Solid Model. Same Color Coding as used for previous Figures.

3 Conclusions

This research focused on the mechanical design of a 3-Axis miniature desktop milling machine that may be utilized as a machining project for an introductory manufacturing course such as 2.670 at MIT.

An axiomatic approach was taken and practiced throughout the design process in an effort to develop an uncoupled machine design with little information content beyond what is absolutely required by the initially proposed functional requirements.

Table 3-1 replicates the first two columns of the initial Design Requirements table (Table 1-1), replacing the third, design parameters column, with corresponding performance estimates of the actual machine. Some of the numbers shown in the third column of this table are not covered within the scope of this thesis. For detailed analysis concerning these numbers, please visit the following website:

http://web.mit.edu/bubby/www/Sub/2ThU.html

Table 3-1: Miniature Desktop Mill Functional Requirements and Machine Specifications

Type	Functional Requirements	Machine Specifications
Machine Type	3-Axis	3-Axis
Working Materials	Aluminums, Plastics	Aluminums, Plastics
Machine Size [in^3]	< 10 x 10 x 10	8 x 10 x 10
Budget per machine [$]	< 150	225 (McMaster Carr)
Overall Machining Time [hr]	< 20	< 25
Cutting Volume [in^3]	> 2 x 2 x 2	2 x 2 x 2
Tool Sizes - Diameter [in]	1/16 - 1/8	1/16 – 1/8
Resolution [in]	< 0.001	0.0005 (manually), 0.0003 (stepper)
Cutting Accuracy [in]	< 0.001	n.a.

Future Work:

Considerable work remains to be done with points 3 thru 7 (See section 1.3), calling for future undergraduate senior thesis or UROP work. The ultimate goal for this project (first paragraph of chapter 1) is the adoption of the herein proposed design (or a derivative thereof) as the main project of an introductory manufacturing course such as 2.670 at MIT.

REFERENCES

[1] MIT 2.670 Home Page. http://web.mit.edu/2.670/www/

[2] Basic Machining Tools. Dartmouth Machine Shop. http://engineering.dartmouth.edu/mshop/facilities/index.shtml

[3] Principal Machining Processes. Wikipedia. http://en.wikipedia.org/wiki/Machining

[4] Introductory Manufacturing Class Syllabus. UCSB Web Site. http://engineering.ucsb.edu/~mshop/Syllabus_S10.pdf

[5] Professor M. Culpepper. MIT Mechanical Engineering Faculty. http://meche.mit.edu/people/faculty/index.html?id=21

[6] Desktop Mill Project Overview. Project Web Site. http://web.mit.edu/bubby/www/Sub/2ThU.html

[7] N.P. Suh. "Axiomatic Design of Mechanical Systems." ASME J. Vib. Acoust., Vol. 117, n°B, pp. 2, 1995

APPENDIX

For additional Information on the desktop mill design project, please refer to the following links:

General Information:

http://web.mit.edu/bubby/www/Sub/2ThU.html

Detailed Part-/ and Assembly-Drawings:

http://web.mit.edu/bubby/Public/2.ThU/Manufacturing/Drawings/MasterDrwg_Mill.pdf

Bill of Materials & Budget:

http://web.mit.edu/bubby/Public/2.ThU/Budget/Budget%20Analysis.xls

Machining Time Calculations:

http://web.mit.edu/bubby/Public/2.ThU/BOM/MachiningTime%20Analysis.xls

Cutting Force Analysis:

http://web.mit.edu/bubby/Public/2.ThU/Analysis/Spreadsheets/Cutting%20Analysis.xls

FEA Analysis:

http://web.mit.edu/bubby/Public/2.ThU/Analysis/FEA/