By

James Andrew Mikes

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The Analysis and Development of a Mechanical Breadboard Structure

by

James Andrew Mikes, B.S.

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The Analysis and Development of a Mechanical Breadboard Structure

APPROVED BY SUPERVISING COMMITTEE:

Kristin L. Wood, Supervisor

Carolyn C. Seepersad

The Analysis and Development
of a Mechanical Breadboard Structure

by

James Andrew Mikes, M.S.E.
The University of Texas at Austin, 2006
SUPERVISOR: Kristin L. Wood

This thesis introduces the mechanical breadboard as a learning / development tool and details the creation of one concept. It begins with a review of the state of the art for mechanical breadboards to include commercial and academic developments and products. It defines what a mechanical breadboard is for this research, what the customer needs are, and what critical functions the breadboard should be able to prototype. Following this analysis, a development team created a new novel structural system for a mechanical breadboard as the research indicated these components were both important to the overall system and had a great opportunity for innovation and improvement. The solution developed is based on node and frame member structural system that allows multiple degrees of freedom in the structural layout. The node is the key component of the structural system and utilizes a three section design to give multiple degrees of freedom and attachment points.

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Chapter 1: Mechanical Breadboard Introduction

The phrase "Mechanical Breadboard" has many different meanings to many different people. Mentioning "mechanical breadboard" to most people will draw more questions than answers, and even among mechanical engineers, most do not have a concrete visualization of what it is or could be. This fact alone highlights how little understood and rarely used mechanical breadboards are in the field of mechanical engineering. The best analogy developed at this point is an electrical breadboard, though not as much for its physical makeup as for the purposes it serves for engineers. This electrical breadboard like its mechanical counterpart serves two primary purposes: to demonstrate engineering phenomena of the field and to allow engineers to prototype various concepts. Mechanical breadboards cover a vast array of potential systems and devices. Their costs vary from under twenty dollars to several thousand dollars and even possibly higher. While a few mechanical breadboards exist in the commercial sector and academia has written several papers on the topic and considering how important hands-on learning is to the development of well rounded engineers, both industry and academia have given comparatively little thought to developing effective mechanical breadboards.

Unlike the engineers of previous generations who typically had at least moderate experience repairing and operation machinery, today's young adults often have very limited if any hands-on experience with machines or even basic hand tools. This lack of basic experience means that giving today's students more emphasis on applied learning is more crucial than ever. Likewise in industry today, many firms have shifted from building physical models first to designs that come completely from the Computer Aided Design (CAD) world. While CAD is a very powerful tool, it is an expensive and sometimes difficult to manipulate tool. Especially in the early stages of a development program, the ability to quickly assemble a concept into a physical system for concept evaluation is a valuable tool. The best solution to an ill defined problem is not the first thought arrived at, but rather the best solution more often results from blending several good initial ideas, which an ability to quickly prototype several concepts gives. For these needs from the commercial and academic areas, engineers must develop better mechanical breadboards in order to improve learning and make more robust products.

1.1 Mechanical Breadboard Definition

It may be easier to define what a mechanical breadboard is not rather than what it is. First, it is not an electrical solderless breadboard or some electro-mechanical variation of this device; though that is what most engineers first think of when the phrase “mechanical breadboard” is put to them. The purpose of the mechanical breadboard is not to prototype electric circuits. Still, the electrical breadboard is an excellent analogy for a mechanical breadboard. Consider that the primary uses of an electrical breadboard are twofold: first, it is used to quickly prototype an electric circuit before going to more expensive and compact layouts, and second it is useful in an academic sense to demonstrate for students fundamental electrical phenomena such as impedance, resistance, inductance, serial and parallel circuits, etc. It is in this sense that a mechanical breadboard and electrical breadboard are analogies; they serve the same two primary purposes for two different engineering fields. So from this analogy, the mechanical breadboard two main purposes are:

1. To allow quick prototyping of a potential mechanical system prior to development of more expensive and complex prototypes.
2. To demonstrate for students fundamental mechanical engineering phenomena such stress, deflection, forces, interaction of machine element systems, etc.

1.2 Mechanical Breadboard Analogies

This section discusses common analogies used for a mechanical breadboard. It defines each analogy and lists pros and cons for each analogy. These analogies provide a reference point for the basis of a mechanical breadboard as well as giving some excellent ideas for how to structure it. In addition, mechanical breadboards share some user needs with these analogies, and the analogies give examples of how to meet these needs.

1.2.1 Electrical Breadboard

As mentioned above, an electrical breadboard is the most common analogy people refer to when presented with the idea of a mechanical breadboard. While the definition above stresses the commonality of two breadboards in how they are used in each engineering field, most people tend to focus on the physical makeup and structure commonality which can be misleading. This is not say there are possible parallels for the mechanical breadboard from the electrical from the physical construction, but the mechanical breadboard will not look exactly like an electrical breadboard.

Figure 1 shows a typical electrical breadboard with some components installed.

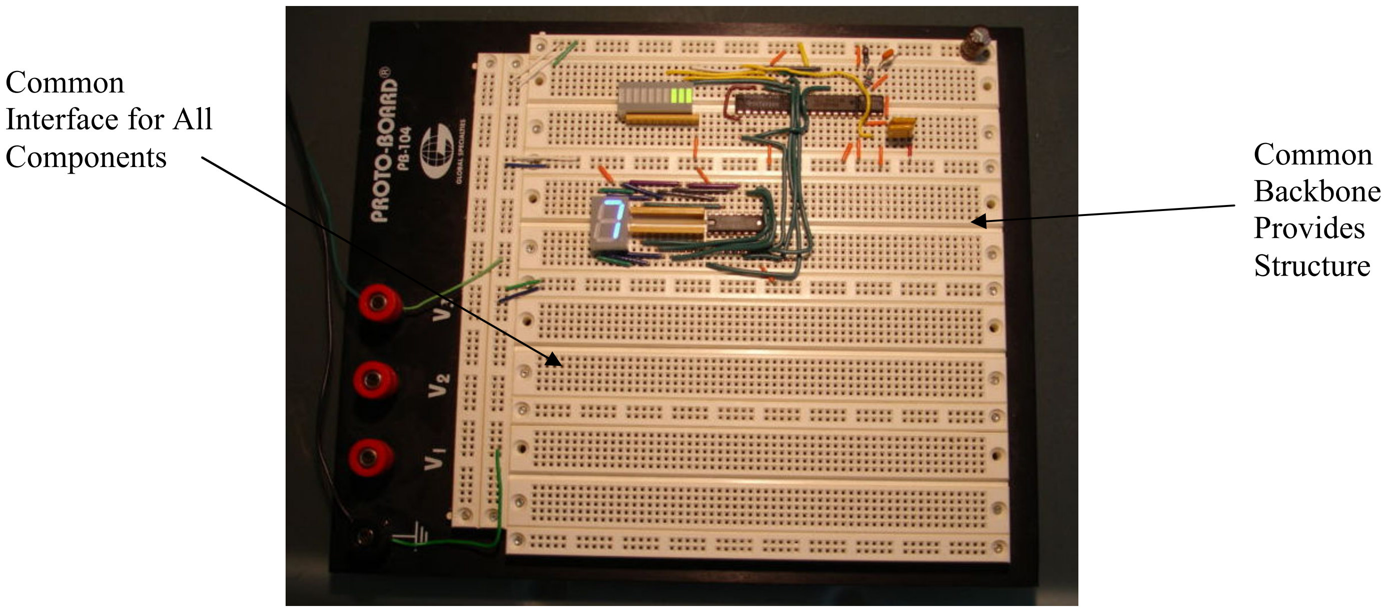


Figure 1: Electrical Breadboard (Wikipedia.org, 2006)

First, the base plate which is shown in white in Figure 1 allows quick connection of a variety of different components. This quick connection is common to all components used on the board and utilizes a simple push-in, pull-out friction fit with friction supplied by the compliance of metal pins and holes. This connection is not designed to be permanent or withstand a severe operating environment such as water intrusion or vibration, but the tradeoff of durability for speed is suitable for laboratory use. In addition to providing a quick connection, the base plate also provides a regular structure or framework for the components to be attached to. This base plate can be thought of like the human skeleton, providing a framework and support for all other components. As shown, the electrical breadboard gives two more important physical analogies for the mechanical bread board:

1. The backbone should provide a means to quickly connect many different components to it, possibly even at the expense of a long term robust connection.
2. The backbone should provide support for the other components.

1.2.2 Lego© Toy Set

One analogy often used that is familiar to most people is the Lego© systems of building blocks. The US patent office granted the first Lego© patent in 1961 (USPTO.gov, 2006). Figure 2 from that patent highlights the key features of the original Lego© system.

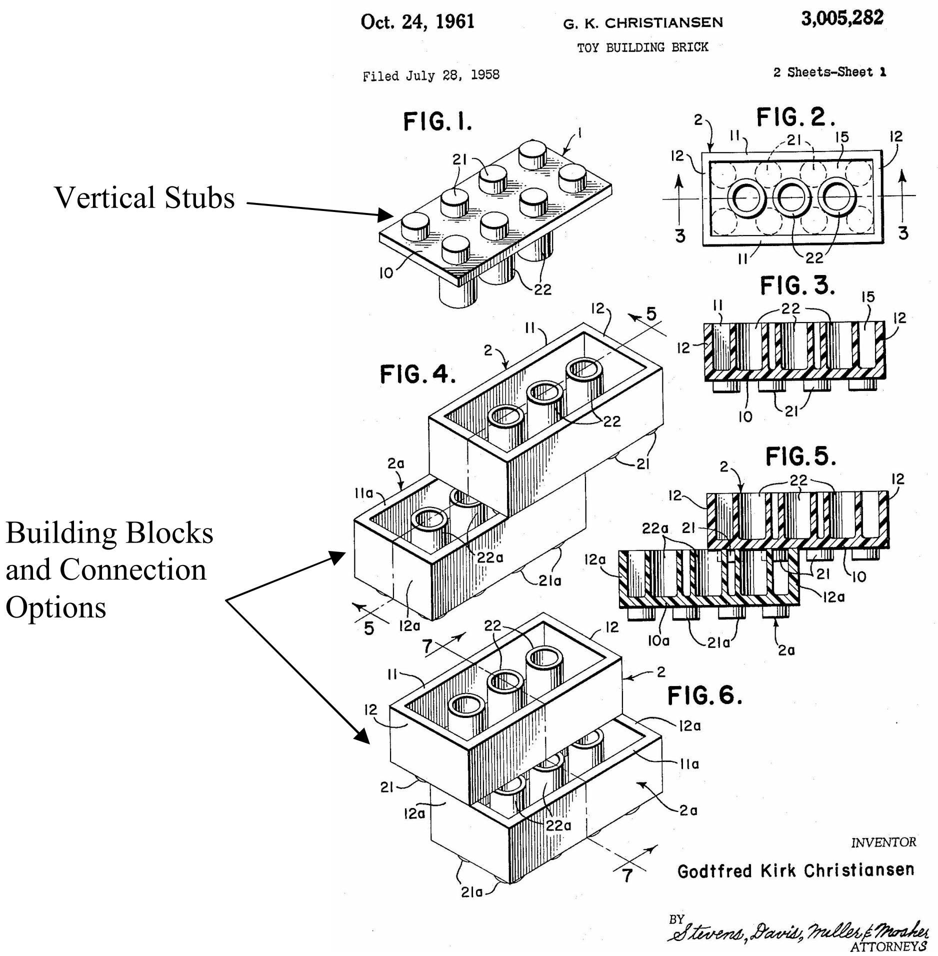


Figure 2: Original Lego© Patent (uspto.gov, 2006)

As shown in the patent, the original Lego© blocks connected to each other through vertical interference connections. Friction from mild elastic deformation of the plastic stubs holds the two blocks together. Through the use of interlocking layers, the blocks can expand in all three translational directions. This system allows for practically limitless building of structures. The connections are limited to either parallel or orthogonal directions by the pattern of small and large stub connectors. They are not truly structural components and are limited in how the pieces interconnect (typically the connections are only in the vertical axis). Later iterations and evolutions of the basic building blocks led to more degrees of freedom and different types of components; the Lego© company developed rods, columns, wheel, hoses, shafts, and other parts which allowed more customization of construction. Figure 3 shows an example of the more modern Legos©; note the vertical stub connectors are still used primarily, but there other connection types used as well.

Figure 3: Current Lego© building set (Lego.com, 2006)

The next major evolution of the Legos© system is the Technic system. This series of sets broke away from the block stub connectors in favor of a system of beam connections to form frame members. The Technic sets further the specialization of individual parts so that more complex and intricate systems are possible. These systems incorporate pneumatic cylinders and electric motors to provide power for motion operations such as turning wheels, raising booms, and lifting rails. Figure 4 shows an example of a Technic auto wrecker set with a pneumatic powered crane.

Figure 4: Technic Auto Wrecker Set (Lego.com, 2006)

The latest Lego© development is the Mindstorm system. While it utilizes the same beam connection frame system as the Technic sets, Mindstorm is a significant departure from previous generations of the Legos© sets in one key way. The Mindstorm set includes very specific and specially made parts used to build and instrument programmable robots. The system includes IR sensors and a programmable controller as well as previously used motion sources such as pneumatic cylinders and DC motors which goes well beyond the original static or unpowered systems and is an electro-mechanical system like that of hobbyist robot builders (Lego.com, 2006). These Lego© sets are more electro-mechanical than previous generations and hint at what mechanical systems will focus more on in the future. Figure 5 shows an example of a Mindstorm robot; note the programmable controller in the torso.

Figure 5: Lego© Mindstorm Robot (Lego.com, 2006)

There is a trade off in the level of sophistication in the Mindstorm set. The original building blocks have thousands of possible uses in a construction system; with the increased specialization of parts, some of this flexibility in each part is lost. To put it another way, the original rectangular blocks could only be connected in a certain number of ways, but every piece in the set could be connected with every other piece in the set. The newer pieces in the Mindstorm set will only interconnect with other specific pieces in specific orientations, but they can be used in ways the original blocks cannot. Still, the sheer number of items and structures that can be built with any Lego© system is an excellent benchmark for mechanical breadboards.

1.2.3 Zome©

Another toy construction set that is commercially available is the Zome© system. This set consists of series of nodes and beams with basic geometric shapes used for connecting nodes to beams. The connector nodes (balls) have 62 possible connection directions and are roughly spherically shaped with a surface defined by a series of rectangles, pentagons, and triangles. The beams are color coded based on which of the three basic geometric shape they insert into (see Figure 6). The system basis is 2, 3 and 5 fold symmetry as well the golden proportion for rectangles (Zometool.com, 2006).

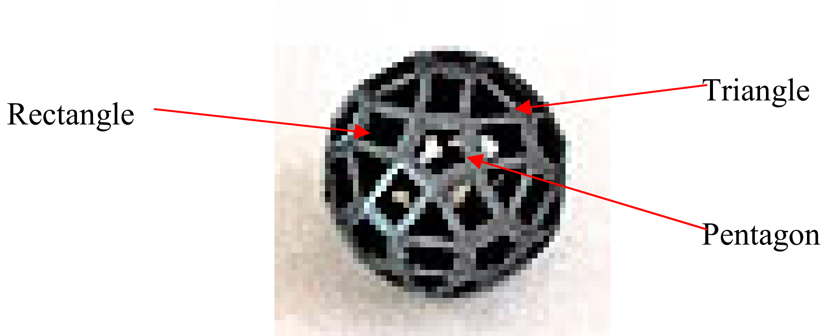


Figure 6: Zome Node (Zometool.com, 2006)

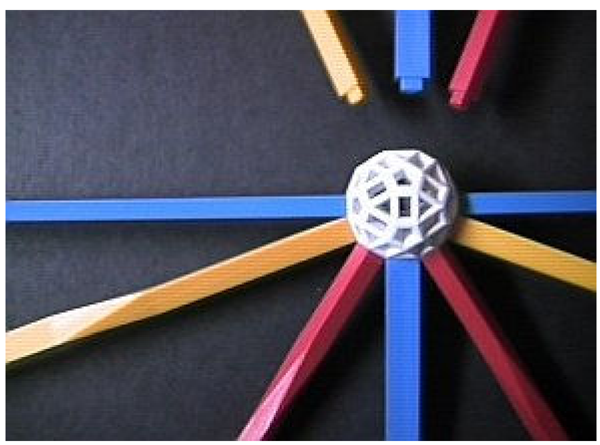


Figure 7: Beam connections to Node (Georgehart.com, 2006)

This system shows how many possible shapes can be made from the node's available connecting angles and the different beam lengths. All components are plastic, and the quick connections are primarily a friction fit with a detent to augment this. While this makes for very light system with easy assembly, it does not yield great strength or rigidity in the system or the connections. Below are two examples of shapes that can be made with the Zome system.

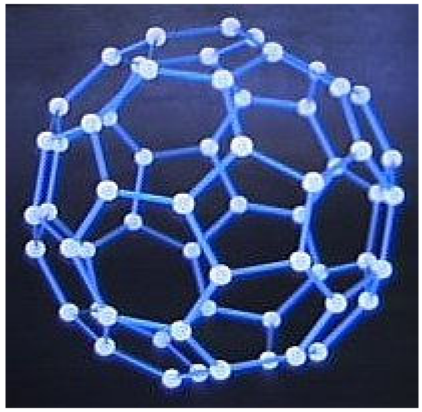


Figure 8: 60 Node Carbon Molecule (Georgehart.com, 2006)

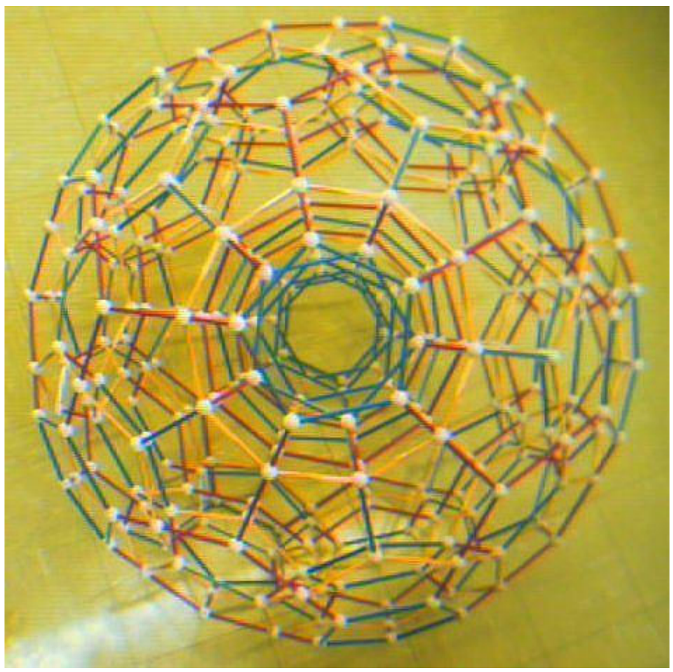


Figure 9: 120 Cell Model (Georgehart.com, 2006)

The department purchased a one of the larger sets from Zometool.com to assess this system as a potential backbone option for a mechanical breadboard. Actual testing of this system demonstrated that it is not designed to take on external loads or provide reaction forces for components such as DC motors. The connections are flexible enough that a load of only a few pounds will deflect the structure enough to see visually. This limitation made the system unusable as backbone and analysis on this system as viable option ended there.

1.2.4 Erector© Set Analogy

Another set that is probably an even better analogy for a mechanical breadboard is the metal Erector© sets popular in the 1950's and 1960's. These toy systems used small metal beams with evenly spaced holes connected by nuts and bolts to allow construction of many different scaled down versions of everything from bridges to construction equipment to vehicles and more. The connections in this system are more representative of how actual components are connected as compared to Lego© sets as they are more permanent. Additionally, Erector sets utilize pulleys, gears and even small electric motors to allow relative motion between parts and assemblies. Shown below are two examples of possible structures with an Erector© set (www.erector-sets.com).

Figure 10: Erector© Set Buildings (www.erector-sets.com)

Figure 11: Erector© Set Crane (www.erector-sets.com)

While useful for building small scale items, they lack the different types of beams and parts to replicate some types of structures. Also the degrees of freedom can be limited in these systems forcing construction along certain angles (typically 90 and 45 degrees). While these analogies are not mechanical breadboards, they are the forerunners to them.

1.2.5 Mechanical Breadboard Analogy Summary

This section highlights the most common analogies to a mechanical breadboard. While countless others exist, these systems are the most commonly used. The electrical breadboard defines the two most important functions of a mechanical breadboard: engineering principle demonstration and prototyping of concepts. The electrical breadboards also offers one approach to the structural makeup of the system with a common backbone to which all other components quickly connect through a common interface or fastening system. The Lego© systems span a large continuum of simple to complex construction systems and highlights the tradeoffs in part specialization versus part generality. The latest Mindstorm systems show off an integrated electro-mechanical system complete with sensors, motors, and a programmable controller. The Zome© system shows different approach to connection flexibility through the use of connecting spheres that offer many different possible connection angles. Unfortunately as currently designed the system is too flexible in its connection to permit any significant loading with visible deformation of the structure. Lastly the Erector© sets offer a more realistic modeling system for structure and vehicles. It mimics actual systems with its use of nuts and bolts to connect various plates and beams together.

1.3 Current State of the Art for Mechanical Breadboards

What is currently available in commercial and research market is very limited at this point. This is surprising since the idea of having a prototyping kit is not new. A search for mechanical breadboards uncovered only two similar mechanical breadboard kits in commercial market. Likewise, a review of current engineering literature turned up only two mechanical breadboards developed by academia. These at least were distinct from the commercially available breadboards and covered different areas of mechanical engineering. The following sections will detail each of these mechanical breadboards.

1.3.1 Commercially Available Mechanical Breadboards

An exhaustive search of patents, on-line companies, and various conferences, resulted in only two companies in the United States that make a dedicated mechanical breadboard prototyping kit: Pic Design and W. M. Berg. Both companies' basic design is similar in that they utilize a two dimensional slotted plate in the horizontal X-Y plane onto which various mechanical components can be attached vertically in the Z axis with nuts and bolts. The slots made in the plate give the board one degree of translational freedom along the X axis while the even spacing of the slots gives a partial degree of freedom in Y translation axis. Both companies have complete kits that include gears of all types, belts, pulleys, shafts, shaft hangers, and couplings for example. Both kits are made of precision components with tolerances of many parts below 0.010” (WMBerg.com, 2006). The kits range in price from around $500 for a basic linkage kit to over $4000 for a complete kit for full prototyping (Pic-Design.com, 2006). While Pic Design’s kit utilizes ¼” diameter shafts for all components (Pic-Design.com, 2006), WM Berg has three kits that use three different shaft diameters ranging from ¼” to $^{3}/_{16}$” to $^{1}/_{8}$” (WMBerg.com, 2006). Note that a patent search results in no findings for either product; when queried about this over the phone, an engineer at Pic Design stated that all parts were pre-existing with similar breadboards having been built since the 1950’s, and therefore there was nothing patentable on their system (Pic Design, 2006). The fact that none of the components are novel or unique is exactly the point. The companies designed these components to be common and useful for most typical machine designs. Figures 12 and 13 illustrate an example mechanical gear train made with each company’s breadboard while Figure 14 shows the complete kit with carrying case from Pic Design.

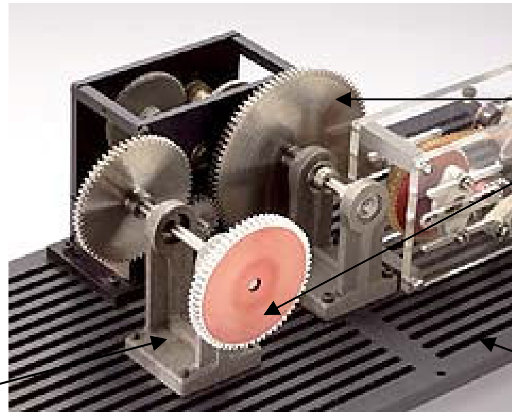


Figure 12: WM Berg Breadboard (WMBerg.com, 2006)

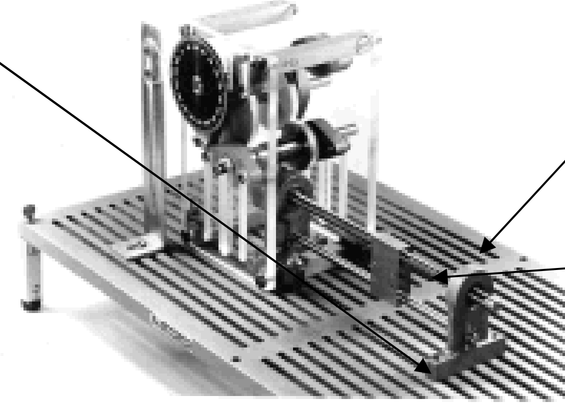


Figure 13: Pic Design Breadboard (Pic-Design.com, 2006)

Figure 14: Pic Design Mechanical Breadboard Kit (Pic-Design.com, 2006)

These mechanical breadboards are priced and designed more to prototype concepts than to demonstrate principles for students. Pic Design does offer educational kits with fewer parts for specific mechanical areas such as linkages or electro-mechanical systems. The design of the slotted plate limits the size and scale of a prototype for example WM Berg's largest board is 16"x16"(WMBerg.com, 2006), and, being plate-based, is fairly limited in 3-D applications requiring more than several inches of height. There appears to be no way to layer the plates vertically to create different levels for construction as in the floors of multi-story building. The cost of these kits being several thousands of dollars coupled with the high precision sensitive parts makes these systems expensive propositions for most universities when considering the wear and tear most students typically put on parts and systems. Still, intricate systems of gears, linkages, etc. can be made with very high precision and offer a reasonably realistic simulation of how a system will physically respond on a larger scale.

1.3.2 Prototyped Statics Mechanical Breadboard

Dr. Van and Dr. Ward of Union University presented a paper at the 2004 American Society for Engineering Education Annual Conference & Exposition entitled "Designing a Mechanical Breadboard for Effective Teaching of Engineering Statics" (Van, 2004). They propose a very simple mechanical breadboard based on system of hinged pegboard sections that allow two or three dimension structures by forming up to three sides of a cube as shown in Figure 15. Figure 16 shows the parts to make this breadboard which are all readily available at most major home improvement stores for total cost of less than $20 (Van, 2004).

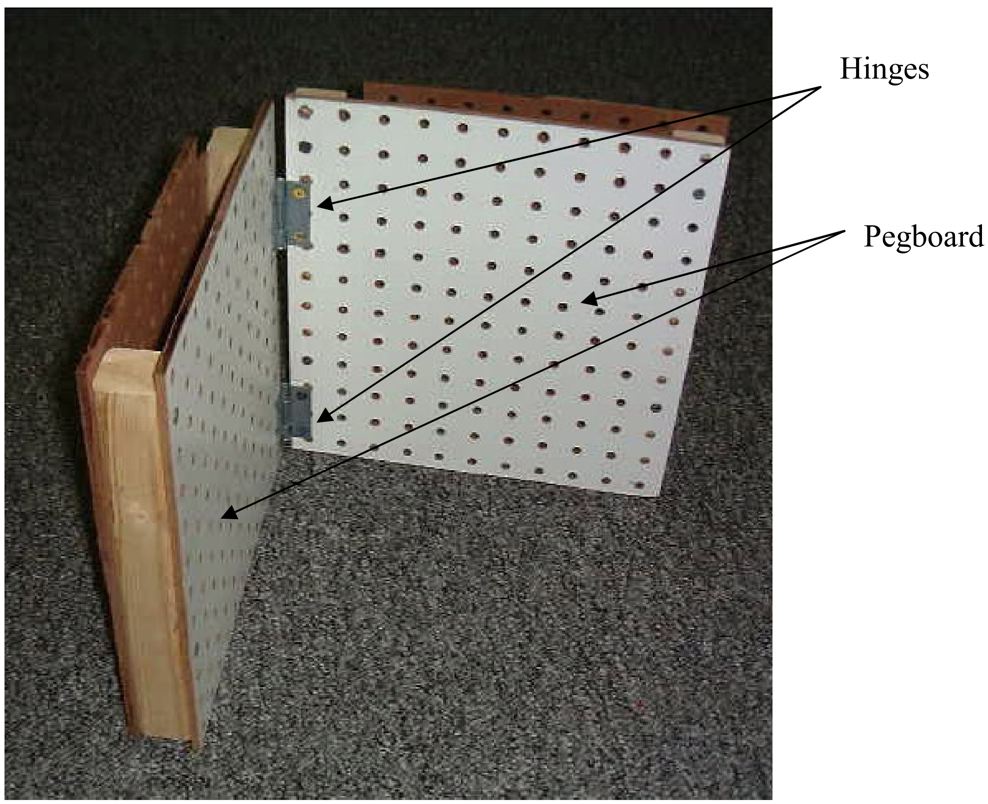


Figure 15: Pegboard based Mechanical Breadboard Backbone (Van, 2004)

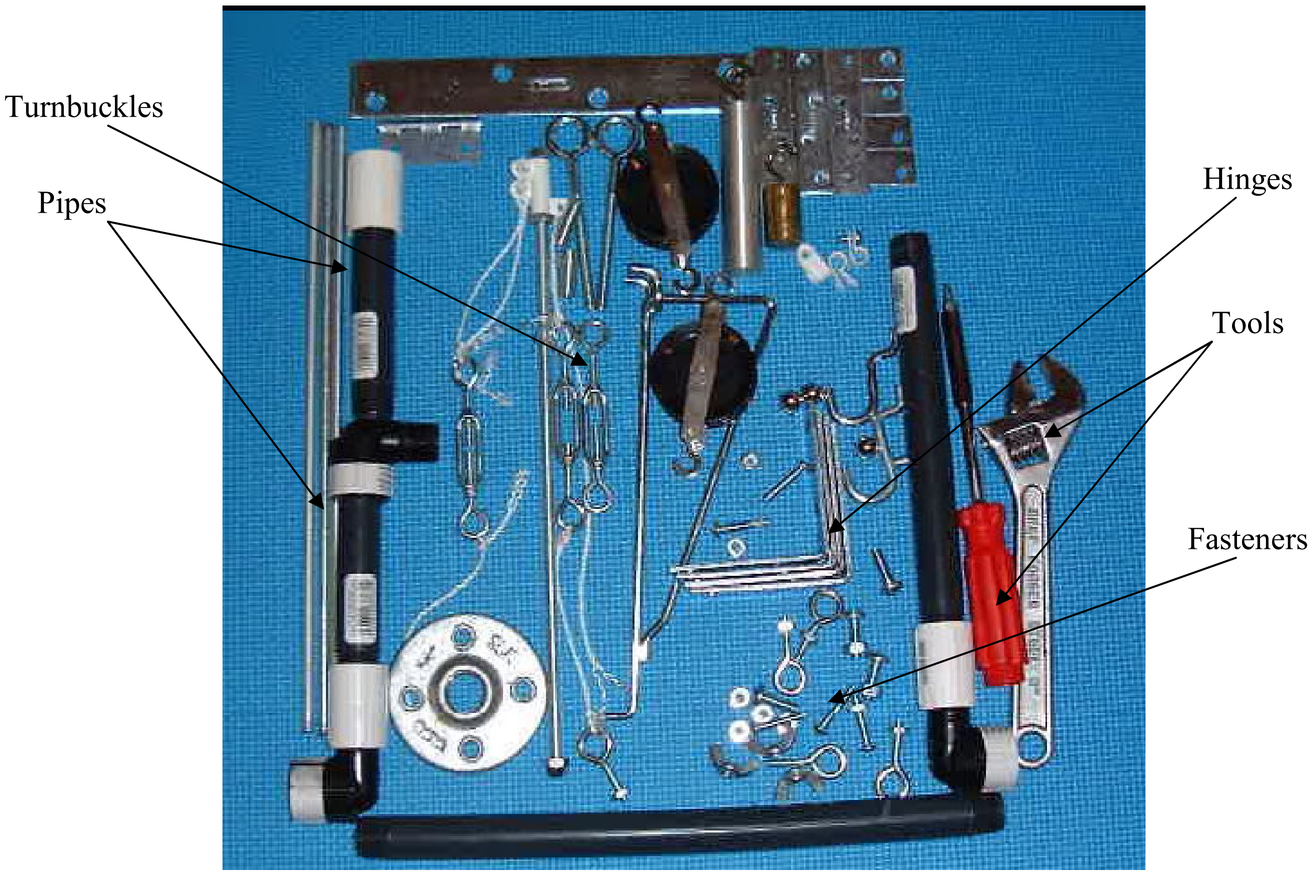


Figure 16: Parts included with Pegboard Mechanical Breadboard (Van, 2004)

The simplicity of this breadboard belies its utility for an introductory statics class; with this system, one can demonstrate bending, moments, stress, combined loading, torsion, and most everything covered in a statics course. Also, being a low cost and lightweight kit, students could purchase this breadboard individually as a supplement to the course book and bring it to class or a lab regularly for use in the lecture or lab. While it would be hard to use for prototyping anything but the simplest mechanisms, it is perfect for the paper's intended use of a statics course. This breadboard would be considered at the low end of the breadboard cost & functionality continuum while the commercial precision mechanical breadboards would be towards the high end.

1.3.3 Thermal Fluids Breadboard

The only other significant breadboard system found during the search was a thermal fluids breadboard developed by Dr. Jeffery Mountain. Dr. Mountain presented this system he calls a "Process Control Breadboard" in several papers from 2002 to 2004 and is pictured below in Figure 17 (Mountain, 2004).

Figure 17: Dr. Mountain's Process Control Breadboard (Mountain, 2004)

The back bone of this system is a series of connected tubes and quick-connect fittings. Each set of five fittings in each vertical column share the same main pipe to which various devices such as heat exchangers, pumps, water heater, steam generators, and valves can be connected. The system incorporates temperature and pressure sensors and well as flow rate meters for measuring or data recording purposes. Using the pumps, heat exchangers, and water heaters or steam generators, different fluids can be used to heat or cool other fluids for simple examples or laboratory projects. More complicated and advanced examples are possible with the use of more sensors and automatic control. The primary purpose of this system as designed by Dr. Mountain is to demonstrate engineering principles to students from elementary school until lower division undergraduate level in hopes of interesting them in pursuing an engineering degree (Mountain, 2004). The cost to build and stock one of these systems would be in the thousands of dollars as just the steam generators and tankless water heaters used are over $2000 (Mountain, 2004). This breadboard can be used for everything from a very simple demonstration for elementary age children up to final projects for upper division undergraduate engineering students based on the complexity of the components used.

1.4 Chapter Summary and Research Objectives

In this chapter, we first defined a mechanical breadboard by its functions and what physically composes it. The electrical breadboard serves as the one of best analogies primarily in how electrical engineers utilize it for prototyping concepts and demonstrating electrical phenomenon, but both types of breadboards also have some potential structural parallels as well in the backbone structure and universal connections among all other components. Following the electrical breadboard, a series of toy construction sets including Legos©, Erector© set, and Zome© gave other approaches to connecting components in a construction set. Lego's© product evolution in particular shows the tradeoffs on the continuum of part generality versus part specialization. The two precision mechanical breadboards by WM Berg and Pic Design show what is currently commercially available. Two educational breadboards follow the commercial breadboards and give examples for other breadboard realms beyond the purely mechanical/machine design regime. The basic statics mechanical breadboard by Dr. Van et al shows how simple the solution could be for specific needs in lower division undergraduate classes. The thermal fluids breadboard by Dr. Mountain shows what a high end system might look like for that regime and is capable of performing complex upper division undergraduate experiments; yet it is simple enough that elementary school children could learn something while using it. All of these products and ideas show that while industry and academia have put some effort into the development of mechanical breadboards, clearly there is room for improvement on current systems either cost or functionality and substantial opportunities for the development of new breadboards.

Examples above have structural architectures that fall into one of two categories. The first type is typified by the electrical breadboard in which the backbone is sheet based has a standard interface to the functional components connect. This style of architecture has a dedicated frame portion that gives some variability to locating other components. The Legos© blocks utilize the other style of backbone architecture where there is no central framework rather the individual components have a standard interface with each other and form the structure themselves. All of these structures provide support and reaction forces for other components as well as giving some variability to the location of the components. Additionally the structures provide the ability to quickly connect components to them. Table 1 shows which architecture category each analogy fall into to.

Table 1: Architecture Styles of Example and Analogies

Architectures	
Dedicated Frame	Integral Frame
Statics Board	Legos© Blocks
Electrical Breadboard	Lego© Mindstorm
Pic Design/WM Berg	
Zome©	
Erector©	

The goal of thesis is to develop an alpha prototype of a new backbone structural system for off-the-self components such as those gears, shafts, bearings, and levers included in the Pic Design and WM Berg breadboards. This backbone will be geared towards the electro-mechanical realm seen in the two commercial breadboards, but could be used as a support structure of other types of mechanical areas. Chapter 3 will discuss these other markets in more detail.

While the components and plates included in those commercial systems allow for very accurate models, the plates lack the ability to support multiple stacked levels like floors of a building or other large three dimensional models. It is my hope to show through out the paper the potential for growth in the development of mechanical breadboards. Mechanical breadboards should play a key role in drawing the interest of young potential engineers and be a key component in their education. They can reduce time and cost for professional engineers to prototype early concepts. I hope to highlight the need for further serious efforts in this area of mechanical engineering as much as to add another stepping stone on the path of this area of research.

The rest of this thesis follows the development of a mechanical breadboard structure. Chapter two discusses the customer interview process and the requirements that evolved from this process. The third chapter details how the customer interviews actually defined several different potential markets on mechanical breadboard continuum rather than just one dominant market. Chapter four sifts through hundreds of common household products and their key functions to determine the most important product functions for prototyping and demonstration. Chapter five highlights the development process and shows many potential ideas that went undeveloped as the process narrowed on a few final options. Chapter six follows the selected solution from initial concept to third prototype. Chapter seven covers feedback from initial testing with customers and suggests area for future work.

Chapter 2: Understanding the Mechanical Breadboard Market

This chapter is devoted to quantifying and defining the potential mechanical breadboard market. In order to understand the market, the first step is to define the customer base. With the customers identified, a sample set of these customers were interviewed to determine customer needs. This chapter details the process used for the customer interviews. Next a summary of the structured questions highlights areas of agreement and disagreement in the customer responses as well as giving overall results. Lastly throughout the interview process, some insightful, unprompted customer responses appeared and gave interesting goals for development. The summary of this chapter will lead to chapter three which takes the customer responses and uses them to define the different segments of the mechanical breadboard market.

2.1 Customer Interviews

In conjunction with researching existing mechanical breadboards, the next step in the development of a mechanical breadboard involved performing a customer needs analysis. This customer needs analysis entailed interviewing both students and professors in the Mechanical Engineering Department at the University of Texas at Austin and professors from the United States Air Force Academy Engineering Mechanics Department. The interviewees' backgrounds spanned the design, machine elements, and thermal fluids areas and were selected with this in mind. University professors and students will use a mechanical breadboard for both of the primary purposes of principle demonstration and prototype development. While there is more of an emphasis on principle demonstration in lower division and early upper division courses, many later upper division courses stress development of prototypes especially the senior level capstone competition projects. By stressing each primary purpose at different times, this one group should cover both purposes better than interviewing engineers in industry who will tend to focus on the prototyping almost exclusively. The chance for bias from just one school's teaching preferences is reduced by interviewing personnel from two different universities. By interviewing some students as well as professors, both sides of the academic fence were represented, and this offered a chance to see of there were difference between the two sides.

A total of ten people (two students and eight professors) participated with the average interview running about 45 minutes. A list of questions guided the interviews. Dr. Matthew Green developed the template for this list of questions; the list was tailored to this specific use by the author. At first the questions were general in nature (e.g. “what would you use a mechanical breadboard for?” and “what components would you like it to have?”) As the interview progressed, the questions became more structured and specific such as “how big should it be?”, “what size should it be when in use?”, and “what should it cost?” These later questions were given with ranges of options; for instance on the cost question, the options were under $300, $300 to $500, $500 to $1000, and over $1000.

The initial questions show the preconceptions each person had, if any at all; in fact, several people had trouble visualizing what a mechanical breadboard would be without some guidance or prompting. The initial guidance was intentionally vague to avoid biasing the customer to a particular solution (e.g. “imagine a mechanical analog to an electrical breadboard”); only if the customer still struggled to visualize something was a more descriptive example given such as the Lego© or Erector Set system. These initial ideas/preconceptions of mechanical breadboard became the different markets discussed later in the paper. There were three general categories of questions:

1. Usage Application (e.g. what mechanical principles, systems, and components should be breadboard cover?)

2. Usage Environment (space for storage and usage, power availability, etc.)

3. Customer Characteristics (customer expectations for cost, durability, maintenance, etc.)

Table 2 shows a sample of the questionnaire with the full list and results in the Appendix A. The context factor succinctly describes the primary focus of the question while the prompt gives the general question phrasing. The next two columns included customer responses and how important this aspect of the product was to the interviews (either from direct statement or inferred from response).

Table 2: Sample of Customer Questionnaire

#	Context Factor	Question Prompts v1.0	Response Notes	Importance: 1-5 (5=very important)
HOW: Usage Application				
a1	task (application, function)	What specific purpose(s) will the breadboard be used for?		
a2	Task Function	What would be your primary use for the mechanical breadboard? What percentage of use will be in this capacity?		
a3	Mech Systems	What areas or types of mechanical systems should this breadboard cover (i.e. electro-mechanical, pneumatic, hydraulic, etc.)		
a4	Mech Systems	Are there any areas/systems you would NOT want to use this for (i.e. too complex or unsafe)?		

2.2 Customer Responses

After completion of each interview, the answers were loaded into an Excel file for later review and to answer two questions. First, were there any less structured initial questions whose answers that were similar or repeated over different interviews? Said a different way, was there a common thread among the ideas of what a mechanical breadboard should be; or were the answers all different with no pattern? Second, among the subsequent more structured questions, was there a general consensus on the correct option for size, weight, etc.? Table 3 shows an example of the compilation with the full set of results in Appendix B. Table 3 is divided in major need subsections such purchase, durability, and portability. The next columns give the weight or customer importance of each need on a scale of one to five (five being very important), and how many responses there were for each importance. The check column gives to total number of response for each need; note that the total number of responses is greater than ten for some questions as some customers gave more than one requirement

Table 3: Sample of Compilation of Customer Responses

Customer Requirement	WT	5	4	3	2	1	0	CHECK
• **Purchase**	**4**							
- Cost over $1000	4		3					3
- Cost $500 to $1000	4		3					3
- Cost under $300	-		1					1
- Cost $300 to $500	4		4					4

As shown in Table 3, some answers spread across options fairly evenly rather than concentrating on one option on same answers. For example, while all customers wanted the system to use DC power rectified from a standard AC wall outlet, there were also six requests for DC batteries, seven for human power options, and four each for pneumatic and hydraulic power. At the same time, several customers responded they did not want batteries used since they can drive the periodic costs up if the system consumes them quickly. The place of usage was diversified as well – six requests for classroom use, eight for laboratory use, and four for home use. The variation in the requirements was more often a result of customers having different embodiments with unique requirements in mind than different requirements for the same concept.

The customers did reach a majority consensus on some questions with the response focusing on either one or two options. Eight of ten customers wanted the annual maintenance cost to be either five or ten percent of the purchase cost. The expected life of the product was five to ten years for all but one customer. Eight interviewees wanted a operation noise level below that of a conversational level in order to talk over it during a lecture. Required assembly time for prototyping concept was split fairly evenly between less than one hour (3 requests) and one to five hours (4 requests), with only one request for an assembly time of greater than 5 hours.

While some requirements appear only once, this interview result does not necessarily imply the requirements are unimportant. Rather these may be unique requirements for a specific niche of the mechanical engineering realm. Likewise having a majority agreement on a requirement does not imply that requirement is universal. These requirements may be typical for most embodiments, but are not by default all inclusive as again certain embodiments for certain niche area of mechanical engineering may not requirement. For example, a breadboard designed to demonstrate statics phenomena may not need an electric power source. Chapter 3 discusses specific requirements for different mechanical specializations in more detail.

2.2.1 Required Components

One early question in the interview asked the customers to list what components they would want in the breadboard. If the customer generated with other components later during the interview, they were added to the previous response. The answers were complied in another Excel file and classified by different groupings. Table 4 shows the final results from all interviews.

Table 4: Customer Components Required

Category	Component	Count		Category	Component	Count
Prime Movers	Motor	6		Bushings	General	1
	Hydraulic Pump	5			Total	1
	Air Compressor	4		Linkages	Four Bar	1
	Actuator	3			Slider Crank	2
	Generator	1			General	2
	IC Engine (e.g. gasoline)	1			Total	5
	General	1		Bearings	General	3
	Total	21			Total	3
Gears	General	6		Fasteners	Bolts	3
	Planetary (Epicyclic)	1			Clamps (C clamps,etc)	1
	Total	7			Total	4
Beams/Shafts	General	6		Sensors	Strain Gauges	2
	Total	6			Pressure Transducers	2
Automotive	Pistons	1			Thermocouples	1
	Differentials	2			IC Controller	1
	Transmissions	2			General	1
	Engine	1			Total	7
	Valvetrain	1		Thermo	Heat Exchangers	1
	Rack and pinion	1			Fans/Blowers	2
	Spindle	1			Heat Source	2
	Clutches	3			Heat Sinks	1
	Brakes	2			Total	6
	Dampers (shocks)	1		Misc	Wheels	2
	Total	15			Chains	1
Springs	General	4			Pulleys	2
	Torsional	1			Propellor	1
	Leaf	1			Joints	3
	Total	6			Total	9

Several points from this table are obvious while some are more subtle. The customers gave a total of 82 responses for an average of 8.2 components per person. Everyone wanted at least one "prime mover" i.e. those devices that convert energy into motion such as a DC motor or hydraulic pump. There were twenty one requests for a prime mover over ten interviews meaning on average each person wanted two different prime mover options in the system. This strong response for prime movers implies most customers want more than static breadboard; they want the ability to put the prototyped system into motion. Another common response was a need for sensors. So most customers not only want motion options but also an ability to provide closed loop feedback or measure data such as pressures, temperatures, or forces.

The second leading category for number of responses is the automotive section. One interview with seven responses for that category skewed this result. Still three other customers mentioned clutches, brakes, transmissions, and/or differentials. So while the automotive category did not dominate as the numbers first suggest, it still is an important category to consider for components.

Beyond the automotive category, customer response varied based on what functionality they focused on with their embodiment. Some focused on electro-mechanical systems; others considered thermodynamic systems; and still others on machine elements topics. Again chapter three will delve into these details further.

2.2.2 Customer Insights

As each interview progressed, interviewees would refine their concept of the breadboard. As they worked it out in their minds, customers would spontaneously offer up ideas not connected to the current question, as if they were still mulling over their prior answers. Often these thoughts gave some of the best insights or customer needs. One that repeated randomly in two of the interviews was a desire to have components colored based on function. The idea is to have different components color coded based on functionality; for instance, the power transmission parts such as shafts, gears, and bearings would all be green while structural components such beams, bolts, and nuts would be blue. In this way, students can quickly determine what function each component in complex system had simply by the color of the component.

Another insightful request in another interview was twofold: first that the system is designed to fail if not properly engineered prior to assembly, and second that certain components be designed as a sacrificial component (like a fuse in an electrical circuit) in the event something does go wrong. Expounding on the first idea, the idea was that the gears in the kit be designed to handle a certain nominal torque and power. This torque and power limit should be such that randomly combining motors and gears could lead to failure of comparatively cheap plastic gears. As this customer pointed out, often students learn more from failures than from success. Having such a failure occur with low power and low cost components is far more inexpensive and safe learning experience than with large, powerful electric or gas motors such as those often used in the senior level Society of Automotive Engineers (SAE) competitions. In fact, never experiencing failure could lead to false sense of security or less of reliance on proper engineering calculations because “it has always worked before”.

The second part of the request was to design into the system inexpensive components that will fail and save the rest of the mechanism should an overload condition occur. This is not a new idea; automotive racing teams have long designed in failure points that are easily and cheaply replaceable. An excellent example of this is the A-arms used on US Air Force Academy Formula SAE car from 2001. The A-arms were designed such that they were sufficiently strong enough when loaded in the vertical axis (such as from road bumps), but when loaded horizontally (from a side impact with a wall or other car) the tube composing the A-arms would buckle and fail prior to transferring sufficient force to the frame of the car to plastically deform it. The A-arms can be replaced in about ten minutes while straightening and welding a frame takes considerably longer, if it can be repaired at all. In this same vein, components should be designed into specific components that will fail before damage occurs to more expensive parts. An example for the breadboard would be shearing the teeth of a plastic gear prior to ruining a DC motor.

Some customer insights are difficult to quantify but still important. For example, one customer requested that the components should only connect in specific ways and that they should "feel right" when being assembled together. The ability to feel whether an assembly is coming together correctly is common in experienced machinists but not so typical for inexperience personnel. One simple solution to this request is to make all connections by hand without tools. Therefore if two components will not connect with just human hand forces, they are not designed to connect directly to each other; this approach can limit the loads a connection can withstand. The use of tools does give the ability to make stronger connections but does require an experienced feel to prevent damage to fasteners and components.

2.3 Chapter Summary

This chapter defined the potential overall market for mechanical breadboards. It followed the customer interview process as way to better understand customer requirements and highlighted key points along the way. The first section detailed the method and format of the interview with the questions broad at first and more specific later. The second section covered to compilation of customer responses and what key facts came from this data. Additionally, it reviewed the components wanted in the breadboard by all the customers and showed the responses varied based on what each person visualized. The last section discussed some the key customer insights which are spontaneous comments made throughout the interview which did not necessarily relate to current question and often gave excellent ideas for innovation on the breadboard.

The results of all the interviews shows there is no definitive consensus as to what the breadboard should be. Some people tended to focus on the electro-mechanical realm, others on the machine design area, while still others focused on the thermal fluids world. It became clear a continuum of cost and functionality exists that the customers spread across. Some customers wanted a very simple, lightweight, and low cost system that every student could purchase while other wanted an elaborate system with many precision components that would have to be purchased by the department due to its high cost. Even without a majority consensus, the responses from the customers did tend to fall into several different categories or potential markets. The following chapter discusses these markets in detail.

Chapter 3: Mechanical Breadboard Markets

3.1 Mechanical Breadboard Market Segments

As the interviews progressed, most interviewees tended to visualize a specific concept for the breadboard after a first thinking of a continuum. However, a few interviewees did not focus on one specific concept but rather stated several options for size, weight, functionality, and so on, based on cost and uses. A review of all responses showed no single concept dominated exclusively. At the same time, several concepts came up time after time. These concepts can be grouped into several distinct markets that spread across a continuum of cost/functionality for mechanical breadboards. These markets broke down into five separate groups after compilation of the data. These five markets each had five key characteristics which defined how they were distinct from each other. The five characteristics are cost, durability, portability, mechanical principles, and components. Though there is some overlap on certain characteristics between different markets, the following sections show the key points of each market.

3.1.1 Statics Breadboard Market

The first market segment on the very low cost and simple functionality end of the spectrum is the breadboard for a statics class. The embodiment by Dr. Van, et al. utilizes a hinged pegboard backbone and common home improvement store parts for cost of less than twenty dollars (Van, 2004). The key customer needs for this segment are as follows:

1. Cost - inexpensive – This category is defined as inexpensive enough that each student can purchase a breadboard for the class. In reality, this means it must cost less than the book for the statics course as students will use the breadboard either as part of the class lecture or as the focus of a complimentary laboratory course. Also by insuring everyone in the course has a breadboard, every student gets a hands-on physical appreciation for these key fundamental mechanical ideas such as stress,

strain, deformation, etc. This initial hands-on experience can be crucial in creating interest and understanding in potential engineers.

2. Portability - Compact/lightweight – If the students are expected to bring the breadboard with them to each class or laboratory, it must be one person portable and fit either into a backpack or have handles like a brief case or duffel bag. Also the weight must be low enough to be carried from the dorm room to class and back without creating a significant burden. One good comparison product group for weight and portability is computer laptops. All of Dell's and Hewlett Packard's (HP) products weight less than 9 lbs (Dell.com & HP.com, 2006). Since by their very nature laptops are designed to be very one person portable, this seems a reasonable upper limit for the weight. Further, most of Dell and HP's laptops that are specifically designed to be thin and light even at the expense of functionality weight less than 5 lbs which is a reasonable lower bound on the weight requirement.

3. Durability – This breadboard would also be in the low end of durability. Minimally, it should last at least one semester so that is can be used throughout the course; better still, if the breadboard will last through two or more semesters, it may be used in follow on classes or simply to prototype simple concepts for later classes. Replacement of parts if needed is easy since they are found at any home improvement store. The least durable part in Dr. Van's kit should be the pegboard, but the cost to replace it would be minimal.

4. Mechanical Principles – Since this product is focus on the introductory mechanical engineering classes primarily statics and possibly a basic dynamics class, the principles to be demonstrated and ideas to be prototyped follow suit. The principles of stress and strain are key to this product. From these two ideas, sub principles are moments and beam bending, shear and normal forces/stresses, 2-D force members, deflection, degrees of freedom, reaction forces, and combined

loading. All of these principles can be demonstrated with simply supported and cantilever beams and weights found in Dr. Van's breadboard. Even in this low end of the continuum, the breadboard still performs both tasks of demonstration and prototyping. For example, students could prototype simple structures and pulley systems to determine if their concepts have sufficient stiffness for potential loading conditions.

5. Mechanical Components - As mentioned above, Dr. Van's breadboard concept has good assortment of what components are needed at an undergraduate lower division level. The figure below shows the components again for reference. Note the assortment of beams, pipes, weights, pulleys, turnbuckles, angle brackets, hinges, nuts, bolts, and eye bolts included in the kit as well as including the required tools to assemble the kit. It should be noted that gears are not part of this system. The rationale for this being that gears are not typically addressed until undergraduate upper division courses such as in a machine elements class.

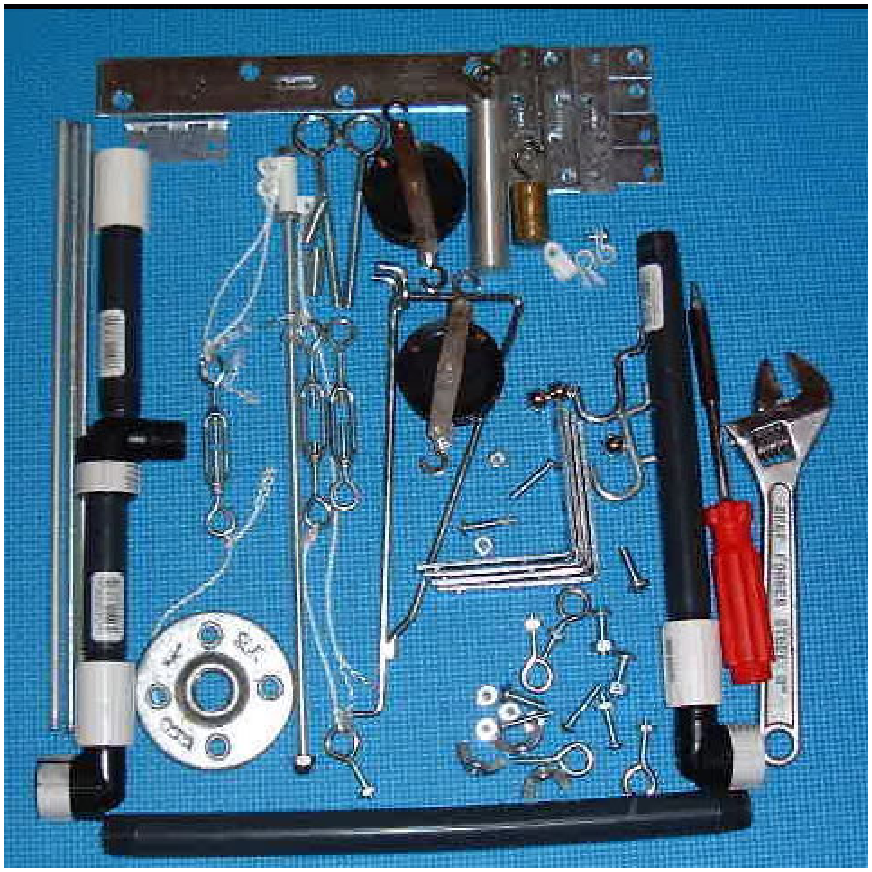


Figure 18: Statics breadboard components

3.1.2 Electro-mechanical Breadboard Market

The next market as alluded to in the interviews would be a mechanical breadboard more geared towards the electro-mechanical realm of mechanical engineering. This market focuses more on undergraduate upper division courses such as controls, advanced dynamics, or a mechatronics (electro-mechanical) class. While there is no dedicated electro-mechanical breadboard in existence today, either a Lego's Mindstrom set or one of the commercially available robotic sets could be used in this capacity. The key requirements of this market are:

1. Cost – moderate cost – Moderate cost is defined as $300 to $1000. The interviewees envisioned the department would purchase this breadboard for specific courses and maintain in a lab, not as a student purchased kit. The components and

controls needed in this system would make the cost unreasonable to expect every student to purchase one yet by keeping the price below $1000 the department should be able to buy enough kits to have one for each pair of students in a class size of twenty to thirty (ten to fifteen total systems). The department can recover the cost for each kit by having a course fee of $100 for each student. This would cover the purchase cost within two to three years assuming two sections of the class and annual offering of the course (versus an offering each semester). Additionally, the majority of interviewees expected periodic maintenance costs (i.e. replacement of broken/lost components) to be no more than 10% of purchase costs for each semester of use. Assuming a $1000 system, the course fee of just one student per year would be sufficient if this requirement is met. If this 10% maintenance cost proved impossible due to student neglect/abuse, the department could require students to pay for any unreasonable loss on each system by using a breadboard assignment system as the start of each course where a set of students are responsible for each breadboard.

2. Portability – Since this market calls for a laboratory setting, absolute portability as seen in the statics breadboard is not required. Still, a need exists to bring a breadboard to class periodically either for demonstration by the professor or to show a student project/presentation to the class. Also since in the laboratory setting there will be multiple sets in use at one time, and since building space is at a premium at most universities, size still must be reasonable. Most customers wanted the breadboard for this market to cover the top of a desk or small workbench when in use, approximately two and half feet by five feet at most. For storage or movement, again a majority wanted it sized like a medium sized suitcase about 1.5 feet by 2 feet by 3 feet at most. As far as weight concerns, the customers desired to keep this system one person portable perhaps by have a wheeled system such as small cart or better still a roller bag style design. The single personal portable requirement leads to a weight limit of less than 51 lbs in order to make lifting practical. The National Institute for Occupational Safety and Health has a single person lifting equation that the maximum

value of which is 51 lbs; this maximum value is almost always reduced due to non-ideal lifting conditions to the thirty to forty pound range (www.cdc.gov, 2006).

3. Durability – Given a choice of three time ranges of less than 5 years, 5 to 10 years, and more than 10 years for how long this breadboard system should last the vast majority of customers asked for a useful life of five to ten years with an emphasis on the ten year life. They typically based this on their expectation of the initial cost of around $1000. Considering the initial cost and the periodic maintenance cost of $100 per year (one semester of use), a ten year life would mean at least twenty sections/classes would use each the breadboard, giving a per class use cost of $100. This $100 cost per class is comparable to other engineering lab course fees at the University of Texas at Austin.

4. Mechanical Principles – With this market, the focus is more on controls/dynamics and machine elements interaction than on statics principles. While stress and loading must be considered, the demonstration of principles such as power transmission, gear reduction, damping, linear and non-linear systems, control, degree of freedom, conversion of rotary motion into linear motion (and vice versa), and linkage motion for example is the focus of the breadboard. This system may be paired with an electrical breadboard to allow construction of electrical systems to operate and control the mechanical systems being built.

5. Mechanical Components – As this breadboard is more focused on undergraduate upper division courses, the components contained in the breadboard system are more complex as well. DC motors as a prime mover are a must if regular motion is going to occur. While it is possible to have other motion sources (aka “prime movers”) such an air or hydraulic pump, both of these tend to create more noise and can have leakage problems. AC motors tend to be more expensive, larger, heavier, and difficult to control. While the user could use a hand or foot crank, the controls focus

of this breadboard usually requires a more regular power source. Gears are a must for power transmission requirement as are shafts to connect and route power. Belts and chains are also needed for connecting gears and pulleys and also to move material along conveyors, though these belts will be of different configuration than those used purely for power transmission between gears. Dampers (often known as shocks) and springs would be required to show damping, overshoot, and other key control parameters. This system would need to either have sensors such as accelerometers, proximity sensors, IR receivers, or be compatible with off the shelf sensors. Also the ability to interface with a PC through a data logging and control program such as Lab View would be definite plus if not an outright requirement again based on customer feedback.

3.1.3 Thermal Fluids Breadboard

The next market on the mechanical breadboard continuum that customers described was a system intended for use in the thermal fluids world. Customers use this system to prototype fluid flow systems and to test heat loss or gain through these systems. In its other primary use, it is ideal in introductory thermal fluids course to demonstrate such phenomenon as heat transfer, pressure loss through systems, and flow rates. This system is biased more towards the demonstration of thermal fluid principles as typically long setup and temperature equilibrium times (greater than one hour) make use of this breadboard as a prototyping system during one lab period difficult. While prototyping with a system such as this is certainly possible, in order to truly develop and optimize an idea, it would take at a minimum of several hours to several days. It would not be a wind tunnel for testing various air foils since these devices already exist and are so specialized that making a device that can perform both as a wind tunnel and work for hydraulic systems is impractical at this time. Again customers came up with some key requirements for this market as follows:

1. Cost – moderate – Moderate cost is defined as $500 to $2000. The customers envision this system as being bought by the department and housed in lab. With the long setup times normally involved in making a fluid system, the customers thought this breadboard would be used by larger groups therefore requiring fewer systems per class. The typical number of users at one time would be between four to six students; with a class of twenty to thirty, this implies that a typical class would need five systems. The cost could be recovered by charging course fee of around $100 similar to electro mechanical breadboard.

2. Portability – This system by its very nature as fluid flow and heat transfer demonstrator could be very large. In order to show pressure loss or heat transfer, long lengths of pipe can be required which make the system quite large say six feet tall by two feet wide by eight feet long. The customers expected the system to still be one or two person portable. They also expected the system to be wheeled to aid in portability. The weight of such a system will be heavier than the two markets previously mentioned based just on size of the system. The goal here should be to keep the system under 100 lbs (two person portable) and ideally under 50 lbs for one person portability. While the customers did not have a great need for this system to be portable, there is still a need to move the breadboard to classroom for demonstrations or final projects so the ability to fit in an elevator and through standard doorways would be useful if not required.

3. Durability – Due the size of the breadboard and cost of sensors, the users expect this system to last at least five years or more likely even ten years. This could prove to be difficult with sensitive components such as pressure transducers and thermocouples. The reusability the pipe and fittings in the system could impact system life; therefore it would have to be a goal to either use very inexpensive replaceable pipe and fittings or else make them reusable from test to test.

4. Mechanical Principles – The key principles this breadboard will need to demonstrate and prototype are straightforward: fluid flow phenomenon and heat transfer. While there are numerous sub-principles and details below these two primary principles, almost everything demonstrated with this system will fall into one of these two categories. Under the fluid flow regime, principles such as Reynolds number, turbulent and laminar flow, pressure drops, flow restrictions can all be shown with a series of pipes and smoke or colored liquid. For the heat transfer area, heat transfer through different materials and thicknesses as well as time for a system to reach equilibrium would be sub-principles or concepts to demonstrate.

5. Mechanical components – As mentioned in principles section, this system would need two different yet possibly complimentary groups of components. In order to demonstrate fluid flow principles, the breadboard will need pumps (either air or hydraulic); pipes which could be PVC, metal, or clear plastic; pipe fittings such as elbows, junctions, splitters, and hangers or clamps; and lastly but equally important, sensors such as pitot tubes, pressure transducers, and flow rate meters. For thermal demonstrations, heating elements, thermocouples, and different samples of insulators and conductors would be required. It is possible that the two groups of components could be used together. For example the heating elements could be placed in the pipes along with thermocouples being placed downstream and the flow rate of the fluid varied to show the effect of flow rate and velocity on fluid temperature. Dr. Mountain's breadboard system has a good example of needed components for working with liquids.

3.1.4 Machine Design Breadboard

The next system on the breadboard continuum is classified as a machine design breadboard. As the name implies, this market is focused on providing demonstrations and components that are discussed daily in a machine design or machine elements class. Ideally this type of breadboard would have an example to go along with each class lecture as different machine components are discussed such bearings, clutches, brakes, transmissions, and linkages. This breadboard is differentiated from the electro-mechanical breadboard by users in that in does not absolutely require electrical power and AC/DC motors to operate. While electrical power and motors may be used within this system, many of the demonstrations done could be accomplished more easily and more safely with hand operated motion. Hand operation eliminates the chance of electrical shock from the breadboard and lowers the likelihood of pinching of finger and hands. Also this system is not necessarily as focused on control and electro-mechanical interaction as interaction of various mechanical components. This system is similar to the thermal fluids breadboard in that is more focused on the demonstration aspect rather than the prototyping regime. While this is not to say that students could not use such a system to prototype concepts, the greater complexity here of the components just as found in the Lego© Mindstorm's kit may limit the interaction of different parts versus as more generic breadboard kit such as WM Berg produces or a basic Lego© kit. Here are the key requirements for this market.

1. Cost – moderate to high- Moderate to high cost is defined as $500 to $2000. A breadboard on the low end of this cost scale would require more plastic parts and fewer complex components while a system on the high end would have more metal parts and may even include actual parts from different machines. With the higher cost of this breadboard, fewer systems would be purchased similar to the thermal fluids breadboard. In the most Spartan case, a professor would need only one kit to demonstrate for the class the components as presented in lectures. For a more hands on experience, the department would need one breadboard for every 2 to 4 students. Customers again expected the maintenance costs to be around 10% per semester for lost or broken parts. If the department purchases only one system for class demonstration purposes, it could either cost significantly more or have much lower associated course fee.

2. Portability - This breadboard would need to be one person portable so it can be transported between classrooms each day for different courses and course sections by the professor. It would be comparable to the electro-mechanical breadboard in size and weight; that is it should have a weight under 50 lbs and be a roller bag size item when in storage or being transported. Again, users expressed an interest in having a wheeled container or a small cart for the breadboard. Having a complete system of this size will most likely require the components used to be smaller than actual size for some components.

3. Durability – Again when offered three different possible ranges of breadboard life span (0 to 5 years, 5 to 10 years, and greater than 10 years), most users preferred a the middle option with a slant towards the 10 year design life. With the cost of this system being most likely between one and two thousand dollars and the typical course fees charged for an engineering lab course, it would take closer to ten years to break even as a department on the purchase cost when maintenance costs are subtracted.

4. Mechanical Principles - The mechanical principles for the breadboard system can be found in any machine design or machine elements course syllabus. The key principles would include linkage geometry, bolt pattern layout, gear interaction, fatigue concerns, spring design, and sizing of various parts such as bearings, clutches, brakes, gears, axles and fasteners. The principles of these courses are often an application of prior classes such statics and dynamics to real world systems and problems. This makes having hands-on experiments even more crucial to student understanding and ability to use lessons on future real world problems.

5. Mechanical Components – Not surprisingly the key components for this breadboard can be found in the index of any quality machine elements book. Such a search would yield components like bolts and nuts, clutches, brakes, gears and

bearings of many different types, axles, shafts, and couplings. Of these components, the most important would be the bolts, gears, and bearings as practically all machines incorporate these three components. Having many different styles of each component would be very helpful for showing the pros and cons of each different design and what each design is optimized for – think of all the different styles of bolts and other fasteners available today. Additionally the system needs plates with multiple configurations of bolt patterns to show how different patterns have different strengths and weakness with tension, shear, or moment loads.

3.1.5 Commercial Prototyping Breadboard

The last and most complex breadboard on the continuum would be what customers described as the professional or industrial prototyping breadboard. The kits offered by WM Berg and Pic Design would be part of this market, but there could be systems that are even more inclusive, functional, and potentially more expensive. In the ideal embodiment of this design, this breadboard would be used by engineers in industry to prototype ideas for any concept. It would incorporate components from all the previous markets so it could be used in the thermal fluids, electro-mechanical, machine design regime or any combination of these areas. Note that both currently available breadboards do not incorporate thermal fluids components into their systems. Ideally, there would be no limit to what could be prototyped in some capacity with this system. It may not have the exact scaled dimensions or custom made specialized parts (again think Legos© Mindstorm), but it would give a good first order approximation as to whether a concept is feasible – just as an electrical breadboard does for circuits. At this date, no such system exists that covers all mechanical areas described above.

1. Cost – High- This system would be at the very high end of cost, high being defined as two to ten thousand dollars, possibly even more with the possible sensors included. As a single use item, this breadboard is not a cost effective solution to prototyping, but over multiple development program and years of use, it would be far

more inexpensive option to having a machine shop custom make parts based on engineer developed CAD drawings for each and every concept and project. The periodic maintenance costs are expected to be in 5% of purchase cost since the purchase cost is high. If care is taken with the components to reduce the chance of damage occurring and proper engineering calculations done prior to assembly of concept, the lower percentage periodic maintenance costs are not seen as being unreasonable. This assumes that it is not used in an undergraduate student environment where less care is typically seen by users.

2. Portability – Due the fact the breadboard would need to incorporate so many different components to cover the various regimes of mechanical engineering, it will be bigger and heavier than the other breadboard systems just based on incorporating the thermal fluids area. It could be housed either in a medium sized cart or in several wheeled containers perhaps grouped by mechanical area of the components. This would be useful to move the system to and from different design groups as projects enter different stages of development. Alternatively the system could be set up permanently in a lab that different design groups in a company could use.

3. Durability – This system due its cost is expected to last the longest by customer, with all stating a need for a design life of over 10 years (the longest option given). When asked what an upper limit would be if the breadboard should last beyond 10 years, the majority responded with an upper limit of 20 to 25 years. This need is similar to that of key machine tools with are expected to last at least that long and often with proper maintenance can last over 50 years. This long term life implies most of the components need to be made of durable materials, materials that will not degrade significantly in the span of 20 years. This means some plastics will not be suitable as they become brittle over time. Also any gaskets or rubber components must be carefully considered as they will often become brittle or fail in that span of time.

4. Mechanical Principles – While there is less emphasis here on the demonstration of principles, the breadboard must be able to build systems that follow the key mechanical principles from each domain. In this case, it is more important to accurately prototype a system so that any failure modes that might be seen on the actual system will show up on a scaled model. If the model is inaccurate about the effects of fatigue for example, there will be more problems to solve at a later stage of development where the solution and engineering involved will cost substantially more.

5. Mechanical Components - As stated above, this breadboard incorporates components for all the above mentioned systems as it is designed to be able to prototyping anything a more simple breadboard is capable of generating. There would be less emphasis on the statics realm as that market is geared more towards demonstration than prototyping, but there would still need to be way of loading the system with forces for example. From the electro-mechanical realm, the keys components are still electric motors, gears, linkages, motion/light sensors, switches, shafts, and pulleys. For the thermal fluids world, Dr. Mountain's system is has a good selection of key components such as heat exchangers, pumps, manual and automatic valves, water heaters, steam generators, and pipes. While the electro-mechanical and machine design domains overlap some, the machine design area brings a great emphasis on gears, fasteners (bolts in particular), power transmission, clutches, dampers, and springs. With all of these components combined in one system and designed to last for a generation, the cost will not be trivial.

3.2 Chapter Summary

This chapter details the five distinct markets that customers described either directly or indirectly during the interviews. Table 5 below summarizes there five markets based on their key characteristics. These markets span a continuum of cost and functionality that spreads from a system with a cost under $20 and demonstrates simple statics principles to a precision elaborate system costing thousands of dollars and able to prototype almost anything in the mechanical realm. Note that within each market there is still a range of functionality, costs, sizes, and weights.

Table 5: Breadboard Market Summary

Market	1	2	3	4	6
Type	Basic Statics	Electro Mechanical	Thermo	Machine Design	Full Prototyping
Prototyping or Demonstration	Demonstration primary	Both equal	Demonstration primary	Demonstration primary	Prototyping primarily
Mech Areas	Statics (Possibly Dynamics)	Statics/Dynamics/Controls	Fluids/Thermo	Statics/Dynamics/Fatigue/ Suspensions/Clutches/ Brakes/ Gears/ Bearings	All of Previous
Price Range	$30-$100	$300-$1000	$500-$2000	$500-$2000	$2000-$10000
Sensors	Simple (weight gauges, rulers, etc)	EO/IR sensors, switches	Pressure Transducers, flow meters, thermocouples	switches	All of Previous
Purchaser	Student	Department	Department	Department	Department
Size (Stored)	Small (large textbook)	Medium (briefcase)	Large (workbench)	Medium (briefcase)	Large (workbench)
Size (In Use)	Medium (briefcase)	Medium to Large	Large (workbench)	Medium to Large	Large (workbench)
Tools Required	Hands or Basic Tools	Basic	Medium Tool Set	Basic	Full Tool Kit
Life Expectancy	6 to 36 months	5-10 years	5-10 years	5-10 years	10-20 years
Place Used	Home/Class	Lab/Class	Lab	Lab/Class	Lab
Data Collection (e.g. connect to LabView)	No	Yes	Yes	Yes	Yes
Portablity/Weight	One person - 5- 9lbs	One person - 20-30lbs	Two Person - 50-100lbs	One Person - 30lbs	1-2 person - 30-50lbs
Usage	Weekly	Weekly	Monthly	2-3 times per week	Varies
Maintainance Frequecny	Disposable	After each semester	After each semester	After each semester	Yearly
Maintainance Cost Per Year	N/A	10-20%	10%	10%	5%
Time to Assemble Concept	5-20 min	10-90 minutes	30-90 min	10-30 min	30 min to several days

The breadboard structure developed in this thesis can be used for several markets. A statics course would find it useful though the complexity may be too great. The real aim of the structural concept is the electro-mechanical and machine design sections which is more inline with the Pic Design and WM Berg products since ideally this new structure could replace the plates included in those products.

While at least one example exists for each market, there should be many more available, and the potential for significant growth in these areas is great at this time. The statics breadboard by Dr. Van is good start; it could be made more durable and offer more variability than the discreet holes of the pegboard. A successful design marketed commercially would find its way into hundreds of colleges as well as thousands of high school physics classes. As stated earlier, a dedicated electro-mechanical breadboard does not exist. There will be challenges to keep the costs of this variant reasonable while supplying enough functionality and sensors to be effective, but one built to satisfy both academia and hobbyists alike would find a sustainable market. Likewise, the first group to develop a low-cost, functional thermal fluids breadboard will find many willing customers among universities and industry alike. The machine elements breadboard has the same dilemma of cost versus functionality of the electro-mechanical breadboard as well as balancing realistic components against keeping to a reasonable size and weight. In order to ensure that the breadboards cover the most key functions, the next chapter dissects many common household products to determine which functions are most common and critical.

Chapter Four: Product Function Analysis

4.1 Introduction

Before beginning the concept generation portion of developing a new breadboard structure, one must know what functions and therefore parts the breadboard needs in order to prototype systems. While the components given by the customer during interviews could be taken at face value, these inputs came after only a few minutes of consideration not days or weeks of analysis and thought. Granted the interviewees have years of mechanical experience between them so their responses is not without merit, but the question is really so vast that the answer truly requires serious thought. The question would be the same as asking an electrical engineer what are all the important principles in that field. In order to better bound the problem and understand what functions are actually used in consumer products, this chapter uses a functional modeling process for various consumer products combined with a customer needs analysis to determine which functions are most important across a continuum of products. This gives a structured reason for selecting specific functions as opposed to using just the intuition of the interviewees.

To begin this process, the author started with five sample products to functionally model and decompose. The sample of five household products was chosen to cover the major areas of mechanical engineering and includes: a cordless drill, a George Foreman© grill, a garage door opener, a smoothie blender, and a heavy duty stapler. The customer needs for each product and their associated importance are cross referenced to the functions developed from functional modeling. The functional importance is totaled across all products to show which functions were the most important to customer needs. With the sample complete, the same process was used on a repository of 69 products maintained and furnished by Dr. Robert Stone of the University of Missouri-Rolla (UMR). Using this much larger sample of products gives a high degree of confidence that the most critical functions for meeting customer needs are determined. The section continues with a summary of these critical functions along with key insights. The development process uses these critical functions to begin idea generation, which Chapter 5 details.

4.2 Initial Analysis

Before tackling the large repository of consumer products developed by Dr. Stone, the first step was to analyze a small number of consumer products to gain understanding and insight into the functional modeling process. Consumer products make excellent specimens for functional analysis since they are more easily analyzed than larger, more complex systems like automobiles and aircraft which have hundreds to thousands of functions and components. The commercially available breadboards contain enough types of parts and numbers of parts to prototype low to moderate complexity products, and this concept will follow suit based on available time and funds. Another assumption that drew the author to this portion of the market is that most engineers even on large system work on only a subsection of the large product. While large systems do have unique interaction phenomena as compared to small systems, selecting low to moderate complexity consumer products still give a large breath of products designed by engineers. By choosing to analyze low to moderate complexity consumer products, the breadboard developed will focus on prototyping these products.

4.2.1 Products Chosen

The five products selected for analysis touch on the major areas of mechanical engineering. The products include a cordless drill, a smoothie blender, a small George Foreman© grill, a garage door opener, and heavy duty stapler. The cordless drill and smoothie blender emphasize the machine design elements, some electro-mechanical details, and some controls aspects. The grill deals largely with the thermal fluids and heat transfer regime as well as some control principles. The garage door opener deals with machine elements challenges partially but has an even greater emphasis on the controls and sensors of the electro-mechanical realm. The stapler has many statics and dynamics issues involved in its development as well as some machine design considerations. Table 6 below summarizes the products and the areas of mechanical engineering they cover. The number of products analyzed was chosen again more to ensure familiarity with the process across mechanical domains than to prove any definitive trends in the functions of the products. With the selection of products complete, the next step was to functionally model the five products individually.

Table 6: Sample Products and Mechanical Areas

Product	George Foreman Grill	Cordless Drill	Garage Door Opener	Smoothie Blender	Stapler
Major Area(s)	Thermal	Electro-Mechanical	Electro-Mechanical	Machine Design	Statics/ Dynamics
Minor Area(s)	Controls	Controls	Machine Design/ Controls	Fluids, Controls	Machine Design

4.2.2 Black box Development

The first step in the functional modeling process is the development of a black box model of the product (Otto and Wood, 2001). This step treats the product as a black box which turns inputs into desired outputs by some unknown process internal to the product. The product is represented as an empty box with inputs entering from the left side and outputs leaving on the right. Figure 19 shows the black box model for the cordless screw driver; note that the drill has two primary functions: drilling holes and fastening/unfastening fasteners. Appendix C contains the black boxes for all products.

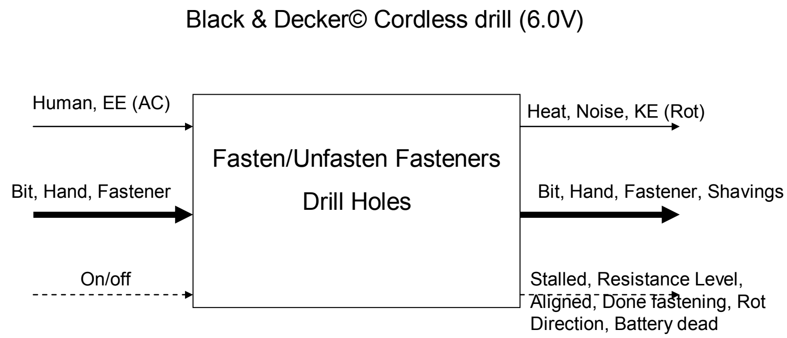


Figure 19: Black Box Cordless Screwdriver Model

The model treats the black box as an open system into and out of which three different types of flows are possible. These possible flows are energy, material, and signals which are displayed on the figure as three different types of arrows respectively. The phrase inside the box describes what the product does with a verb followed by a direct object (noun). This phrase accurately describes the key action or use of the device. The black box considers all flows both into and out of the system so it identifies all potential input and output flows. The flow of energy, material, and signals through the black box is used to develop the functional models of the product such that the completion of the black box model is the basis for the creation of the functional model of the device.

4.2.3 Functional Model Development

A functional model breaks a device down into discreet functions that the components of the device perform. It allows one to follow the flow of any input through the device and see how the device changes that flow into the desired output by a series of performed functions. As stated above, the flows of energy, material, and signals come from the black box model. Every flow from the black box is mapped out from input to output. The functions needed to change the flow from an input to a suitable output can either be developed from inference or by disassembly of the product. It can be useful to first make an educated guess as to what functions are needed prior to disassembly as this will improve one's ability to make better inferences in the future. Figure 20 shows the functional model for the cordless drill.

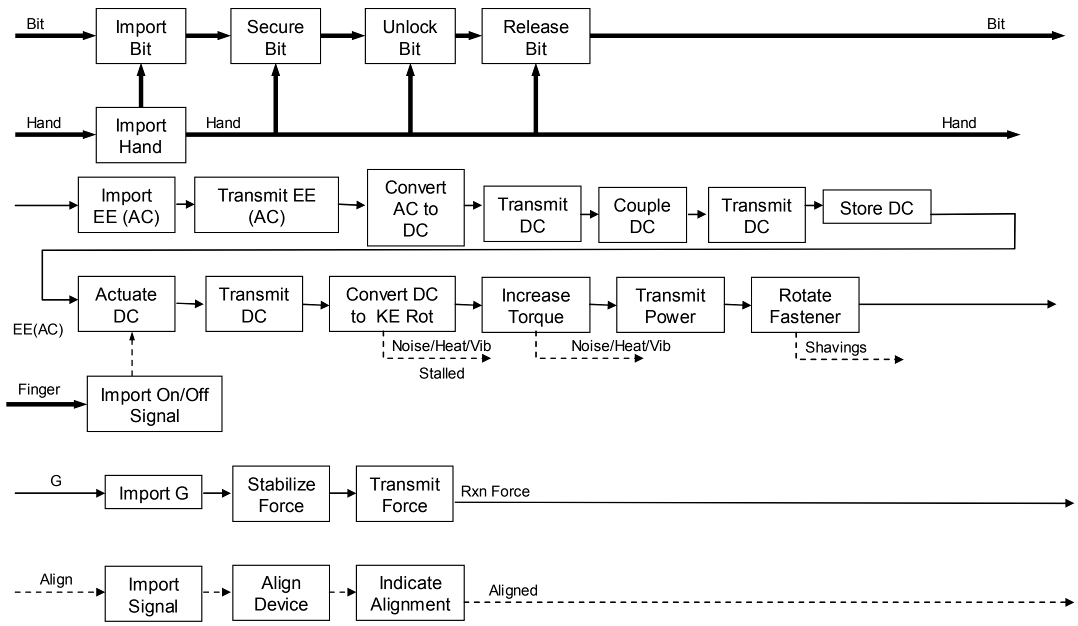


Figure 20: Cordless Drill Functional Model

As shown in the figure, each input flow from the black box is traced through the device to its final output. For example, the material flow of the bit at the top of the figure shows the bit being imported into the system via the user's hand into the chuck; the chuck then secures and unsecures the bit before being exported by the user's hand. The model traces every action on or by a flow to understand the process of conversion from inputs to outputs. Note that some inputs combine together to form outputs. With all functions determined by tracing input flows to outputs with inferences and affirmed by disassembly of the device, the functional model is ready to be converted to a more general form for incorporation into a functional matrix with other functional models.

In order to compare and compile all the functions across many products, one needs to use a "basis" of functions. In reality, there are only a limited number of functions which all products use. By standardizing the functional model to this common basis of function, the analysis and comparison of products and their functions becomes a much easier and quicker task. Each functional model is converted to a common basis of flows and functions. For example, each material acted upon is made into a generic state of solid, liquid, or gas. One flow in the drill is to accept a drill bit called "import bit" in the model; in common basis, the bit as a material converts to the generic term "solid". Table 7 shows the common flows for energy, material, and signals as well as subsets in each basic flow and what complements each flow has (Little et al, 1997; Stone & Wood, 1999; and McAdams & Wood, 2000). Likewise, every product action or function can be described by a list of common verbs or functions shown in Table 7 (Little et al, 1997; Stone & Wood, 1999; and McAdams & Wood 2000).

Table 7: Common basis flows (McAdams & Wood, 2000)

Class	Basic	Sub-basic	Complement
material	solid		hand, foot, head, etc
	liquid		
	human		
	gas		
energy	human		motion, force
	biological		pressure, volumetric flow
	mechanical	rotational	torque, angular velocity
		translational	force, velocity
		vibrational	amplitude, frequency
	electrical		electromotive force, current
	hydraulic		pressure, volumetric flow
	thermal		temperature, heat flow
	pneumatic		pressure, mass flow
	chemical		affinity, reaction rate
	radioactive		intensity, decay rate
	acoustic		pressure, particle velocity
	magnetic		magnetomotive force, flux rate
	electromagnetic	optical	intensity, velocity
		solar	intensity, velocity
signal	status	auditory	tone, verbal
		olfactory	
		tactile	temperature, roughness, pressure
		taste	
		visual	position, displacement
	control		

Table 8: Common basis functions (McAdams & Wood, 2000)

Function Class	Basic Function	Flow Restricted	Synonyms
channel	import		input, receive, *allow*, form entrance, *capture*
	export		discharge, eject, dispose, remove
	transfer		
		transport	lift, move, channel
		transmit	conduct, transfer, convey
	guide		direct, straighten, steer
		translate	
		rotate	turn, spin
		allow DOF	constrain, unlock
support	stop		insulate, protect, *prevent*, shield, inhibit
	stabilize		steady
	secure		*attach*, mount, lock, fasten, hold
	position		orient, align, locate
connect	couple		join, assemble, *attach*
	mix		combine, blend, add, pack, coalesce
branch	separate		switch, divide, release, detach, disconnect, disassemble, subtract, valve
		remove	cut, polish, sand, drill, lathe
	refine		purify, strain, filter, percolate, clear
	distribute		diverge, scatter, disperse, *diffuse*, empty
	dissipate		absorb, dampen, dispel, *diffuse*, resist
provision	store		contain, collect, reserve, *capture*
	supply		fill, provide, replenish, expose
	extract		
control magnitude	actuate		start, initiate
	regulate		control, *allow*, *prevent*, enable/disable, limit, interrupt
	change		increase, decrease, amplify, reduce, magnify normalize, multiply, scale, rectify, adjust
	form		compact, crush, shape, compress, pierce
convert	convert		transform, liquefy, solidify evaporate, condense, integrate, differentiate, process
signal	sense		perceive, recognize, discern, check, locate, verify
	indicate		mark
	display		
	measure		calculate

The application of this common basis reveals commonality between products based on their functions. The common basis will also reveal which functions are most common among all products. Figure 21 shows the same functional model of the cordless drill converted to the common basis.

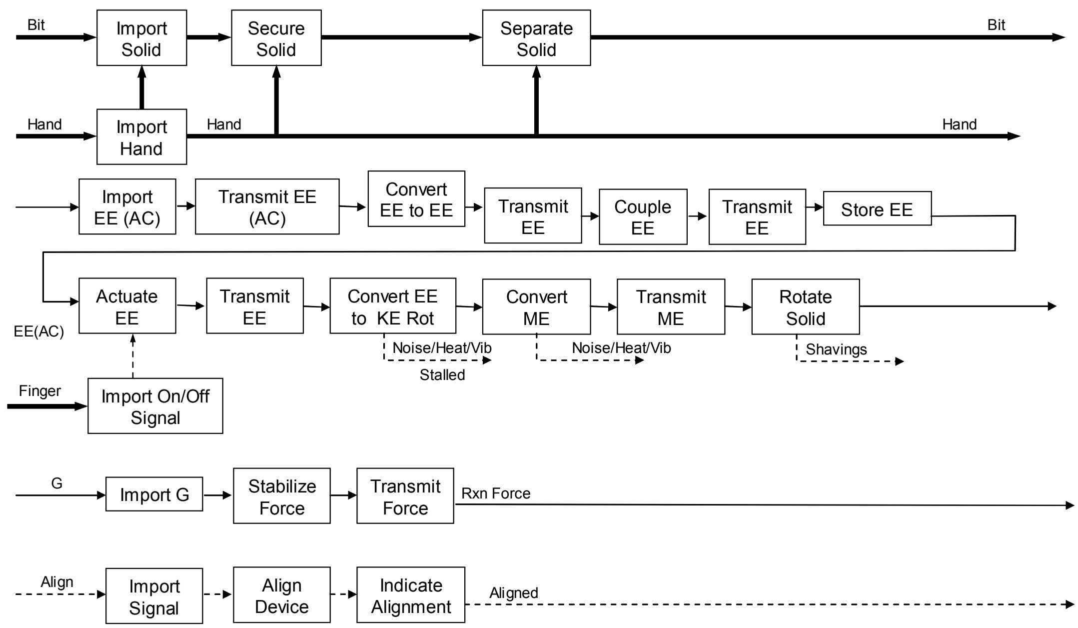


Figure 21: Cordless Drill Functional Model in Common Basis

As stated above, this standardized model has all flows for materials, energies, and signals. All specific functions are converted to common basis as well. In this common language, it becomes easier to compare different products and determine trends and commonalities among products. For instance, "transmit EE" appears four times on this model alone; anytime electrical energy transmits in another product it will counted under this same function and show a commonality. See Appendix C for all specific and generic functional models.

4.2.4 Sample Functional Importance Calculations

With the functions converted to common basis, the customer needs can be related to these functions to determine functional importance. Each time a function is related to a customer need, the importance of that need is added to running total for that function. Using the example of the cordless drill again, the accepting of the bit function called "import solid" is related to just two customers needs: accepting many different types of bits and having a quick and easy to use system of accepting and removing bits. Since both needs have an importance of four from the customer needs survey, the total functional importance is four plus four for a total of eight. This process is repeated for every customer need for every product. Table 9 shows the results for the cordless drill as an example.

Table 9: Function Importance Calculation for the Cordless Drill

Average Customer:				21										
				Total Funct	Import Solid	Secure Solid	Separate Solid	Import Hum	Import EE	Transmit EE	Export Hum	Convert EE	Couple EE	Store EE
		CUSTOMER DESCRIPTION FROM DESIGN BRIEF		Multiplier	1	1	1	1	1	3	1	1	1	1
				Weight	8	8	8	18	0	60	0	4	16	18
				Average Wt	10.84									
		Customer Requirement	**WT**											
•	**Fasten/unfasten Fasteners**		**4**											
	-	Sufficent Torque	5							1				
	-	Quiet Operation	3											
	-	Adjustable clutch	3											
	-	Accept many different bits/fasteners	4		1	1	1							
	-	Quick/Easy to use chuck (ie no key)	4		1	1	1							
	-	Easy to operate on/off	4											
	-	Variable speed	2											
	-	Fasten many fasteners on one charge	5							1				1
	-	Easy to align with fastener	3											
	-	Easy forward/reverse operation	3											
•	**Safety**		**5**											
	-	No shorting risk	5							1			1	
	-	Isolate Battery from User when in use (burns)	5											1
	-	No exposed wires	5							1			1	
	-	Motor Isolated from fingers	5					1						
	-	Sufficient Venting	4											
•	**Setup**		**4**											
	-	Easy to Operate	4					1						
	-	Clear user's manual	3											
	-	Ergonomic	5					1						
	-	Llightweight	4					1						1
	-													
•	**Chraging Battery**		**3**											
	-	Battery charges quickly (15min to 1 hr)	4									1		1
	-	Charger easy to connect	3										1	
	-	Charger only connects in correct orientation	3										1	

The other four products go through the same process to determine the functional importance for their functions. Table 10 shows results of all five products complied into a product function matrix. The top line in yellow shows the number of functions per product while the bottom line in pink shows the average importance per function for each product. On the far right of the figure in blue is total importance of each function totaled for all five products. The middle portion in green shows the function importance elements for each product and associated function if any. Those elements without values indicate those functions are not present in certain products. Lastly in red at near the bottom is the total of all functional importance values for each product.

Table 10: Product Function Matrix for the Five Products

	Garage Door	Blender	Stapler	B&D Drill	George Grill	Total
# of Functions	14	14	20	21	19	88
Import EE	10	5			5	20
Transmit EE	10	9		60	9	88
Convert EE	10	0		4		14
Regulate EE	15	8			22	45
Convert EE to ME	26	15		17		58
Convert ME	16		22	17		55
Transmit ME	8			13		21
Import Signal	72		6			78
Transmit Signal	30					30
Import Hand	4	7	17	18		46
Import Solid		12	4	8	6	30
Position Solid		8	13	8	10	39
Mix Solid		26				26
Export Solid		10			10	20
Import Force		3	7		3	13
Stabilize Force		3	7		3	13
Transmit Force		3	7		3	13
Convert HE			4			4
Store PE			24			24
Import HE			4		5	9
Store Solid			8		3	11
Separate Solid			5	8	22	35
Align Solid			3			3
Indicate Alignment			3			3
Couple EE				16		16
Store EE				18		18
Acutate EE				13		13
Rotate Solid				6		6
Transfer Heat					4	4
Guide Solid					3	3
Convert HE to ME					4	4
Distribute EE					15	15
Convert EE to Heat					4	4
Total	201	109	134	206	131	
Avg Per Function	14.4	7.8	6.7	9.8	6.9	9.1

In order to prevent complex products with many needs and functions like the garage door opener or the cordless drill from dominating the analysis, the data must be normalized. The normalization process used here was developed Dr. McAdams and Dr. Wood and covered is covered in detail in their paper *Quantitative Measures for Design by Analogy* from the 2000 ASME Design Engineering Technical Conference. First, the matrix shown in Table 10, which we will name Φ, is made up of 5 products and 35 distinct functions generically referred to as an *m* product by *n* product-function matrix. The totaled functional importance for the i^{th} product and the j^{th} function is described by the element ϕ_{ij} (shown in green in Table 10). To normalize all values of ϕ into a new matrix named *N* made up of elements ν, the equation used is:

$$\nu_{ij} = \phi_{ij}\left(\frac{\overline{\eta}}{\eta_j}\right)\left(\frac{\mu_j}{\overline{\mu}}\right).$$

The unfamiliar variables will be named and solved for in the equations that follow. First we solve for the average customer importance rating with the following equation:

$$\overline{\eta} = \frac{1}{n}\sum_{i=1}^{m}\sum_{j=1}^{n}\phi_{ij}\ .$$

The average customer value as shown in Table 10 is 9.1. Next the total customer functional importance for the j^{th} product is:

$$\eta_j = \sum_{i=1}^{m}\phi_{ij}\ .$$

For the five products, the values of η_j are 201, 109, 134, 206, and 131 (shown in red on Table 10).

The number of functions for the j^{th} product is:

$$\mu_j = \sum_{i=1}^{m} H(\phi_{ij})\ .$$

Where H is a Heaviside function that states for all values of ϕ_{ij} greater than zero the function is equal to 1 while for ϕ_{ij} values of zero the function is also zero. This gives an easy way of totaling functions in a spreadsheet tool rather than manually adding up all the cells that have a value in them. For these five products, there are a total of 88 functions are divided 14, 14, 20, 21, and 19 functions respectively and shown in yellow in Table 10.

The average numbers of functions across all products is

$$\overline{\mu} = \frac{1}{n}\sum_{i=1}^{m}\sum_{j=1}^{n} H(\phi_{ij}).$$

The average number of functions per product is simply 88/5=17.6 functions per product for this small test case. Utilizing this equation for every element of the matrix in a new spreadsheet yields the normalized matrix shown in Table 11; note that the products have been resorted based on total function importance in descending order.

Table 11: Normalized Product Function Matrix

Functions	Garage Door	Blender	Stapler	B&D Drill	George Grill	Total
Transmit EE	5.0	8.4	0.0	66.5	12.8	92.7
Convert ME	8.1	0.0	34.0	18.8	0.0	60.9
Import Hand	2.0	6.5	26.3	19.9	0.0	54.7
Position Solid	0.0	7.4	20.1	8.9	14.3	50.7
Separate Solid	0.0	0.0	7.7	8.9	31.4	48.0
Regulate EE	7.6	7.4	0.0	0.0	31.4	46.4
Convert EE to ME	13.1	14.0	0.0	18.8	0.0	45.9
Import Signal	36.3	0.0	9.3	0.0	0.0	45.6
Store PE	0.0	0.0	37.1	0.0	0.0	37.1
Import Solid	0.0	11.2	6.2	8.9	8.6	34.8
Mix Solid	0.0	24.2	0.0	0.0	0.0	24.2
Export Solid	0.0	9.3	0.0	0.0	14.3	23.6
Distribute EE	0.0	0.0	0.0	0.0	21.4	21.4
Store EE	0.0	0.0	0.0	19.9	0.0	19.9
Transmit ME	4.0	0.0	0.0	14.4	0.0	18.4
Import Force	0.0	2.8	10.8	0.0	4.3	17.9
Stabilize Force	0.0	2.8	10.8	0.0	4.3	17.9
Transmit Force	0.0	2.8	10.8	0.0	4.3	17.9
Couple EE	0.0	0.0	0.0	17.7	0.0	17.7
Import EE	5.0	4.7	0.0	0.0	7.1	16.8
Store Solid	0.0	0.0	12.4	0.0	4.3	16.6
Transmit Signal	15.1	0.0	0.0	0.0	0.0	15.1
Acutate EE	0.0	0.0	0.0	14.4	0.0	14.4
Import HE	0.0	0.0	6.2	0.0	7.1	13.3
Convert EE	5.0	0.0	0.0	4.4	0.0	9.5
Rotate Solid	0.0	0.0	0.0	6.6	0.0	6.6
Convert HE	0.0	0.0	6.2	0.0	0.0	6.2
Transfer Heat	0.0	0.0	0.0	0.0	5.7	5.7
Convert HE to ME	0.0	0.0	0.0	0.0	5.7	5.7
Convert EE to Heat	0.0	0.0	0.0	0.0	5.7	5.7
Align Solid	0.0	0.0	4.6	0.0	0.0	4.6
Indicate Alignment	0.0	0.0	4.6	0.0	0.0	4.6
Guide Solid	0.0	0.0	0.0	0.0	4.3	4.3
Total	101.4	101.4	207.0	228.3	186.8	825.0

While this table shows rankings of functions based on importance, Table 12 shows other several useful points based on the percentage of functions and the percentage of functional importance. The last two columns in Table 11 are the most important as they show how the percentage total of functional importance compares to percentage of functions counted; the top three functions account for one quarter of total functional importance while being just 9.1% of the functions. While this very small sample set does not follow the Pareto 20-80 rule, the top 20% of functions still account for 43% of the total functional importance.

Table 12: Function and Importance Percentages

		1	2	3	4
Functions	Total	# of Funct	Tot Funct Wt	% Funct Wt	% # Funct
Transmit EE	92.7	1	92.7	11.2	3.0
Convert ME	60.9	2	153.6	18.6	6.1
Import Hand	54.7	3	208.4	25.3	9.1
Position Solid	50.7	4	259.0	31.4	12.1
Separate Solid	48.0	5	307.0	37.2	15.2
Regulate EE	46.4	6	353.4	42.8	18.2
Convert EE to ME	45.9	7	399.3	48.4	21.2
Import Signal	45.6	8	444.9	53.9	24.2
Store PE	37.1	9	482.0	58.4	27.3
Import Solid	34.8	10	516.8	62.6	30.3
Mix Solid	24.2	11	541.0	65.6	33.3
Export Solid	23.6	12	564.6	68.4	36.4
Distribute EE	21.4	13	586.0	71.0	39.4
Store EE	19.9	14	605.9	73.4	42.4
Transmit ME	18.4	15	624.3	75.7	45.5
Import Force	17.9	16	642.2	77.8	48.5
Stabilize Force	17.9	17	660.1	80.0	51.5
Transmit Force	17.9	18	678.0	82.2	54.5
Couple EE	17.7	19	695.7	84.3	57.6
Import EE	16.8	20	712.6	86.4	60.6
Store Solid	16.6	21	729.2	88.4	63.6
Transmit Signal	15.1	22	744.3	90.2	66.7
Acutate EE	14.4	23	758.7	92.0	69.7
Import HE	13.3	24	772.1	93.6	72.7
Convert EE	9.5	25	781.5	94.7	75.8
Rotate Solid	6.6	26	788.2	95.5	78.8
Convert HE	6.2	27	794.4	96.3	81.8
Transfer Heat	5.7	28	800.1	97.0	84.8
Convert HE to ME	5.7	29	805.8	97.7	87.9
Convert EE to Heat	5.7	30	811.5	98.4	90.9
Align Solid	4.6	31	816.1	98.9	93.9
Indicate Alignment	4.6	32	820.7	99.5	97.0
Guide Solid	4.3	33	825.0	100.0	100.0

4.3 Functional Importance from UMR Data

The same process used on the data from five sample household products is applied to data graciously provided by Dr Rob Stone from a repository of over 69 products developed and maintained over a period of several years covering 241 distinct functions. This repository requires hundreds if not thousands of hours to populate with data. The products included range from an air purifier to an electric wok and cover all realms of mechanical engineering. These products have from 5 to 43 functions each with a total for all products of 1,318 functions. With 69 products in the data, this gives 19.1 functions per product on average. Table 13 lists the top 20% of functions below. The two columns on the far right show the percentages of functional importance and functions respectively. With this much larger data set, note how the top 20.2% of functions account for 79.8% of all functional importance correlates very well with Pareto's 20-80 rule.

Table 13: Top 20% of Functions from UMR Repository

Product-Function Matrix	Total Importance	Number	Tot Function Weight	% tot func wt	% of funct
transfer electrical energy	472.0	1	472.0	15.7	0.41
transfer mechanical energy	225.1	2	697.1	23.2	0.83
import human material	122.0	3	819.1	27.3	1.24
export human material	100.8	4	919.8	30.7	1.65
import human energy	98.1	5	1017.9	33.9	2.07
change mechanical energy	91.0	6	1108.9	37.0	2.48
import solid material	87.8	7	1196.7	39.9	2.89
guide human material	76.9	8	1273.5	42.5	3.31
export solid material	71.0	9	1344.5	44.8	3.72
actuate electrical energy	69.9	10	1414.4	47.1	4.13
guide solid material	59.8	11	1474.2	49.1	4.55
import electrical energy	58.6	12	1532.7	51.1	4.96
actuate control signal to electrical energy	45.3	13	1578.0	52.6	5.37
convert human energy to control signal	40.3	14	1618.3	53.9	5.79
convert electrical energy to mechanical energy	36.7	15	1655.0	55.2	6.2
change rotational energy	35.8	16	1690.9	56.4	6.61
supply electrical energy	35.2	17	1726.1	57.5	7.02
separate solid material	34.8	18	1760.9	58.7	7.44
store electrical energy	34.4	19	1795.3	59.8	7.85
guide mechanical energy	32.9	20	1828.2	60.9	8.26
distribute mechanical energy	31.6	21	1859.8	62.0	8.68
export human energy	31.5	22	1891.3	63.0	9.09
transfer control signal	31.4	23	1922.7	64.1	9.5
store solid material	27.5	24	1950.2	65.0	9.92
stop mixture material	26.0	25	1976.2	65.9	10.3
convert human energy to mechanical energy	23.6	26	1999.7	66.7	10.7
guide gas material	23.5	27	2023.2	67.4	11.2
import mixture material	22.8	28	2046.0	68.2	11.6
store mechanical energy	22.7	29	2068.8	69.0	12
export mixture material	21.0	30	2089.8	69.7	12.4
convert human material to control signal	19.1	31	2108.9	70.3	12.8
transfer rotational energy	18.6	32	2127.5	70.9	13.2
regulate control signal to electrical energy	18.2	33	2145.7	71.5	13.6
supply mechanical energy	18.0	34	2163.7	72.1	14
stop solid material	17.2	35	2180.9	72.7	14.5
export mechanical energy	16.8	36	2197.8	73.3	14.9
import mechanical energy	16.7	37	2214.5	73.8	15.3
distribute electrical energy	16.1	38	2230.6	74.4	15.7
stabilize mechanical energy	16.1	39	2246.7	74.9	16.1
couple solid material	15.7	40	2262.4	75.4	16.5
guide mixture material	15.7	41	2278.1	75.9	16.9
export gas material	15.5	42	2293.6	76.5	17.4
secure solid material	15.3	43	2309.0	77.0	17.8
convert mechanical energy to pneumatic energy	15.2	44	2324.1	77.5	18.2
convert electrical energy to rotational energy	15.0	45	2339.1	78.0	18.6
guide human energy	14.7	46	2353.8	78.5	19
regulate electrical energy	13.7	47	2367.5	78.9	19.4
transfer solid-liquid material	13.2	48	2380.7	79.4	19.8
change electrical energy	13.1	49	2393.9	79.8	20.2

Several valuable insights come from this data from both a flow and functional point of view. First, the top two functions deal the transfer of energy either electrical or mechanical and account for over one quarter of the functional importance making the transfer of energy the most important function by far. The transfer function also appears three other times for five total functions in the top fifty. Importing and exporting flows may not be critical as transferring flows, but they account for more of the important functions; of the eight other functions in the top ten, five of them deal with importing or exporting flows of energy or material, and they account for twelve of the top fifty. So while transferring energies internally are critical first and foremost, import and exporting flows are still very important to meeting customers since they are the primary interactions the customers have with the products. Of the remaining thirty-three functions in the top fifty, over one third of them are covered by these three functions: convert (6), guide (5), and store (3). Of these three functions, converting energy deals with different energy forms, but the more important aspect maybe the conversion efficiencies and minimizing number of required conversions between forms. The guiding functions deal primarily with materials (four out of five); storing functions deal with both energies (2) and material (1). With the key functions covered, this leads to a discussion of how the top functions are divided among the three types of flows.

While the top ten functions are split evenly between material and energy flows, overall twenty nine of the fifty functions deal with energy with only nineteen dealing with material flows. This seems logical as most home appliances have energy flows (either mechanical or electrical) through them while not all have material flowing through them. Meanwhile functions dealing with signal flows account for only five of the top fifty functions yet they all occur in the top thirty three. Note that some functions deal with two different types of flows accounting for the three types of flows totaling up to fifty-three functions. Signal flows deal primarily with the conversion of energy into signals or vice versa. In fact, the top two signal functions, numbers thirteen and fourteen, are "actuate control signal to electrical energy" and "convert human energy to control signal." It would seem reasonable that these two functions would occur in series often as manual control often deals with the conversion of human inputs into a control signal which becomes an electrical voltage.

There are two points of view on how to deal with the functions that entail electrical energy. The major electrical functions are transfer, actuate, import, supply, store, distribute, regulate, and change electrical energy. A typical electrical breadboard has the ability to perform all of these functions. Therefore some would say it is reasonable to ignore these functions for a mechanical breadboard. While this may be allowable for a statics breadboard, the electro-mechanical, thermal fluids, and full prototyping breadboards would require use of some of these functions in order to meet customer needs. One possibility would be to use an electrical breadboard in conjunction with the mechanical breadboard. While this is possible, the physical size and rigid shape of a breadboard limits where it can be placed and requires significant time to setup circuits on it.

Another option would be to have a dedicated electrical capability integral to the mechanical breadboard. This would require a power supply input/output as a device for a variable power source, sensors for feedback and/or control, and a signal conditioner/generator to input, output, or alter control signals at a minimum. An easily programmable controller as seen in Lego© Mindstorm would be a nice addition as it would reduce the time to build and program circuits. The development of this option would not be a trivial event since it would potentially have to handle many different levels of voltages and amps of current. Likewise there are many different connections for off-the-shelf electrical components. With all the variables in this electrical regime, it would be a serious undertaking to develop this portion of the system.

As far as the purely mechanical realm, the most important functions are the transfer, changing, guiding, distributing, converting, and storing of mechanical energy. Changing of rotational energy appears at number sixteen, but it is really a subset of changing mechanical energy. Another important function is the conversion of electrical energy in the mechanical energy (again the rotational energy variant falls under the overall mechanical description) though this is typically done with electric motors.

It is interesting to note that the two key functions of the electrical breadboard backbone did show up in the top 50 in indirect ways. Those two key functions were described in non-basis terms as “provide support to components” and “provide a common interface for components”. The provide support function can be found under the "stabilize mechanical energy" function at number thirty-nine and under the "guide material" functions at numbers eight, eleven, twenty, twenty-seven, forty-one, and forty six. Though not in the top 20%, the "position solid material" function at number ninety-two also falls under this function and is probably a better analogy to the need. The common interface is covered under the "couple solid" at number forty and the "secure solid" function at number forty-three. "Secure solid" also counts for the "provide support" function as well since this function typically means "attach" which is ambiguous from this point of view. Further "secure" can also be interpreted as "join" for the connect function or as "mount" or "fasten" for the provide support function. The electrical breadboard demonstrates the importance of "couple solid" and "secure solid" as the two "structural" functions. While not the primary functions of a device, they are critical supporting functions and are enablers for all other functions. Said another way, these two functions are prerequisites to being able to perform the primary functions; without this form, function is not possible. The rankings of "couple solid" and "secure solid" are expected from the functional modeling as these supporting functions typically receive a lower weighting than primary functions by the customer.

To summarize the functions, Figure 22 below shows the flow of primary and supporting functions. The top flow shows the generically how the functions key to customer needs import flows, act on them, and then export the desired outputs. Running parallel to these primary flows are the supporting functions required to allow the primary flows to happen. This flows and functions deal with the backbone or support structure of the system. In the electrical breadboard system, this flow is the familiar white board. These functions provide the form of the system without which no other functions would be possible. Chapter 5 will detail in depth the concepts developed to meet the "secure solid", "locate solid" and "couple solid" functions shown in the lower flow.

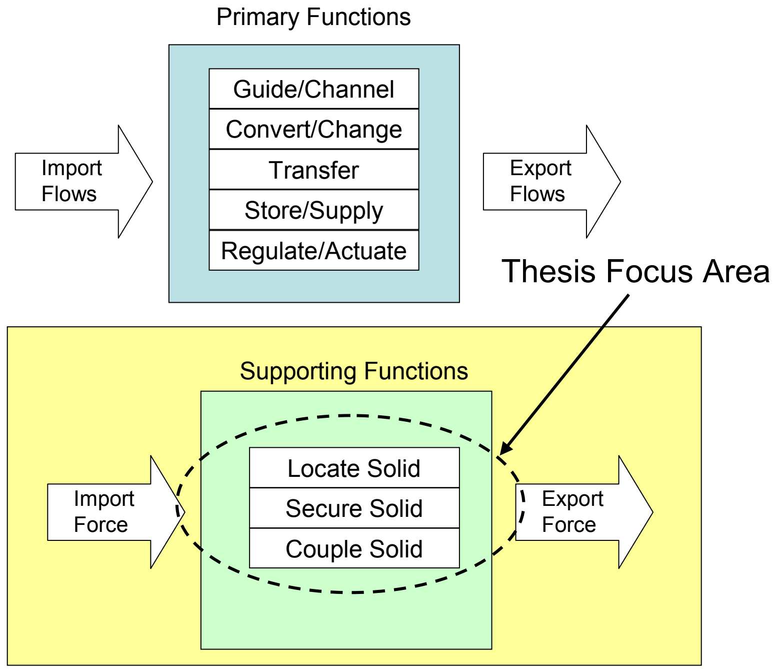


Figure 22: Primary and Supporting Functions Flows

4.4 Chapter Summary

This chapter deals with the determination of the key functions for the mechanical breadboard. The five sample products chosen covered most of the major areas of mechanical engineering. By using common consumer household products, the analysis remains simple and is done more to ensure familiarity with the process of functional modeling than to reveal any important trends in the data. Functional modeling starts with the development of a black box which simplifies the product into an input/output device. This identifies the key flows of energy, materials, and signals into and out of the device. Building the functional model traces these key flows from input to output first using intuition then by disassembly and inspection of the product's components. With the functional models developed for each product, the models are converted to a common basis of general flows and functions developed initially by Dr. Little et al and refined by Wood, Stone, and McAdams over the next few years (Little et al, 1997; Stone & Wood, 1999; and McAdams & Wood, 2000).

The next step in the process correlates these common basis functions to customer needs and their associated importance. The functional importance total for each product is recorded in a spreadsheet that contains all functions and products studied. In order to prevent complex products with many functions and customer needs from dominating the results, the results are normalized for each product and function using the method developed by Dr. McAdams and Dr. Wood (McAdams and Wood 2000). Once a new normalized matrix is formed for the raw data, the functions are sorted according to total functional importance across all products. Pareto's 20-80 rule states that 20% of the functions will contain 80% of the total functional importance. While the small sample set did not agree exactly with 20-43 results, this rule is born out in the 20.2-79.8 results seen in Dr Stone's product repository data using a much larger data set of 69 products. The top 20% of functions from the repository data were analyzed for trends and to determine which functions should be focused on for development of the breadboard.

In a complete system, the energy and material flows dominate the signal flows for both total importance and percentage of functions in the top 20%. The transfer of energy dominates all other functions with the top two spots and around one quarter of the total importance. Next, the importing and exporting of materials and energy rank as very important probably due them being the key interactions the customer has with the device. This is logical since many products that get poor human interaction reports do not fare well on the market regardless of how they function otherwise; think of how "plug-and-play" devices have become the gold standard in home computers or how a car that performs well but gets poor ergonomic marks will not sell well typically. Functions related to electrical energy can often be met with an electrical breadboard, but it would be up to the developer to utilize that solution or have a "plug-and-play" included electrical solution that requires less electrical engineering expertise. Other key functions deal with the converting of energies, guiding of materials, and storage of both energies and materials. While signal flows maybe less important for the simple statics market, for electro-mechanical and thermal fluids regime and beyond, sensors are integral to determining feasibility of prototypes and demonstrating principles. Lastly the two key traits of the electrical breadboard backbone appeared in the functional importance matrix under “couple solid”, “locate solid”, and “secure solid” primarily. These two functions are critical to the structure of any mechanical breadboard. Without these functional enablers, primary functions will not perform well. Chapter 5 will spend considerable time on the supporting structural functions.

Chapter Five: Innovative Breadboard Concepts

5.1: Introduction

This chapter covers the development of the mechanical breadboard concepts after identification of the key functions of consumer products. The development focuses on the “couple solid” and “secure solid” functions as they have the most opportunity for growth and innovation. This chapter does not discuss the other functions in the previous chapter since for two reasons: first, since this structure concept is designed to replace the plate system already in use in the Pic Design and WM Berg products so it will utilize those components and second, the development process for these other functions in many cases should be more a parts selection from off the shelf sources than a development of new components. The goal of the mechanical breadboard development is not to develop new components for the other key functions, but to allow variability in the connection and location of components to prototype various systems. The components contained in the WM Berg and Pic Design breadboards were designed by each company and not off the shelf components, but the novelty of their designs lies in the connection methods than in the actual functions the components perform. For example, gears are a staple of most mechanical breadboard systems beyond the most basic of static systems. The goal of this thesis is not to develop a new type or system of gears, but to develop a system of locating gears on the structure quickly, easily, and with as much flexibility as possible. There is far more opportunity to create an innovation in the ability to connect or locate components on the mechanical breadboard than trying to re-invent or improve all the mechanical components which a breadboard includes. Other companies spend countless hours and dollars to improve these key mechanical components every year. This thesis and chapter focus on improvements to the structural functions of the mechanical breadboard.

While the plate structures of the WM Berg and Pic Design breadboards have some variability inherently with the slotted layout, the focus of their designs are clearly in the other components and their connections, not in the structural pieces that allow for variability in location and connection. The kits do offer the common thread of standard shaft sizes for connection of various components and use a limited number of hand tools to achieve this connectivity. So while they have created a satisfactory connection system, this leaves a significant opportunity to substantially improve the structural components of the breadboard.

Therefore, the focus of this chapter will deal with the development of a structural system that maximizes location and attachment flexibility while keeping costs as low as possible. The goal is to create a support system that maximizes the flexibility to locate components in all three dimensions. It needs to be lightweight and give the ability to connect components in any angle or plane. It should connect reasonably quickly and require a minimal number of tools to assemble. The structural system should be able to reasonably mimic the actual support structure of a system.

This chapter walks through the development of the new mechanical backbone structure. The core design group includes the author and two undergraduate students. Occasionally the team involves other graduate and undergraduate students to bring fresh ideas and critique group-developed concepts. Throughout the concept generation process, the development team discarded several good ideas for various parts of the system due to cost, complexity, or other issues. This chapter will highlight some of those ideas in the hopes of sparking innovation in others who can further refine these concepts. The remainder of the chapter deals with the improvements made to the chosen concept and the initials prototypes built from it. The chapter begins with an introduction on how the groups generated ideas and concepts.

5.2 Mind Mapping

Mind mapping is one approach to the problem of idea generation and organization (Otto and Wood, 2001). It begins with a central idea or issue such as "couple solid" and tries to categorize all possible solutions into various fields or branches. Rather than just recording the ideas and grouping them, with each new category identified a group moderator focuses the entire group on developing a solution based the new category. For instance, one category of solutions for “couple solid” is adhesives. Instead of just one person offering up an idea such as an epoxy solution and the group moving on, the moderator then asks the team to focus on adhesives as a solution category and develop as many solutions as possible based on adhesives. This approach leads to more ideas and solutions than letting each person focus on only a few of their own ideas; as an added benefit, this type of group involvement leads to more refined ideas from a cross-pollination of different people’s inputs than if the moderator left the group to each individual’s own devices. Our development group uses mind maps to start most idea generation sessions for the various challenges. As stated, the mind map helps categorize and expand possible solutions and often by combining various solutions from different branches, better final solutions evolve. For example, the group mind mapped how to connect skeletal frame members to central nodes which Figure 23 shows below with categories of degree of freedom allowed. The long numbers displayed below reference the patent numbers of various connectors. This mind map spawned three major categories and seventeen solutions based on those categories. It is unlikely without the mind map the group would develop seventeen unique ideas. Some of these ideas became innovative solutions that the following sections detail. Appendix D contains the original minds maps for the major function or issues the group tackled. Ultimately the group filled three separate 50 page drawing notebooks with ideas and sketches covering hundreds of concepts.

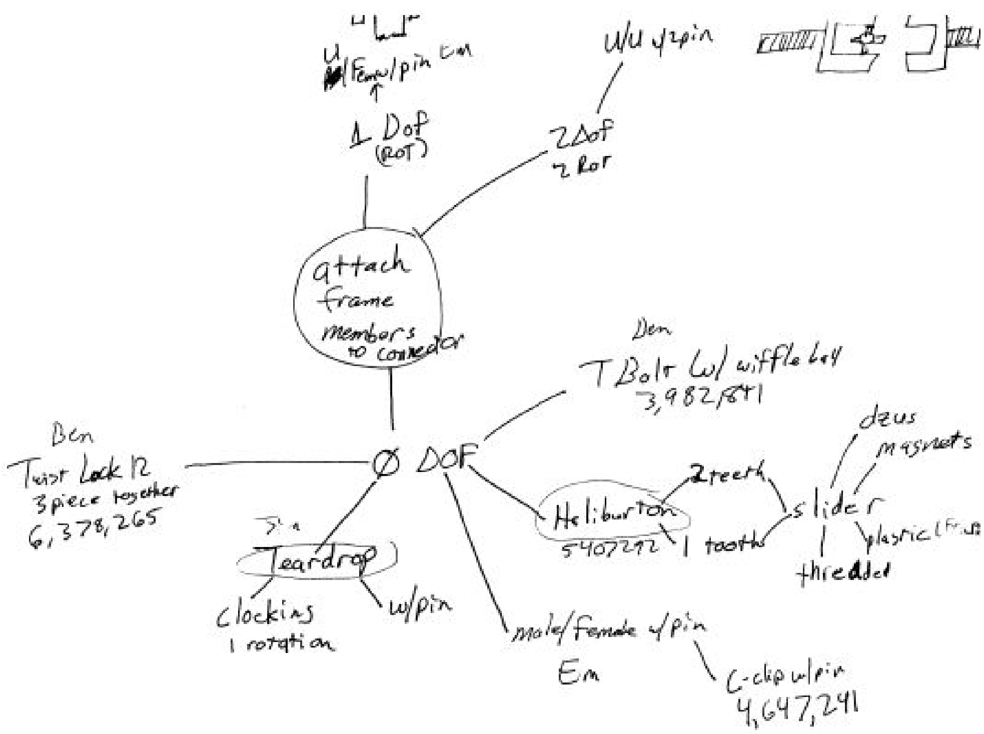


Figure 23: Original Mind Map for Connecting Frame Members to Nodes

5.3: Structural Breakdown

Two general categories divide the structural possibilities for mechanical breadboards as the group ultimately defined them. These options mirror the structural options for living organisms of exoskeleton or endoskeleton. The group developed the terms “skeletal” and “modular” to describe the two possibilities. Modular systems have components which do not require external support to locate them and can carry loads without additional bracing. The original Lego systems are a modular system where practically every component provides its own structure and adds to overall structural stability. In these systems, typically no distinction exists from sections which provide structure or locate components and those which perform other user functions. A variation of the modular systems can also be likened to insects where by on the exterior is the structural load bearing portion of the component, but there are internal components housed in the exoskeleton which perform operations just as an insect leg carries weight on the exterior while arties and veins carry needed fluids internally. In the mechanical realm, the primary advantages of these systems are a reduced number of components by the deletion of dedicated structural components and reduced construction time since they do not require construction of a separate support structure. However, like in an insect, the exoskeleton approach limits the growth and flexibility of the components.

On the other side of the fence are the skeletal systems. These systems have components whose primary function is to locate and provide a rigid structure for other components which perform the critical functions required by the user. These structural components are the form which allows the function of other components. An Erector© set is an example of a skeletal with distinct components such as beams and rods to support loads and locate other components such as pulleys, wheels, gears, etc. as they perform operations. The WM Berg and Pic Design breadboards have distinct structural components such as the connection plates, shaft and bearing hangers, and mounting brackets and so belong in the skeletal family of breadboards. As mentioned in Chapter 1 and shown in Figure 24, these structural systems give one analog (continuous) degree of freedom in the Y axis via the long slots in the plates and a discrete degree of freedom in the X axis with the regular spacing of the slots. Figure 24 shows the plate with the slots and their spacing along with a linkage system installed on the plate.

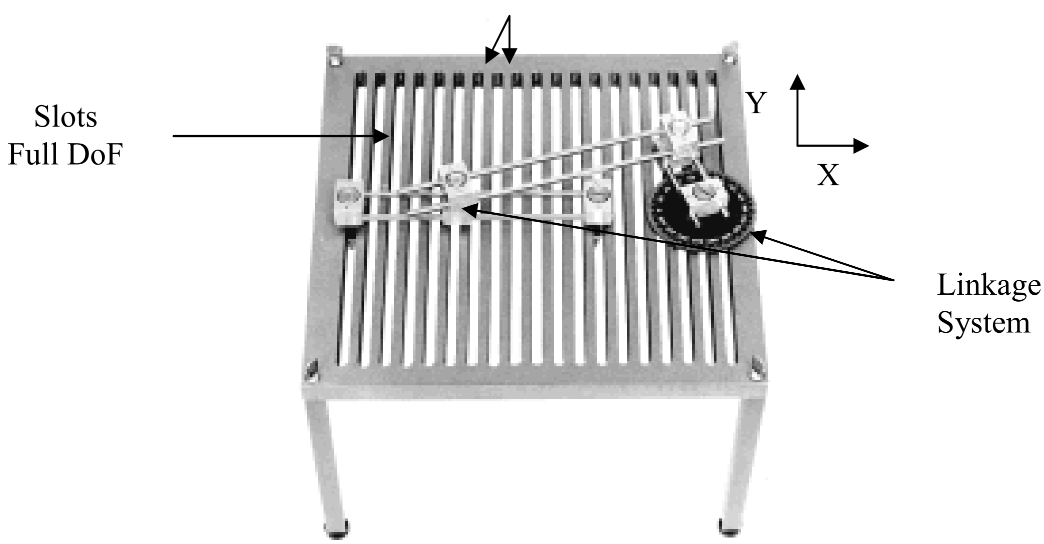


Figure 24: WM Berg/Pic Design Plate Layout (www.wmberg.com, 2006)

With the introduction to the two major structural categories complete, the next section covers the modular concepts in detail.

5.3.1 Modular System Concepts

The group spent considerable time considering solutions based on a modular system and developed several ideas with some merit. Admittedly these series of systems are more difficult to visualize since most current systems and components rely on a dedicated support system rather than having functional components which have their own built in support structure. The ideas developed under this branch revolve around either prefabricated blocks or a system of plates which come together to form blocks. The rest of this section details the two major modular solution branches and their advantages / disadvantages.

5.3.1.1 Block Concepts

Several concepts focus on a central idea of having a series of rectangular blocks that have a standardized interface at each face of the blocks. These blocks have at least two sides with the same length with a third length either equal to or a multiple of the primary length, giving either a rectangular or cubic shape as Figure 25 shows below.

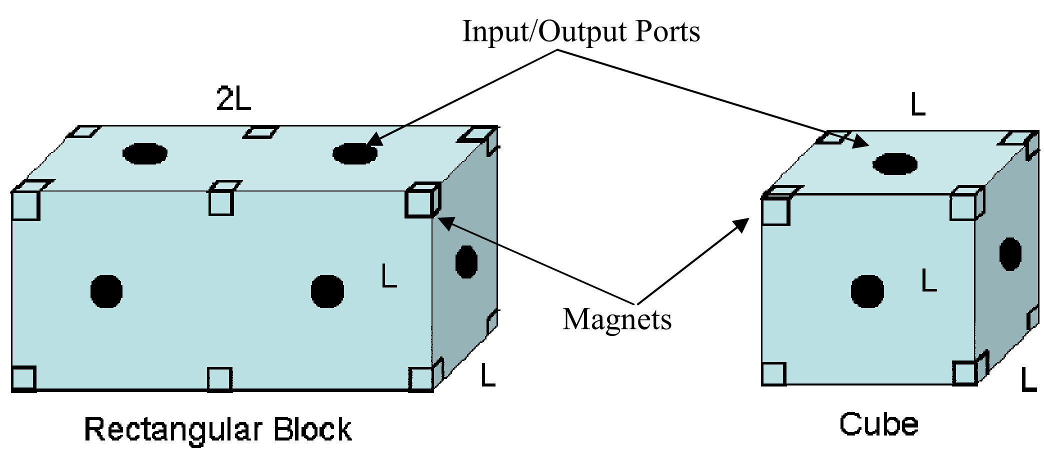


Figure 25: Modular Block Options

These blocks and cubes house the components which perform the primary functions such as transmission and conversion of energy. The blocks would be color coded depending on which function they perform as requested during the customer interviews. Some blocks would simply have shafts to transmit power; others might be gear boxes to change direction or convert torque to rotational velocity; still others might contain DC motors or other prime movers. The circular input and output ports would be located in the center of the faces so that every block can connect with every other block on any face. To allow for variability in internal components and routing of inputs and outputs, the blocks need an ability to open for functional component replacement and modification.

The group developed several options for connecting the blocks to each other. Figure 25 shows a concept utilizing magnetic and steel cubes. By using an equal number of magnetic and steel cubes, this minimizes the chances of having like poles in contact and creating repulsion.   Another option uses dove tail notches made in the center of each edge with separate dove tail connectors to join the blocks. A third option utilizes a turn-buckle-like setup of expanding threaded rods. The threaded rods screw outwards into female ends in the other blocks by rotating thumb knobs in the blocks.

Each idea has advantages and drawbacks. The magnetic system is truly a quick connect system, but the magnets provide only limited strength especially in a shearing force setup. Assuming a two inch cube, the magnets in each corner would need to be no larger than ¼". Cubic magnets of this size provide around six pounds of pull force each in an N40 grade (www.rare-earth-magnets.com, 2006). With a cost of nine dollars plus shipping for twenty cube magnets which is enough for just 2.5 cubes or 1.67 rectangular blocks, the small powerful magnets become expensive very quickly as a connection system. The dovetail joint system would require cuts for each edge in either a horizontal or a vertical plane, but not in both planes as the chances for tear out would increase greatly.   The limitation of having only one plane in which to connect blocks limits the connection options for multiple blocks stacked together. For a better visualization, consider the original Legos cubes which have the same limitation of only connecting in the vertical axis so that connecting to two blocks side by side requires a connecting block either above or below. The third concept of using threaded rods is the most stable and rigid of the ideas because of the threaded fasteners, but it would require more of the internal volume of the blocks and would be expensive because of the complexity involved. Additionally, this concept revolves around connecting along only the major axis of the rectangular blocks which is even more limiting than the dovetail concept. Of these options, the dovetail connectors appear to offer the most potential with their low cost yet solid connections especially since they would offer the same connection flexibility as the original Lego© systems which have been very successful as a construction set.

5.3.1.2 Face Based Modular Systems

The other major solution branch of the modular systems developed from the block systems. In order to maximize the flexibility of the blocks, the need to be able to change the internal workings of the block is apparent. In the previously discussed systems, the blocks have one face that slides or removes. In this branch of modular systems, the blocks are built from "faces" that are plates with connection cubes on all four edges of each plate. By having connections on every edge, these faces connect in either parallel or orthogonal directions. In fact a well thought out design allows connection of the faces in two planes at one edge.

For these concepts, two promising ideas both based on the idea of interconnecting cubes of "male" and "female" edges emerged. Female edges have half of the possible cubes while male edges have only two cubes. Figure 26 shows the key concepts below.

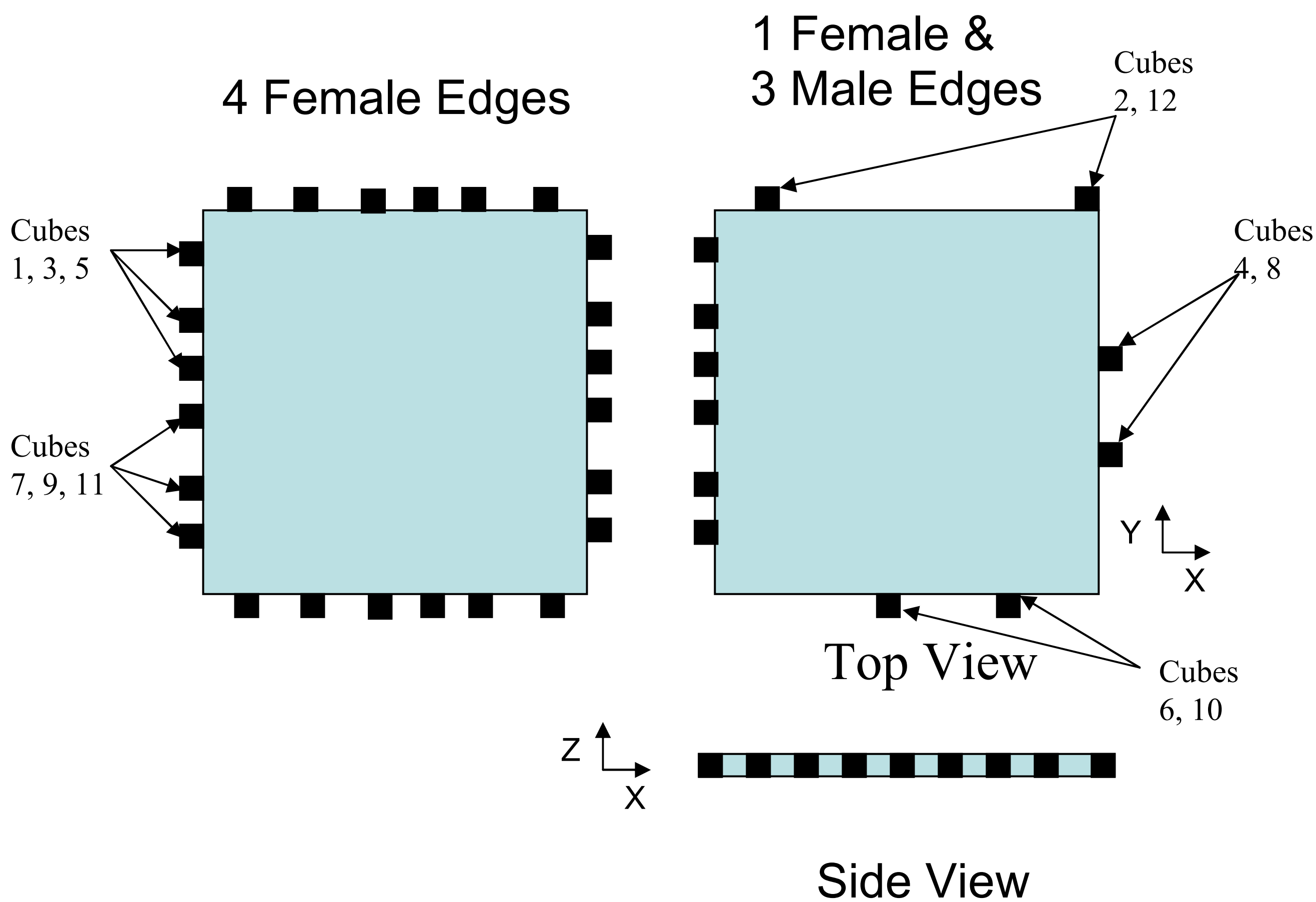


Figure 26: Male and Female Edge Face Concept

The above examples are based on a one and half inch edge on the square faces. The one and half inches on each edge divides into twelve 1/8" cubes numbered one to twelve sequentially from the left to right for example. Connecting separate faces requires that the edges have different numbered cubes in order to prevent physical interference. Our solution uses female edges with the odd numbered cubes (1, 3, 5, 7, 9, and 11) while male edges have two each of the even numbers cubes (2, 4, 6, 8, 10, and 12). One way to allocate the cube pairs to each male edge would be pairs of 2/12, 4/8, 6/10. Using this system of pairings allows the connections of three different male edges without interference to one female edge meaning every connection requires one female edge at every junction but can have one to three male edges joined to it. The system in Figure 26 shows two types of plates with either all female edges or one female and three male edges. In a perfect system that utilizes all edges fully by having three males edges at each junction, the system needs only the plates shown on the right since there will be a perfect ratio of three male edges to one female, but no system requires four plates are every junction since the outer portions of the structure will not fully utilize all of their edges. Therefore the system needs some plates have ratio greater than 3 male edges to 1 female edge; Figure 26 shows the example of the four female edges on the left as a possible solution.

This system is not a series of connected discrete cubes or blocks but rather a series of shared plates that allow the building of blocks to different dimensions in different axes. For example if one builds a cube from six of the plates, the edges of the cube will still have unfilled cubes along each edge. Additional plates can be attached at these unused cube slots to create additional cubes. In that sense, this solution is more of hybrid between a true modular and pure skeletal system as the faces have the functions of connecting components and providing structure for them while they still form an endoskeleton type setup where the other components are housed internal to the support structure.

The actual fastening system concepts developed centered either a series of small cube magnets or a pin system. With the magnet system, either the female or male edges would be magnet cubes while the opposite edges would be steel cubes. This prevents repulsion due to like poles being in contact; the fact that edges connect up to three faces at one edge makes preventing repulsion with an all magnet setup impossible. This concept has the same problem of limited holding power (say 12 pounds with two magnets used per edge) and the expense of six magnets for each plate with six faces to make a cube for a total of thirty-six magnets per cube at a cost of around twenty dollars.

The pin system relies on the cubes having a hole drilled down the length of the face. This allows the connection of several faces together, and then a pin placed into the aligned holes fastens all faces together. This system would either have to be made with very tight tolerances to prevent significant play in the faces or have much looser tolerances in order to ensure misalignments and production variances do not create pin insertion problems. Obviously, the tradeoff is in the free play of the system versus production costs for tight tolerances. Removal of the pins requires either an end that protrudes from one end or a smaller pin to drive out the primary pins. This strength of this system is limited by the diameter of the pins and cube cross sectional areas. Creating a stronger system requires thicker plates to allow for larger pins and thicker cubes.

5.3.1.3 Modular Conclusions

These modular systems offer some advantages. By standardizing sizes and interfaces, these systems like the Lego© systems connect quickly and perform both form and function in one component. With the color coding idea from the customer interviews, a system based on these modules would be excellent for young children as they learn to associate different modules with different functions. One idea in the same vein as the color coding is to have one face of the modules made of a clear plastic so users can see the inner workings of the modules. One company in Great Britain makes an electrical analog of this concept for young children called Logiblocs shown below in Figure 27 (www.logiblocs.com, 2006). Each block provides its own structure and performs a specific electronic function based on color.

Figure 27: Button, Switch, and Connector Logiblocs (www.Logibloc.com, 2006)

While offering a standard interface for each block, these modular concepts are limited to primarily orthogonal directions. Most real systems have more than just ninety degree angles in their construction. Even with the use of shapes such as pyramids and other more complex shapes, these shapes still limit the variation possibilities in the connection angles. Additionally because each module has both structure and other functions inherit to them, these modules will have some wasted space and weight due the standardization of sizes and connections. For example, not every gear box needs to be the standard block size so most gear boxes would contain empty space just to meet the size standard. This standardization ensures compatibility but trades off volume and weight efficiencies; in order to meet a plug-and-play need, size and weight increase across the system as a whole. One can think of the convoy analogy in that the group of ships can only move as fast as the slowest ship; in this case the size of the largest function determines the standard size of the blocks or at least the multiples of the standard size. So while these modular systems appear to offer promise for an early educational systems, the limitations imposed by a standardized connection system will limit the variability and freedom of prototyping most complex systems developed by engineers. This is an area where more effort could yield significantly better results if variability in the connections improves.

5.4 Skeletal systems

While the work devoted to the modular systems did not yield a viable system for our purposes, the efforts give the group a larger perspective as concept generation begins for the skeletal systems. A review of existing structural systems reveals several commercial examples. One family of these skeletal systems uses a system of slotted frame members into which connectors for other beams and components attach. These systems although rigid and strong are somewhat expensive. Additionally, the systems utilize the same ninety degree and other standard connection angles as the modular concepts so this limits the freedom in angle of connection. One major goal of the group is to maximize the degrees of freedom of the skeletal structure and of the connections to it by components. Figure 28 shows a one of these T slot type solutions with its ninety degree connection options (www.mkprofiles.com, 2006).

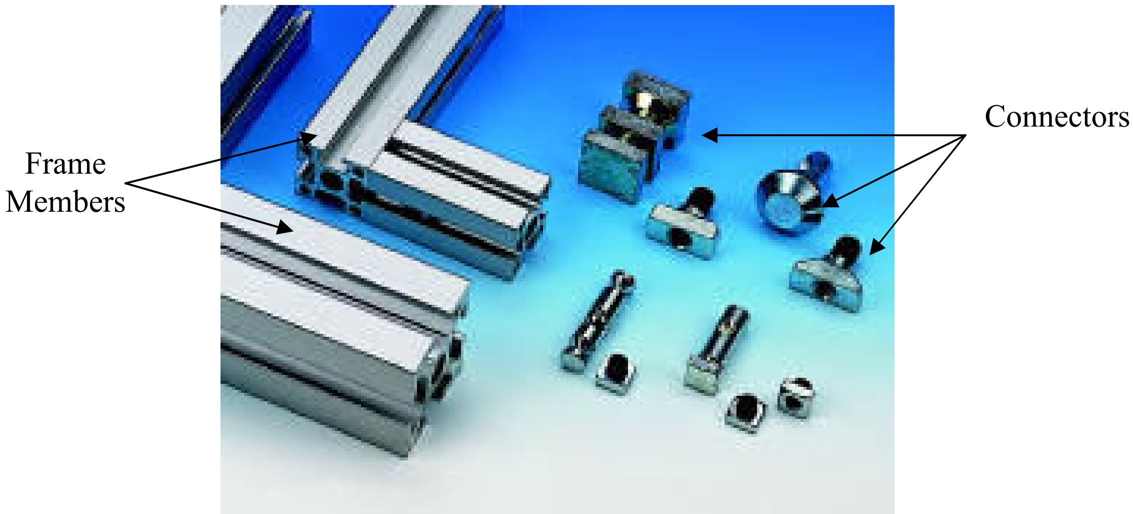


Figure 28: T Slot Type of Variable Structures (www.mkprofiles.com, 2006)

The group concepts eventually centered on two options for a skeletal system: a plate based system and a system of nodes and frame members. Both of these concepts share the idea of having beams as frame members who define the structure of the system. One focuses on maximum flexibility in a plane of connections while the other has slightly less instant flexibility but offers a true three dimensional approach.

5.4.1 Plate Based Systems

The plate based system arose from the plate systems of WM Berg and Pic Design. As stated previously, these plates have one full degree of freedom and one partial degree of freedom. The group's goal is to have two full degrees of translational freedom in the X-Y plane at least. Having slots in both directions would have partially met this need but is not physically possible with the layout of those plate designs. Even having slots in both axes still gives only a partial or discrete degree of freedom in each axis. Still the idea of slots as an infinitely variable method of locating a fastening point is very appealing to the group for its infinite flexibility in at least one translational direction. The idea for the best plate concept may have come from the gyroscope. Figure 29 shows an example of a gyroscope; note how the one pair of gimbals locates the other pair to give two independent degrees of rotational freedom.

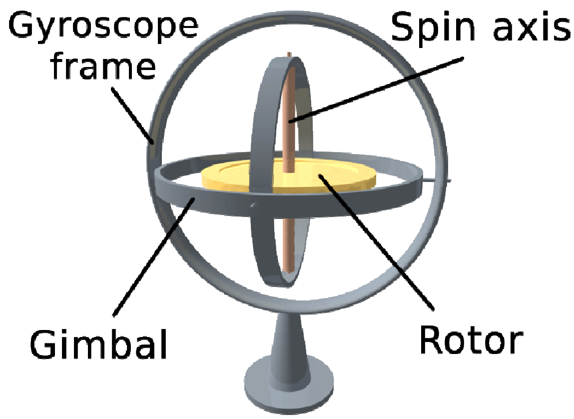


Figure 29: Gyroscope (Wikipedia.org, 2006)

This idea of one degree of freedom embedded in another led to the concept of embedding one slot inside another slot. The basic concept involves having a fastening point set in the slot of a beam. The beam ends are set in slots of fixed beams. The main beam offers a degree of freedom in the Y axis while the slot in the main beam gives the degree of freedom in the X axis. The limits of the freedom are the end of the main beam and the beams that locate it. The systems allows placement of the fastening point anywhere within that two dimensional space defined by the plate and beam ends. The original concept involved using a rectangular main beam with a “T” shaped slot cut into it for the sliding fastening point. This variant requires fastener attachment in the vertical plane. If the customer wants an additional degree of freedom, a cylindrical rod main beam coupled with a fastening component with a hole drilled through the center would allow the fastener to rotate in one direction as well as translate in two more. Figure 30 shows the rectangular variant of the concept.

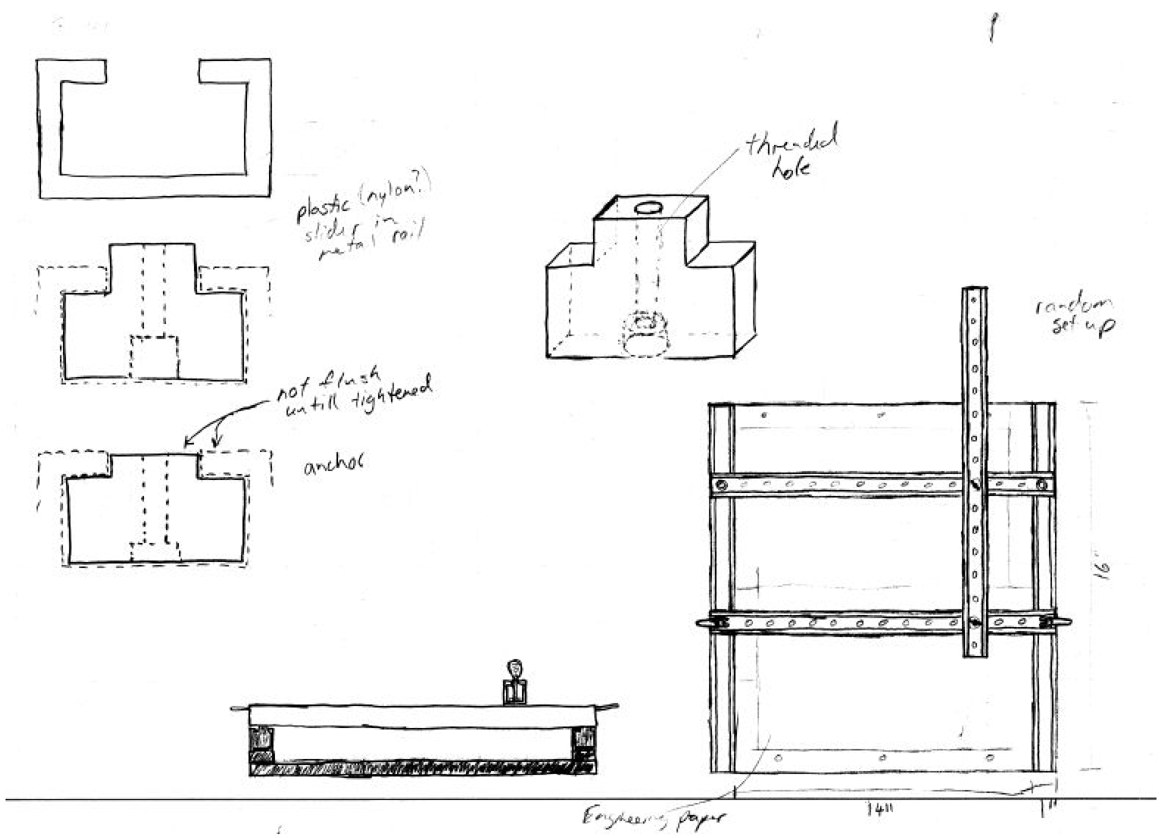


Figure 30: Sketch of 2-D Plate System

The obvious limitation of this concept is the two dimensional setup. A series of plates put together to form a partial cube offers a workaround to this issue. This still limits connections to six planes at most as opposed to a true three translation degrees of freedom, but by attaching beams in between existing planes, one can create new planes for attaching components. In a similar vein to the face based modular systems, connecting multiple plates allows expansion in all three planes. This expanded system still limits movement of the fastening points to individual plates. In the end, the design group decided to continue concept generation in hope of finding a more three dimensional solution. Hopefully this section shows the promise of this approach even though the design team settled on the next concept as the most promising.

5.4.2 Node and Frame System

The final concept developed and chosen is a structural system based on a series of frame members and nodes. The Tinker Toy© system is an analogy to the concept. The wooden rods are the frame members while the cylindrical hubs are the nodes. In this system, the frame members carry and transmit load to nodes which both connect and locate multiple frame members. The rigidity of the systems is based primarily on the frame members as well as the connections between the nodes and frames members. Both components of the structural system have key needs that require solutions. The frame members need to connect quickly to at least the nodes and possibly each other as well as allowing connection of functional components. The nodes ideally allow connection of frame members in any orientation at any angle. The following sections detail the development of both the frame members and the nodes. Figure 31 shows an example Tinker Toy© creation for reference; note the distinct nodes and frame members.

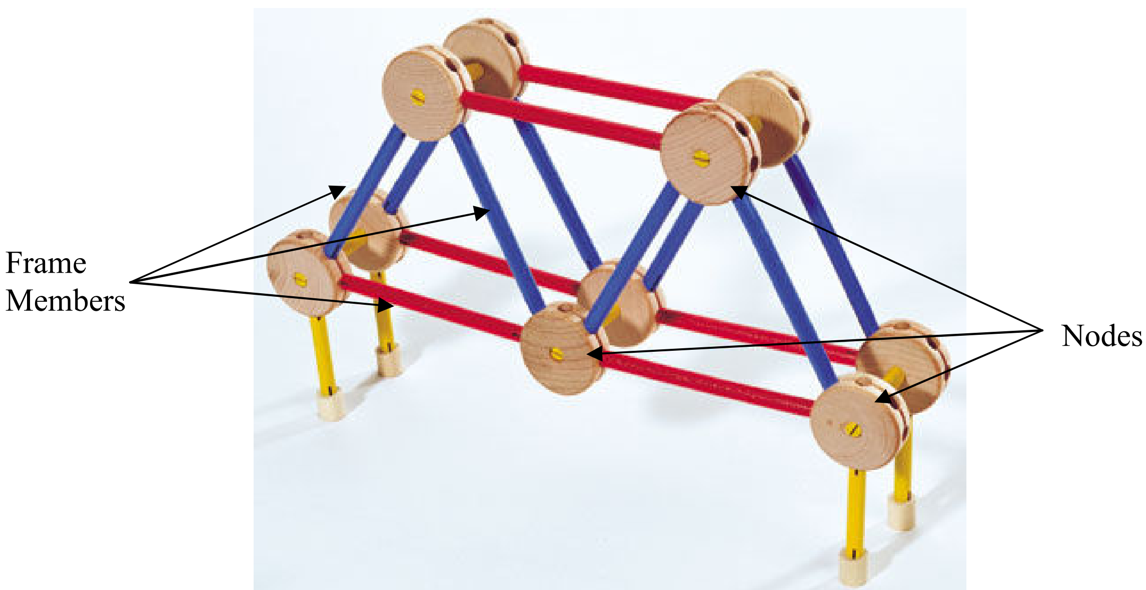


Figure 31: Tinker Toy Bridge (www.hasbro.com, 2006)

5.4.2.1 Node concepts

The group determined quickly the nodes would need to support connections in all three axes in order to build a three dimensional structure. Additionally, the nodes need variability in as many degrees of freedom as possible to support the connection requirements. In a perfect solution, the nodes would have a fluid or semi-solid consistency that allows placement of frame members at any angle but then goes to a solid when one applies a control signal. This approach is beyond the technical and monetary limitations of this research so the group focused next on using spherical nodes to give maximum versatility.

Spheres give a surface to attach frame members at any angle in a spherical coordinate system. The curved nature of the spheres does not give a flat face at any point for attaching the frame members however. The sphere nodes immediately brought in the idea of using steel nodes with magnets on the ends of the frame members. Steel nodes would be far more inexpensive than comparable magnetic spheres just based on the cost of the materials and production costs. Using magnets for connections on the face of sphere means a minimal connective force since there is so little physical contact. Having spheres with grooves cut into them to more positively locate the frame members is another option, but brings with it a similar limitation to the slots in the plate except that in this case there is one degree of translational freedom and an additional degree of rotational freedom. Also machining grooves into the spheres is a non-trivial exercise. Ultimately the cost of steel spheres versus other shapes made them impractical for this project. The group received a quote of $15,000 for 200 spheres from a vendor giving a price of $75 per sphere (www.precisionballs.com, 2006). While spheres may be financially possible for plastic parts, the expense of creating molds drove the group to pursue other solutions. Since spheres were impractical, the next logic step is to consider polyhedra.

The group evaluated many different polyhedra from cubes up to thirty plus faced polyhedra. The group discounted cubes since they offer the same basic ninety degree connections as the commercial skeletal frames. Conversely, the many sided polyhedra become increasing more difficult to make and locate the center of each face. Still the rhombicuboctahedron with twenty-six sides offered promise. Figure 32 shows the basic shape and our prototype made of aluminum.

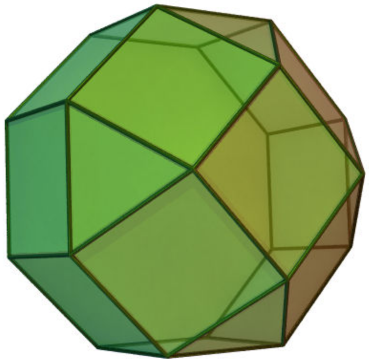
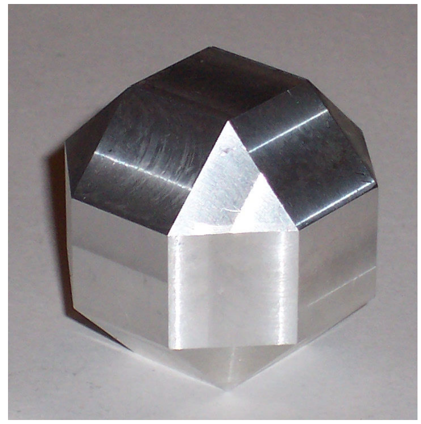
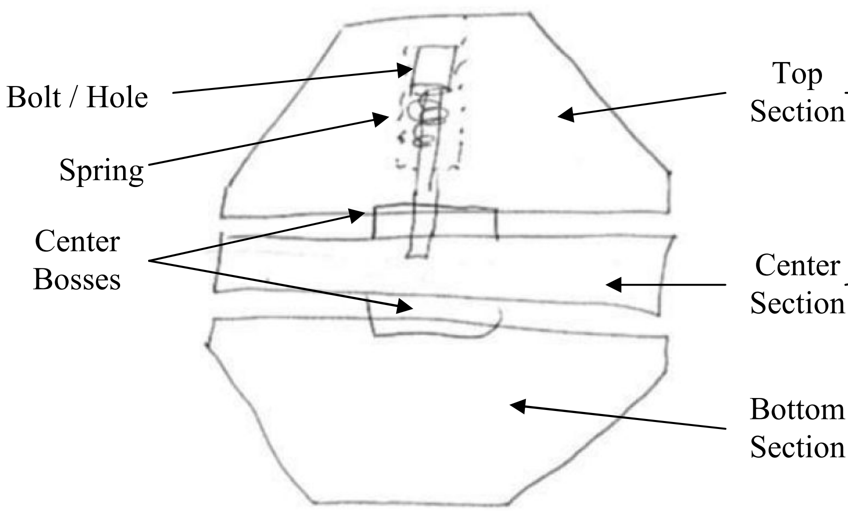
 

Figure 32: Basic Rhombicuboctahedron Shape and Prototype (Wikipedia.org, 2006)

The layout offers the same orthogonal faces as a cube with a forty-five degree face between each cube face as well. In additional, the triangles give eight more faces at forty-five degrees to the original forty-five degree faces. Effectively, this polyhedron gives a face at every possible multiple of forty-five degrees from a point. The group made two prototypes to determine the difficulty of making such a shape as well as the needed steps for a repeatable process. The first prototype took around three days just to make the shape. Additionally during the creation process the group discovered that no repeatable way exists to set the shape in a vise to mill the eight triangular faces. Milling the triangular faces requires a very slow and careful approach using eyesight to ensure an even and flat cutting plane. Obviously, this is not a practical approach for mass production purposes. While the shape does offer twenty-six different directions to attach frame members, this is a small number compared to the infinite possibilities in three dimensions. So based on the difficulties in prototyping and the comparatively limited connections, the group decided to continue concept generation in hopes of creating a more flexible and easier to manufacture node.

The group kept coming back to a design they dubbed “the Easter Egg” since it involved having a multipart node with rotating circular sections similar to the plastic Easter eggs children find candy in at Easter. The initial idea centers on a three part design with identical top and bottom sections attached to a center section via a vertical bolt and spring combination. The center section has bosses that rise above and below main portion of that section and provide the threaded hole for the bolts that connect the top and bottom sections. By fastening the top and bottom sections in this manner, all three sections can rotate about the vertical axis giving a rotational degree of freedom for two of the three sections relative to fixing one section. The top and bottom parts provide eight attachment points at forty-five degrees above and below the horizontal plane while the center section gives eight horizontal attachment points spaced every forty-five degrees. This arrangement gives a similar connection opportunity as the rhombicuboctahedron and also offers the ability to rotate two of the three parts relative to each other. The bolts provide a rigid ultimate connection while using springs between the bolts and the top and bottom sections allows the varying of the friction forces until full compression of the springs. The group built the first prototype with this concept as the basis. Figures 33 and 34 show the first sketch and prototype prior to drilling the holes.



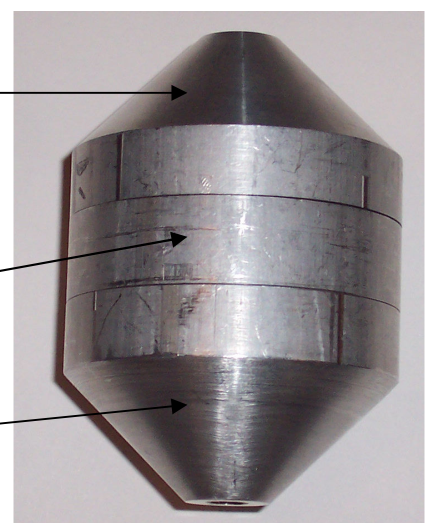


Figure 33: First Easter Egg Sketch **Figure 34: First Prototype**

The diameter of the assumed frame members and their associated bolt thread size of 3/8” x 16 dictated the primary diameter of 2.5 inches. The recommended number of engaged threads to ensure sufficient fastener strength is six threads however two more threads must be added to the total since the first two threads that do not provide a significant source of load carrying capacity as they are not fully formed typically (www.gizmology.net, 2006). With thread per inch count of 16 threads per inch, this implies a minimum thread depth of 0.5 inches.

Creating this first prototype took approximately two days in the shop. The weight and size of the initial prototype are substantial. It was readily apparent that making a structural system with this concept as the nodes would be impractical for small scale use as the prototype weighs several pounds and the system would require dozens of them to be useful. Still this prototype was much easier to produce since most of the angles can be cut on a lathe since the three sections come from large rod based blanks. In fact a CNC lathe can turn rod blanks into the proper shape in less than two minutes per part. So despite the drawbacks of this initial prototype, the group saw enough promise in this design to improve it rather than look for another solution.

The next iteration of the concept scaled the frame members to ¼"x20 thread size. This reduced thread size allowed the next prototype to have a primary diameter of 1.5 inches with a minimum thread depth of 0.4 inches. The forty percent reduction in diameter leads to a nearly eighty percent reduction in volume and therefore weight as well so the new prototype weighs only a few ounces compared to almost two pound weight of the first prototype. Figure 35 shows the vast difference in size between the 1st and 2nd prototypes.

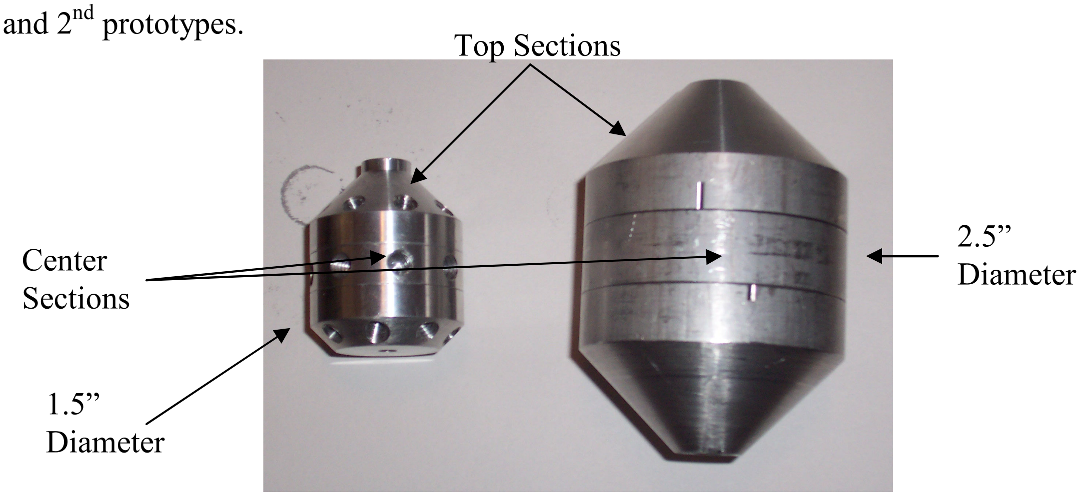


Figure 35: Comparison of Size of 1st and 2nd Prototypes

The actual prototype's top and bottom sections have different configurations as shown in Figure 36 below. The top section includes additional height to allow tapping of a vertical hole to allow connection of a frame member in that axis. A complete prototype of this variant called "2B" has a height of 2.25 inches versus the horizontal diameter of 1.5 inches. The bottom section, the "2A" variant, contains only a bolt to connect it to the center section and has no provision for attaching a frame member vertically which keeps its height shorter at 1.5 inches and weight lower. This result gave the group the opportunity to consider the tradeoff of size and weight for added connectivity. Another innovation in this variant is the change of one pair of threaded holes in the center section into one unthreaded ¼" through hole. Having an unthreaded through hole through the center of the node allows placement and sliding of the node on a frame member. This setup allows translation along the frame member as well as rotation about the frame giving two more potential degrees of freedom to the node. In order to lock or unlock these degrees of freedom, the node utilizes a #4-40 set screw in a center section hole at 90 degrees to this through hole. The initial prototype took approximately one week to build with the initial learning curve and the need to make jigs for drilling the holes every forty-five degrees. Figure 36 and 37 show the actual prototype and two CAD drawings of the two variants with cross sectional views.

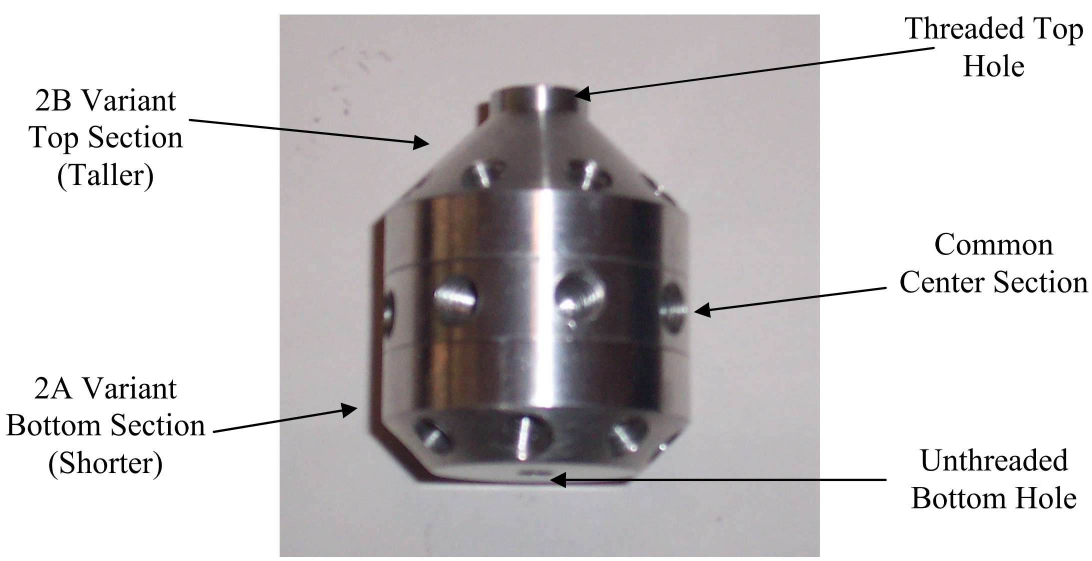


Figure 36: 2nd Hybrid (2B Top and 2A bottom) Prototype

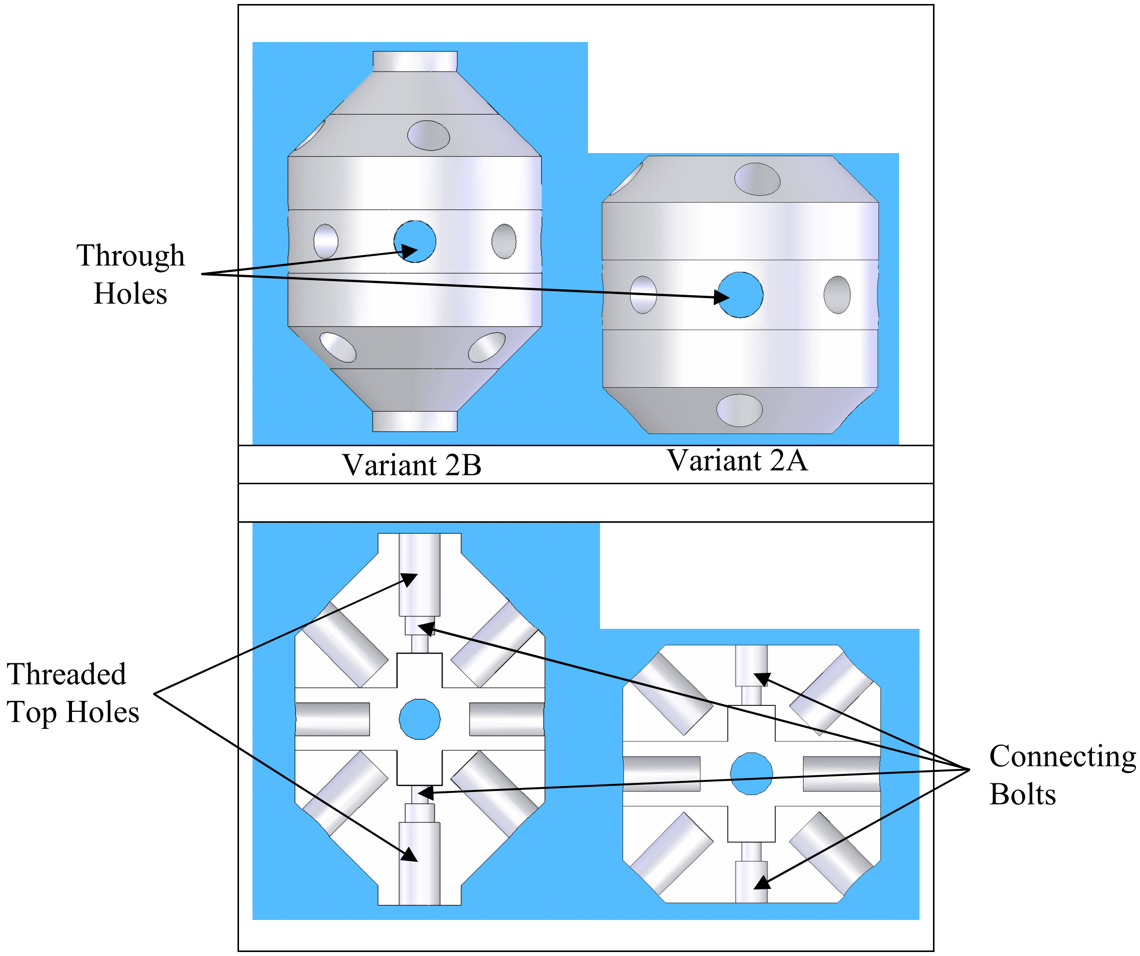


Figure 37: Variants 2A and 2B of second prototype

The assessment of this iteration of the concept both in physical form and CAD led to several discoveries. Since only one prototype existed, the group utilized CAD to determine if there would be any issues when used in multiple sets. The CAD work quickly demonstrated that with the unequal distance from the center of the node to each plane of holes, building a three dimensionally symmetric shape such as a cube required different length rods for the different planes. Additionally the threaded depth of each hole varied based on which planes the hole was in. In fact none of the planes of holes had the same depth. Therefore if the user is not careful when screwing in the frame members, each plane of frame members will become a different effective length even if all members were the same length.

To deal with these issues, the group developed two innovations. First, having two sets of threaded holes and bolts in the vertical axis, one to connect the top/bottom sections to the center section and then another for the frame member connection, drives the total vertical height greater than the horizontal diameter. Expanding the horizontal diameter to match the vertical height would have made the node almost as large as the first prototype. The solution lay in function sharing by having the vertically attached frame member become the bolt that connected the two components together. The group achieved this by enlarging and lengthening the boss on the center section to accept the ¼"-20 frame member threads and threading the frame members for a longer length to allow placement of a nut on the frame members. Figure 38 shows the difference in the two center bosses.

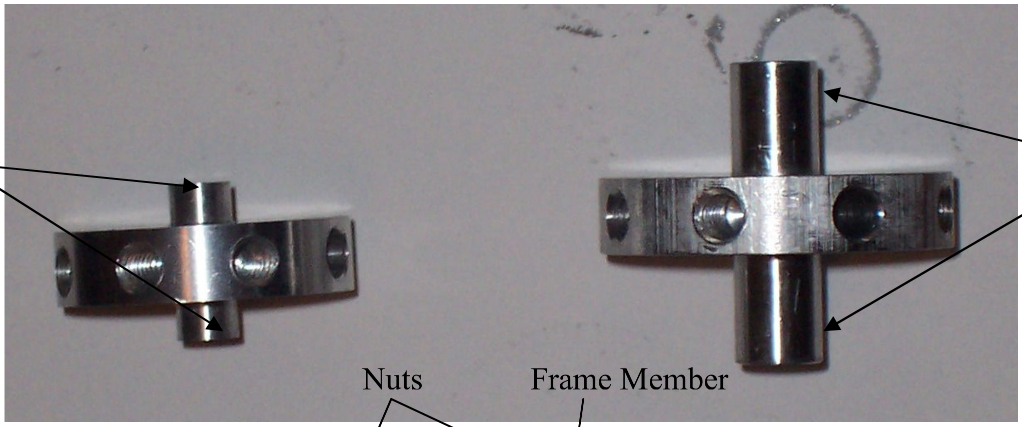


Figure 19: Bosses on Center Sections 2nd and 3rd Prototype

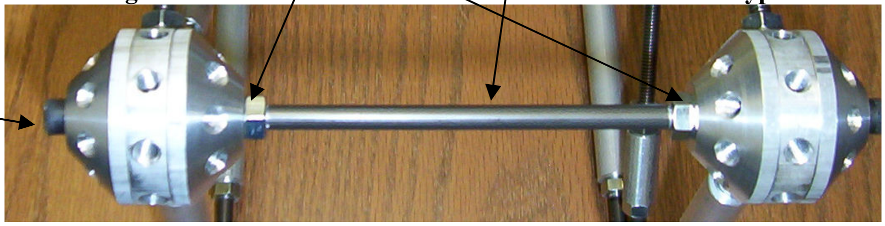


Figure 39: Top & Bottom Sections Attached to Center Sections by Frame Member with Nuts

The nut on the frame members tightens down on the top/bottom section to provide the needed clamping force. This setup makes the frame member and nut the connecting bolt. Alternatively if there is no vertical frame member, the user can substitute a standard ¼" bolt. Figure 40 shows the third prototype versus the second prototype; note how the third prototype is shorter and slightly wider.

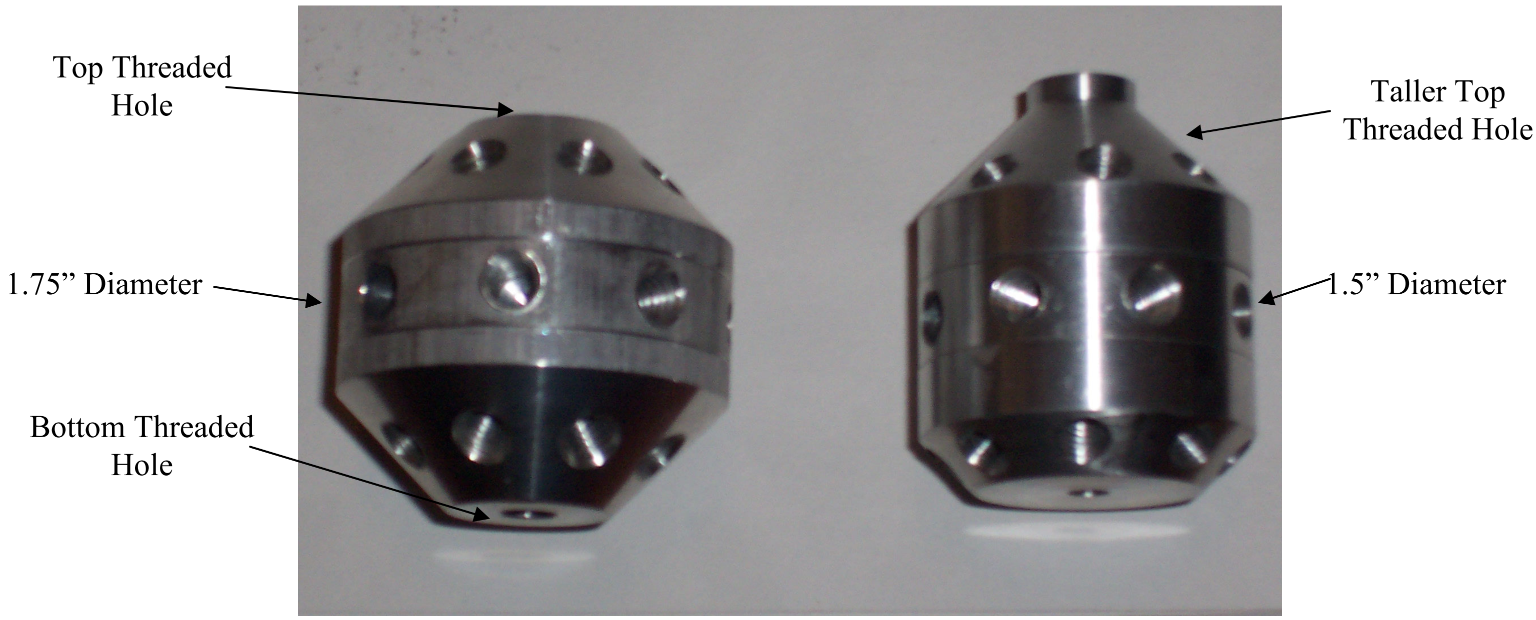


Figure 40: 3rd (left) and 2nd (right) Prototypes

By eliminating the need for two threaded portions in the vertical sections, the vertical height was almost the same as the horizontal diameter. The larger bosses in the center section did require a slight increase in the nominal diameter from 1.5 inches to 1.75 inches in order to maintain a sufficient thread depth in the off axis holes. Now all threaded holes are the same depth in all planes. This matching of horizontal diameter and vertical height gives the nodes an octagonal side view and cross section. The octagonal proportions coupled with circular layout in the vertical plane means that all holes in all planes are equidistant from the center of the node. With this setup, cubes and other symmetric shapes are possible with using only the same length frame members. Figure 41 shows in the section differences especially in the center sections.

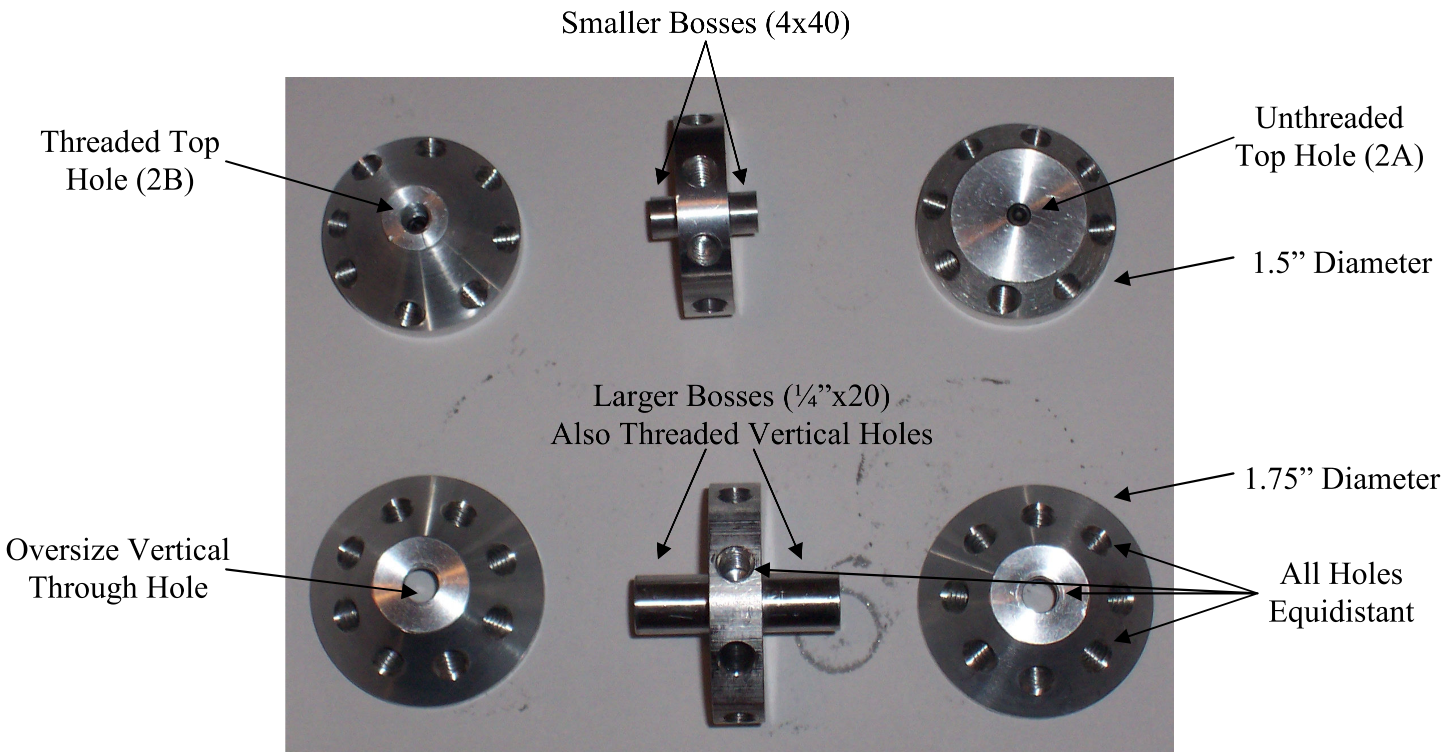


Figure 41: 2nd (top) and 3rd (bottom) Prototype Sections

Another benefit is rotation of the node about any axis yields the same effective fastening location whether utilizing a top, center, or bottom section hole, the only difference being the holes on the off axis and center sections can be rotated about the vertical axis while the vertical holes are effectively fixed. The plane in which a user requires a rotational degree of freedom determines in which orientation the user should attach frame members. The group also determined with this larger diameter node that the set screws holes could be a ¼”-20 so that all threads are now ¼”-20. This advancement reduces the tools needed to produce, assemble, and use the nodes. Another subtle detail involved tighter tolerances in the bosses in the center section and receiving holes in the top/bottom sections than the vertical through hole for the frame member/bolt in the top/bottom sections. This tolerance difference ensures rotating the top/bottom sections will not case the vertical frame member to loosen or bind. The nut on the vertically attached frame member will determine if the top/bottom section can rotate. These nodes slide along a frame member to offer one degree of freedom in translation as well as two degrees of rotational freedom: one about the frame member longitudinal axis and another degree of freedom each in the top and bottom sections about the node's own vertical axis. With this many degrees of freedom, the nodes can project a frame member at almost any angle from a point. This is as good as a tradeoff of flexibility for structural integrity as the group found in three plus months of creation and testing. Figure 42 shows the two variants of the 2nd prototype versus the 3rd prototype with a 0.375 inch experimental through hole while Table 14 compares the two variants of the 2nd prototype with the 3rd.

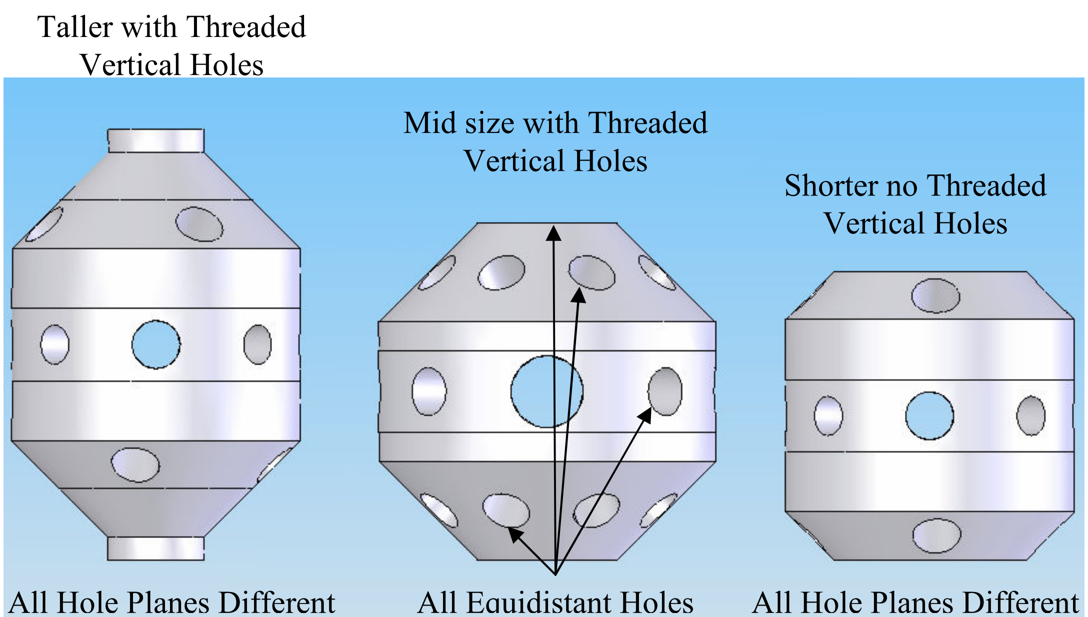


Figure 42: Variants 2B, 3, and 2A respectively

Table 14: Easter Egg Prototype Comparisons

Prototype	2A	2B	3
Threaded Top Holes	No	Yes	Yes
Major Diameter (in)	1.5	1.5	1.75
Height (in)	1.5	2.25	1.75
Normalized Volume	0.90	1	1.01
# of different center-to-hole distances	2	3	1
Min Thread Depth (in)	0.49	0.49	0.45

With this iteration built in CAD first, the group made the decision to have a set of these nodes produced. A university machinist built a set of twenty-two nodes using a CNC lathe and CNC 4-axis mill. Setup took around three days primarily because the process required rotating the chuck of the 4-axis mill for the top/bottom section holes. Actual production took another three days for sixty-six sections. The raw stock used for all sections of the node was 1.75 inch diameter 6061 aluminum. The frame members in this setup are the weakest link not the nodes so material strength for the nodes is not a key concern. The group chose 6061 aluminum for its low cost, lightweight, and ready availability. Each 1.75 inch node requires around 5 inches of raw stock in order to have sections to grip in the chucks of the CNC machines. Drilling and tapping the twenty-six holes in each node took the longest time in the production process. The total cost for the twenty-two nodes was $750 for an average cost of $34 a prototype. This $34 cost broke down between $5 for materials and $29 for labor. While still very expensive in prototype form, with a mass production process in place the cost will be a small fraction of this prototype cost. This batch of third generation nodes will be used for preliminary testing of the frame concepts.

5.4.2.2 Frame Member Concepts

Frame ideas for the skeletal systems quickly centered on cylindrical rods. Rods have several advantages over other shapes. One major advantage is the low cost of rod in a large variety of materials and sizes. Second the circular nature inherently gives a rotational degree of freedom about the frame member. Additionally threading the ends of a rod is far easier than other cross sections as pressing a die onto the rods threads them easily. This is not to say threading was the only solution studied or experimented with. Several other potential ideas developed throughout the idea generation process.

One of the concepts with significant potential involved a quick connect system of snap together frame members. The process to connect rod ends involved chamfering the ends followed by cutting a square groove just behind the chamfer. To join the rods ends, a larger diameter tube has two holes drilled near either end. To hold the rods inside the tube, two PVC pipes sections with a similar internal diameter to the tube have a ninety degree section cut out. A small cutoff nail is driven into the PVC sections. With PVC sections snapped onto the tubes so that the nails protrude through the tube holes, inserting the rod end into the tube causes the PVC sections to flex upwards as the nail rides up the chamfer. When the nail reaches the square groove, the stored energy in PVC section causes them to snap back to their original position and drives the nail into the groove. Figure 43 shows the prototype.

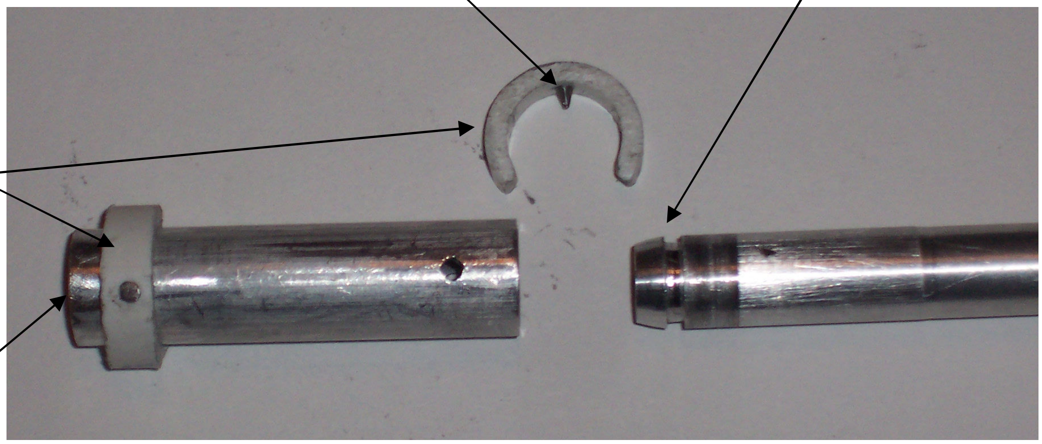


Figure 43: Quick Connect Prototype

The nail prevents translation of the rods in one axis while the tube prevents translation and rotation in two axes respectively. The rods can still rotate about the longitudinal axis but that is the only degree of freedom. To disconnect the rods, a tool such as a screwdriver slides under the PVC sections forcing the nail upward and allows removal of the rods. This still a fairly quick disconnect system. The major drawback is similar to the pin and block connection of the modular face systems in that to minimize play, the connection needs tight tolerances which translate into greater expense. Still if some flexibility in the structural system is allowable, this approach offers a quick and simple connection. The potential free play in this system or tight tolerances required concerned the group enough to look for other options.

Another concept utilized a pin approach as well. This setup however is more like a simple key slot coupled with an inclined plane to secure the rod ends to together. Each rod has a male and female end. The male end is a reduced diameter shaft with a pin driven into a pilot hole made perpendicular to the longitudinal axis. The female rod end has half of its diameter drilled out and pressed into this cavity is an insert with a vertical longitudinal slot cut for the male pin to travel. The insert has an inclined slot cut about its circumference at the end of the vertical slot. To connect the two ends, the male end travels down the vertical key slot until it reaches the end. At the end of this key slot, the male end rotates with the pin traveling along the inclined slot. The incline draws the pin and male rod end in until the unreduced male end meets the female end. With this type of setup, the only degree of freedom at the completion of the connection is rotation back against the inclined slot. Figures 44 and 45 show the male end and the female insert respectively.

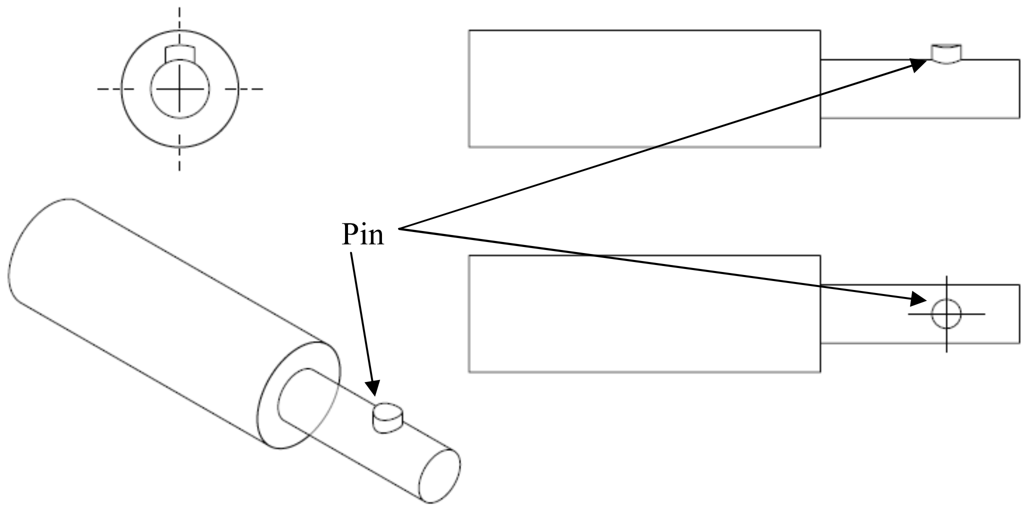


Figure 44: Male Frame Member end

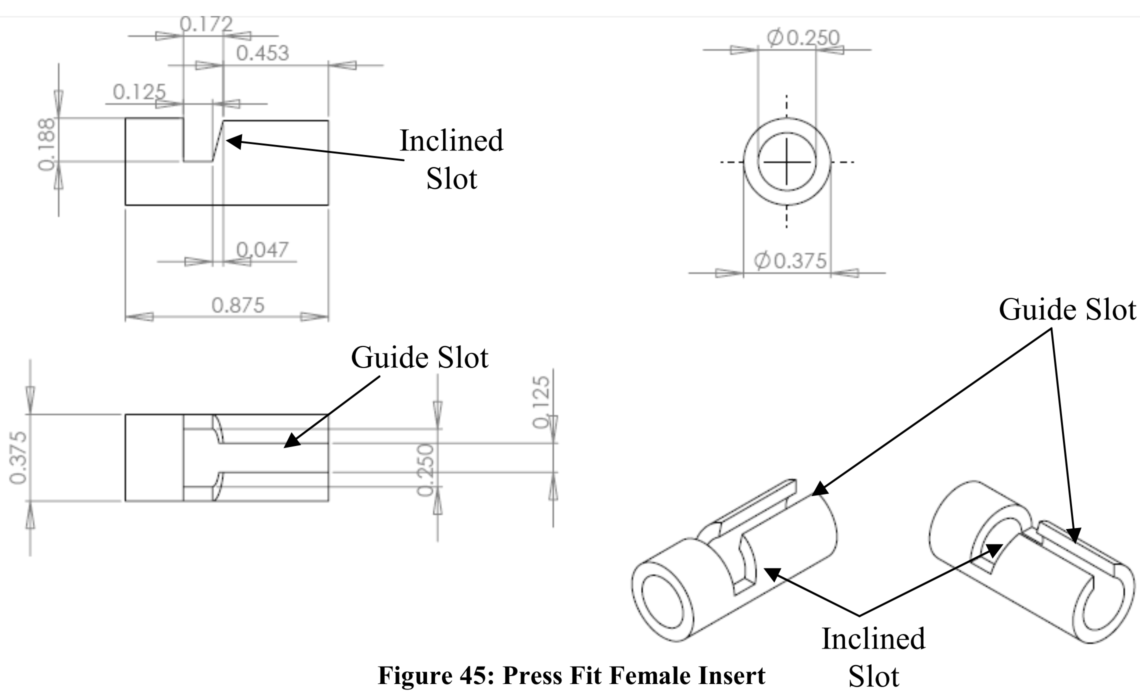


Figure 45: Press Fit Female Insert

The advantages of this connection are the quick connection and simple construction. However, load carrying capacity of this connection is limited by the simple fact that the male end is reduced to half of it nominal diameter in order to fit into the female end. The pin inserted in the reduced male end transfers all tension loads so a reduced diameter male end has potential tear out issues as well. This connection may work for large diameters where load carrying capacity is not an issue, but in a ¼" nominal diameter the reduction in load carrying capacity may be too much for the applied loads. In addition, constructing the ends with sufficient tolerances is challenging in such a small diameter with work piece bending and deflection issues.

An off the shelf solution considered was the use of quick connect air fittings such as those used with air compressors and air powered tools. These connections use a three balls and sliding collar to positively connect the male and female end. The design of these connections allows rotation of the ends about the longitudinal axis but fixes all other degrees of freedom. The drawbacks of this approach are the comparatively large size of the connectors and each pair of connectors costs at least one dollar. With dozens of connections potentially in a system this solution would be a significant component of the total system cost.

The final solution the team developed was a tradeoff of quick connectivity for simplicity and rigidity. The solution uses ¼" diameter aluminum rods with the same ¼"-20 threads as the nodes in order to simplify connections between frame members and nodes. All frame members have threading for 0.75 inches of length on each end. This extra thread length allows placement of nut on each end while still giving full engagement in the node threads of 0.4 inches. The team determined that with three lengths of members of two, four, and ten inches one could easily join them to create most other lengths. Note that using the frame joiners does add 1 inch to the length of the connected frame members. Figure 46 shows the three different frame members with nuts installed at each end as well as the frame member joiners.

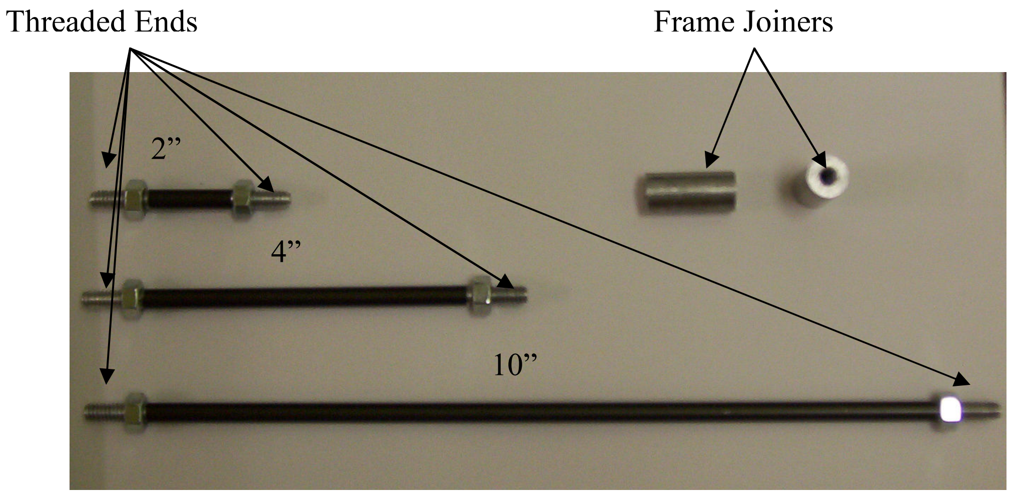


Figure 46: Frame Members and Frame Joiners

To join the rod ends, a 0.5 inches diameter rod of one inch length is drilled and tapped with ¼”-20 threads internally. This setup allows nodes to translate only between frame members since the frame joiners are 0.5 inches in diameter and the node’s through hole is only 0.25 inches. The frame joiners are easy to manufacture and provide a rigid connection between members. While not a quick connect system, it still takes a minimal amount of time to join members together utilizing these frame joiners. This is not to say the solution is perfect. Figure 47 shows two frame members connected with a frame joiner. To tighten the frame members in the joiner, one simply uses a wrench to turn the nut on the opposite end clockwise until snug. Note that the frame joiner adds one inch to the combined length of the joined members.

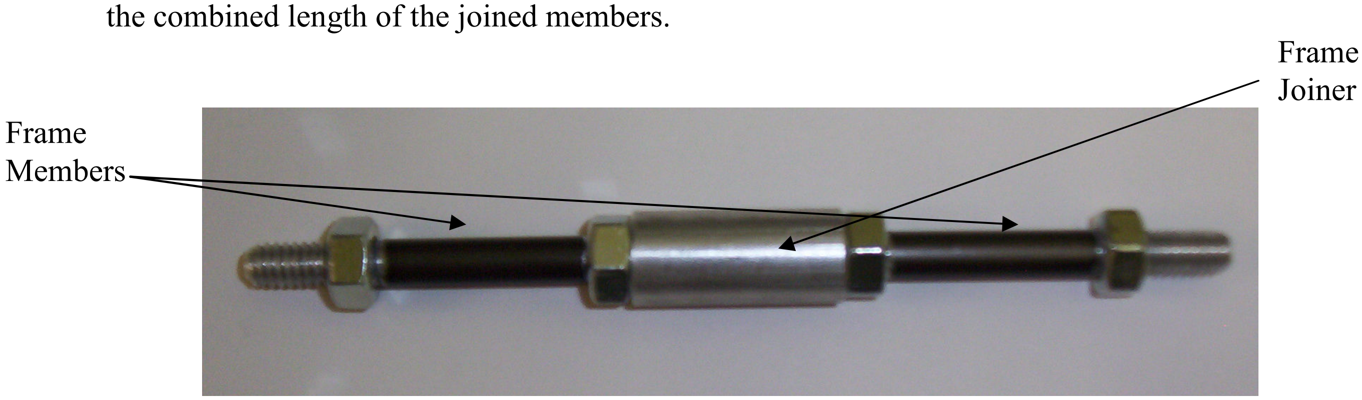


Figure 47: Frame Members Connected by a Frame Joiner

The group also discovered during development that the system required some sort of turnbuckle like rod since with all right hand threads throughout the system, it would be impossible to connect more than one frame member to a single node since threading the member into one node would unthread it from the other. The group devised another component named a rod extender which allowed both threading together multiple nodes and gave the frame member an additional measure of flexibility. This component consists of hollow tube with nut inserts pressed into the ends. A long threaded rod is used in one end with a pair of nuts while the other end connects to another frame member. The long threaded rod can be screwed in or out by using the pair of nuts together giving an almost 2:1 variable length to the extender. Figure 48 shows an assembled and unassembled rod extender.

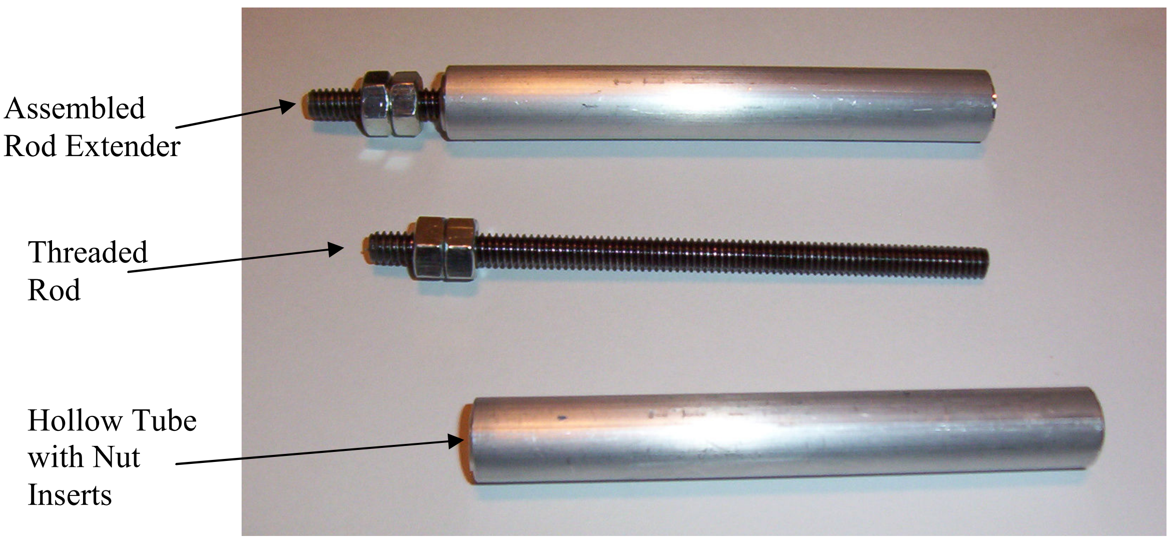


Figure 48: Assembled and Unassembled Rod Extenders

It would be ideal to develop a frame member joiner that allows translation of a node along multiple frame members by being no larger in diameter than the frame members while giving close to the same load capacity as the beams themselves have. Also it would be ideal to avoid using a frame member tightening system that has a larger diameter than the frame members themselves. The group considered cutting slots in the frame members to allow wrench to grip it, but this solution is labor intensive and require accurate milling to ensure proper wrench engagement. Additionally, cutting the slots removes material with creates a weak spot in the frame members. The group did not develop a solution that met all of these requirements. This is definitely an area for future work and an opportunity for further innovation.

5.4.3 Structural Assemblies

During the analysis of the Easter Egg prototypes, the group used CAD to determine the feasibility the node and frame system for creating structure to support various systems. The two simple system chosen were a gear train and a motor system. Figure 49 and 50 show the two systems in CAD.

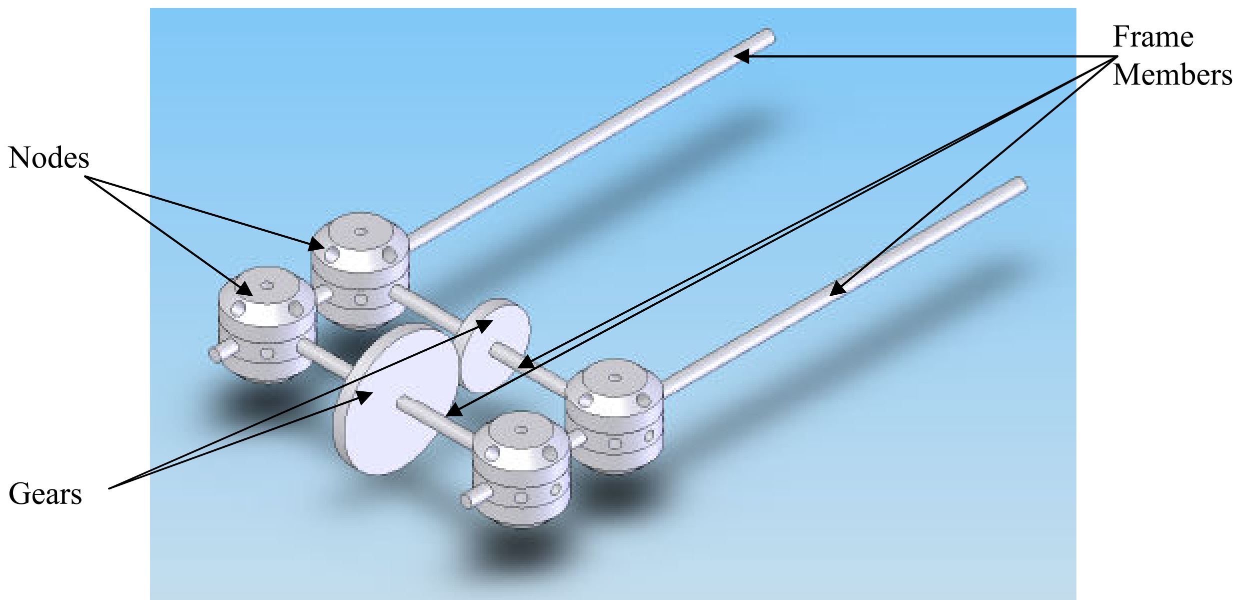


Figure 49: Gear Train System

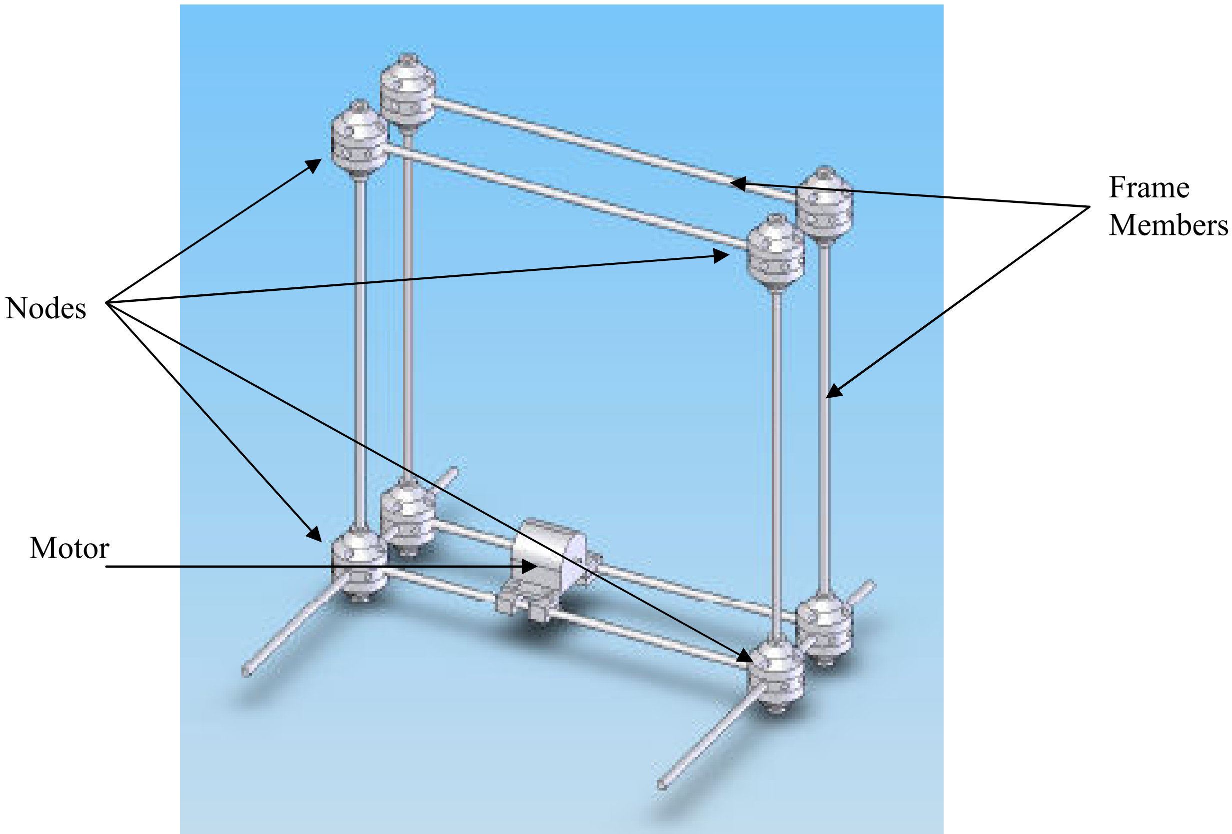


Figure 50: Motor Mount System

Once the set of prototypes were ready, the group created a simple box structure to test out the connection and structure system. The box contains two inch frame members, frame joiners, and rod extenders in order to test out all types of components. Figure 51 shows the box created.

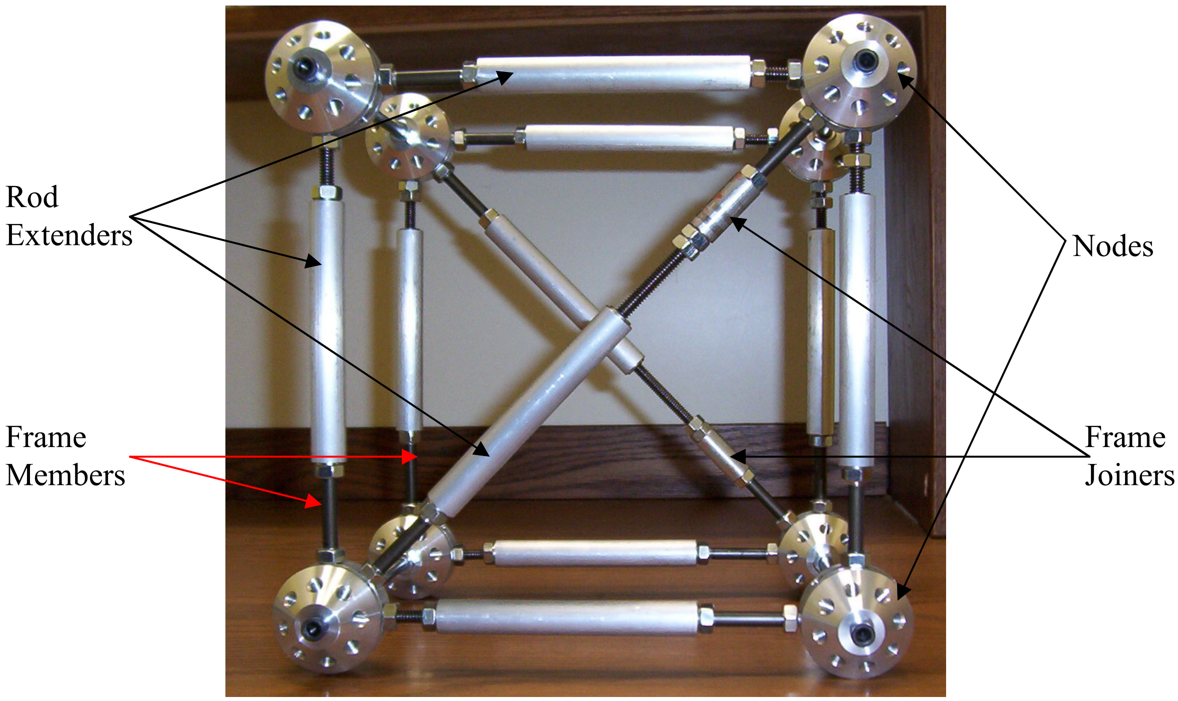


Figure 51: Structural Box

The rod extenders add considerable flexibility. The four inch tube length gives almost an equal amount of variability in length so the frame expands fairly quickly in any plane. The overall structure feels rigid and requires only a pair of 7/16" wrenches to assemble the box. Components can clamp to either the ¼" frame members or the ½" rod extenders. If more rigidity is desired, the system will accept even more cross braces. While not as quick to assemble as a quick connect system, the system offers good flexibility in angle and lengths as well as excellent rigidity. Figure 52 offers an alternate view of the system below.

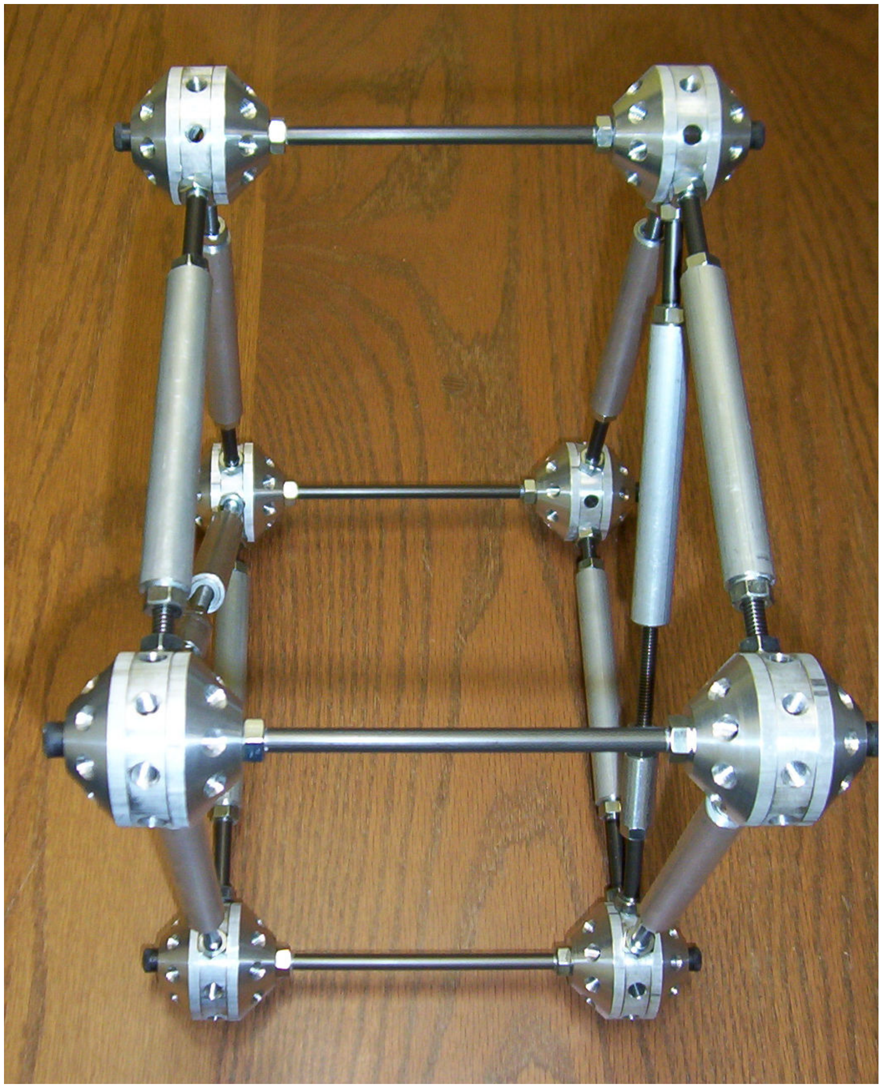


Figure 52: Alternate View of Structure (Top Down)

At the same time, the group performed simple loading calculations to determine the beam deflection. The loading condition used is a beam of length "l" with simple supports at both ends loaded with a single center load. The equation from Shigley's Mechanical Engineering Design is: $y_{max} = \frac{Fl^3}{48EI}$, where E is the elastic modulus and I is the second moment of inertia about that axis. Table 15 shows the basic spread that gives the max deflection for various lengths across the horizontal axis and diameters across the vertical axis of 6061 aluminum. The table shows that for a one foot section with a five pound center load will deflect 0.375 inches or one and half diameters of the rod. If this amount of deflection is unacceptable, the options are to increase the rod diameter, lessen the load, or decrease the span.

Table 15: Deflection for Various Loads and Rods Sizes

	Deflection (**inches**) with **one pound** at **X** feet				5	lb		
Al rod	0.25	0.50	0.75	1.00	1.25	1.50	1.75	2.00
1/4"	-0.006	-0.047	-0.158	-0.375	-0.733	-1.267	-2.012	-3.004
3/8"	-0.001	-0.009	-0.031	-0.074	-0.145	-0.250	-0.398	-0.593
1/2"	0.000	-0.003	-0.010	-0.023	-0.046	-0.079	-0.126	-0.188
3/4"	0.000	-0.001	-0.002	-0.005	-0.009	-0.016	-0.025	-0.037

5.5: Chapter Summary

The greatest opportunities for innovation are not in the included opponents but rather in how the breadboard flexibly locates and quickly connects those components. WM Berg and Pic Design appear to focus on the connection of components and the components themselves. Our design group focused on creating a structural system that maximizes flexibility in locating components. The two major branches of structure options vary in how they support both loads and other functional components. Modular systems have the structural support integral to the functional components. These systems are in the minority in general due to the inflexibility in the rigid sections that house the components. The early Legos systems based on simple building blocks are an example of a modular system. These systems do offer a significant reduction in components in the breadboard but have fewer connection options as they meet a connection standard. Skeletal systems, on the other hand, have more components in order to offer more flexibility in the construction of a structural system. The group developed two major solutions in the skeletal domain: one based on 2-D plates while the other uses frame members and nodes in a space-frame-like setup. The two dimensional plates utilize sliding connections housed in a slot on another sliding member to offer full translational freedom in entire plane of the plate. One of these new plates by itself would be a major improvement over the plate included by WM Berg and Pic Design. By using multiple plates hinged together, 3 dimensional structures are possible. Still the plate system was limited its utility in a 3 dimensional role so the group developed a frame and node solution.

The group worked through many ideas for nodes from spheres and polyhedra before developing the concept dubbed the "Easter Egg." This three section node gives connection angles similar to the rhombicuboctahedron shape, but, with its additional rotational degrees of freedom about it vertical axis coupled with an ability to rotate about a frame member for another pair of rotational and translation degrees of freedom, the Easter Egg gives far more flexibility in frame member location. The Easter Egg went through several revisions before becoming the octagonal outline shown above. This final iteration of the Easter Egg offer maximum symmetry and frame member placement flexibility while keeping all attachment points equidistant for the center of the node. This third generation prototype utilizes the same thread size for all holes simplifying production, assembly, and use. With the core design focus on radial symmetry, the Easter Egg sections come from the same round stock which also helps with production. While the design seems simple and obvious at first glance, the many hours spending iterating on the design and adding all the little details make this node unique, useful, and innovative.

The frame connections developed are functional if not ideal. The goal of having a quick connect system that is inexpensive, strong, and rigid remains unmet. The current frame joiner solution of larger internally threaded cylindrical sections does offer excellent rigidity and strength for a moderate amount of connection time. In addition, these sections require very few steps to produce and have no difficult tolerances associated with them. Also by using the same thread sizes and nuts throughout the component, the entire system assembles with only two wrenches and one Allen wrench. The challenge remains to devise a connection system that is no larger in diameter than the frame member and yet does not significantly reduce the load carrying capacity. The simple solution would be to use larger frame members so that there is a large enough factor of safety that a significant reduction in that capacity due to joints is not an issue. This solution would then drive the size of the connecting nodes exponentially larger. So while the current frame joiner solution is acceptable, it is not the hoped for ideal solution. This discussion leads to Chapter 6 which covers the conclusions and future work.

Chapter 6: Future Work and Conclusions

6.1 Motivation

This thesis introduces and describes the concept of a dedicated mechanical breadboard. With students today having less hands-on experience than their predecessors, the experience gained from experiments and projects is critical to developing well rounded engineers. An engineer's ability to recite formulas is useless if manufacturing cannot reliably and economically produce the designed component. Most engineers can design a system, but designing a system that is efficient, compact, and low cost requires experience. Consider how well a person performs a difficult task such as repairing an automobile the first time versus the second, third, or fiftieth time. Consider how improved the production model of a product is versus the first prototype. The improvements between production model and prototype are evolutionary versus revolutionary typically, but these minor changes often make the difference between a best seller and an also-ran. A mechanical breadboard gives the opportunity to develop both evolutionary and revolutionary designs. While most ideas are evolutionary, one could take existing components and combine them on the breadboard in novel ways to affect a revolution in a product.

Using a mechanical breadboard gives students firsthand knowledge of component interaction, connection methods, and packaging. The breadboard will also familiarize students with key mechanical components used throughout the field. In design, analogies especially from different fields are an excellent starting point for design concepts. Otto and Wood give an example in Product Design of developing a guitar pickup winder from an antique apple peeler (Otto and Wood, 2001). This seemingly unrelated product in actuality shares many customer needs and functions with a pick winder. Such analogies yield many novel and useful products. By prototyping different systems on a breadboard, students will have a set of new analogies to utilize as they develop systems in their careers. The rest of this chapter details the areas for further efforts as well as gives an assessment of the efforts so far.

6.2 Current Assessment

This thesis first defines what a mechanical breadboard is for purposes of this research. It also surveys what is available or analogous to a mechanical breadboard to define the state of the art in the field currently. This search returned only four dedicated mechanical breadboards, two designed by academia and two by the commercial sector. The two commercial breadboards by WM Berg and Pic Design are multi-thousand dollar machine design breadboards that give the ability to make precision systems for analysis of machine element interactions. The statics breadboard by Dr Van is great example of a low cost solution that meets many needs for its intended market. The thermal fluids breadboard by Dr Mountain gives more functionality at a tradeoff of significantly higher cost. This breadboard is flexible enough to teach students from the elementary level up through upper division students various thermal fluids principles.

Beyond these four systems, numerous analogies to mechanical breadboard exist especially in the children's construction set realm. The most famous of these systems is probably the Lego© system which is a benchmark by which all other toy construction sets are judged. The Legos© world has evolved from simple plastic interconnecting blocks to more complicated shapes to the Mindstorm© programmable robotics system. The Zome© system is a relative newcomer to the market and offers a node and frame construction system geared more towards geometric shapes than replicating real life systems. The nodes used by Zome© are truly novel for their symmetry, multi-angle connectivity, and compact size. Lastly, the Erector© sets can be used as a poor man's mechanical breadboard. They offer many components found in other products and offer a more realistic bolt and beam structure as seen in actual structural systems. Though the designer's did not intend these toy construction sets to be an engineering mechanical breadboard, they all offer some insights into construction design and some actual utility as well.

The electrical breadboard as a physical analogy offers two insights into the connection and structure of a breadboard. Standardizing interfaces across the components and backbone maximizes connection flexibility while the backbone should provide the required support and location structure for all other components. This leaves the other components to focus on performing their primary functions while the backbone covers the supporting functions of location and support.

The results of this background research show how comparatively little effort the industrial and academic communities have spent on this key tool. Consider the advances made in machine tooling over the last thirty years as CNC machines have gone from rare and expensive tools reserved only for large companies to now when any competent machine shop has several of them. We have yet to see such an evolution in the realm of mechanical breadboard development. Admittedly, the development of CAD gives students and engineers the ability to quickly model various concepts in the digital realm. In fact, engineers now design many complex systems such as aircraft and automobiles completely in CAD before building any prototypes. It is not my intention to state mechanical breadboards will rival or replace CAD as a development tool, but nothing rivals hands-on experience for developing a well thought out, reliable concept. Having concrete experience in one's background can only enhance the ability to design and gives a reference point when issues arise during development.

Using a mechanical breadboard gives this concrete experience, especially to students with little or no mechanical background. The military air war experience during and after Vietnam shows value of physical experience. The US Air Force determined a pilot's chances of survival increased exponentially after serving ten combat missions (www.wikipedia.org, 2006). The service created its own air combat school named Red Flag to give pilots as close to a real ten combat mission experience as possible. The performance of our pilot's in combat in the Gulf War has proven this approach to be very sound. In the same way, an engineer using a mechanical breadboard during undergraduate studies to prototype concepts and understand mechanical principles will be far more effective than a student who learns only from textbooks and begins his physical experience in the workplace. Having at least a familiarity with various components will give the student who uses a mechanical breadboard an advantage over the student who does not.

Chapter 2 defines the customer market. This process begins with a customer interview process designed to understand the customer needs for this market. The choice to use college students and professors stemmed from an accessibility factor and an understanding that these users utilize a breadboard in both capacities fairly equally. This balance in usage should lead to a balance in requirements. Also by choosing people with specialties from the entire mechanical realm, the needs developed should span the entire realm as well. In addition to answering the formatted questions, some users developed insightful comments as to the look, feel, or utility of the system. Two customers independently asked for color coding components based on functions. This insight makes the system easier to understand for the mechanically uninitiated as well as younger students. Other less concrete requests while harder to define may be even a better indicator of how well a system executes the total package. One ill defined request asked the components "feel right" when being connected together. One metric to measure this request would be required force for proper versus improper installation as either linear force or torque. While some customers wanted a basically indestructible system since undergraduate students are not known for their patience and care, one insightful customer wants the system intentionally designed to break if students do not use proper engineering calculations. This wrinkle of the design concept has a two fold result: it teaches students the importance of performing calculations to prevent failure and shows that the calculations have merit.

Chapter 3 defines the customer markets from the interviews of Chapter 2. While most customers did not specifically spell out a market, several general trends emerged most of the time. These trends grew into the five markets defined in detail in Chapter 3. These markets span the continuum from the simplicity of the statics realm to the all encompassing professional breadboard which covers all areas of mechanical engineering from statics to thermal fluids. Typically these breadboards have functionality and cost directly related. Again because of the limited investment by industry and academia, only a few examples exist with no true all encompassing professional system in existence today. Each market has the conflicting needs of reasonable cost and high functionality.

Chapter 4 determines the top fifty functions for household consumer products. While most of these functions deal with primary functions, the two secondary functions of “couple solid” and “secure solid” are also on the list. It is these two functions which the development process detailed in Chapter 5 covers. The current solution came from hundreds of possibilities developed over several months. This structural solution utilizes a frame and node construction. The nodes have a circular cross section from above and an octagonal cross section from the front or side. The ¼” frame members are simple and easy to make. Additionally, the system is compatible with off the shelf ¼”-20 threaded rods or studs. With multiple nodes used in a system, virtually any angle is possible within the system. The nodes give one rotational degree of freedom naturally and when placed on a frame member give two additional degrees of freedom, one each translation and rotation. This gives a much freedom as possible in all three dimensions while still giving positive placement capability. The aluminum gives light weight and good strength while the use of common nut and bolt sizes means only two wrenches and one Allen bolt are needed to assemble the structure. This creation is a novel three dimensional backbone capable of creating many different size and shape structures.

6.3: Future Work

While this thesis is a start to developing a new breadboard or improving the two existing commercial ones, many areas need further efforts. Obviously, this thesis provides the structural components of the breadboard but leaves the determination of components for primary functions unanswered. Because the system utilizes the ¼” frame members, the system should be compatible with off the shelf parts from Pic-Design and WM Berg. While readily available parts met many of the primary functions, novel solutions would minimize the part count and add to flexibility of the breadboard. Later work will need to determine what components give the greatest functional utility.

The structural concept presented here is not in final form. The set of nodes and frame members built is more of an alpha prototype set than a preproduction version. This set needs serious testing by both the developer and potential users to determine other improvements needed in this variant. The general shape and layout seem promising, but the cost to produce these nodes in metal is probably prohibitive for mass production. Another possibility would be to make these nodes in an injected molded plastic process. This would reduce the weight as well as cost. As mentioned in the previous chapter, the current frame member and joiner solution is not ideal. Further efforts may yield a solution the keeps all frame members and connections at the same diameter while keeping connection load carrying capacities closer to the nominal frame member capacity. The tightening system will probably need further refinement after testing also.

The analysis remains to be done to determine what tolerances would be reasonable and usable if one made the nodes of a polymer material. It would also be useful to determine a process plan to include production and assembly. While this system will not match the simple plate structures of Pic Design and WM Berg for cost, the added functionality of being able to build in the three dimensions must be accounted for when comparing the two structural options. Also the packaging needs to be developed in portable, lightweight, and compact way. Perhaps it could also form the base of the system when in use.

6.4 Conclusion

The very fact that the fruits of nine man-months of serious effort and around $1500 yielded a structural solution should point the level of effort and funding needed to develop a complete, functional, robust, and low cost system. As mentioned previously, creating the structural concept took three months of full time effort and came from literally hundreds of ideas and options. Like any other development of a complicated system, a mechanical breadboard requires significant thought on many facets of the system in order to perform well and please a variety of customers. Consider the thought put into the layout of the planes of holes in the nodes to make them all equidistant from the center or the vertical holes serving two functions as once to save volume and height. It takes dozens of little touches like these across many components to make the system novel and functional.

I hope that this thesis highlights an opportunity for the mechanical engineering community to add another tool to our learning and development inventory. This is not intended to be a definitive statement on mechanical breadboards, only a start on a much longer and more involved development. If nothing else, this thesis should make evident the level of effort needed to make a serious impact in area and yet this must happen to improve learning opportunities for students and give another development tool for professional engineers.

Appendix A: Customer Interview Questionnaire

Instructions: This a questionnaire for the customer needs of a mechanical breadboard. Consider an electronic breadboard as an analogy to a mechanical breadboard (a mechanical breadboard would be used by a mechanical engineer in the same way an EE uses an electronic breadboard in concept; however in reality a mechanical breadboard would be more like a Erector Set or Legos versus a flat EE breadboard). Complete the following questionnaire and return to Dr Jensen (if at USAFA).

	Name	School	Classes Taught/Mechanical Specialty	Contact Info (if desired)
#	**Context Factor**	**Question Prompts v1.0**	**Response Notes**	**Importance: 1-5 (5=very important)**
HOW: Usage Application				
a1	task (application, function)	What specific purpose(s) will the breadboard be used for?		
a2	Task Function	What would be your primary use for the mechanical breadboard? What percentage of use will be in this capacity?		
a3	Mech Systems	What areas or types of mechanical systems should this breadboard cover (i.e. electro-mechanical, pneumatic, hydraulic, etc.)		
a4	Mech Systems	Are there any areas/systems you would NOT want to use this for (i.e. too complex or unsafe)?		
a5	Mech Components	What are some key mechanical components you would like included in the kit (based on what systems to want to model)?		
a6	Mech Components	Are there any mechanical components you would NOT like included (due to safety and/or complexity)?		

a7	Mech Principles	What mechanical principles would you want this device to cover (e.g. bending, moments, shear, reaction forces, etc)?		
a8	task frequency	How often will the device be used (e.g. daily, weekly, etc) over a semester or a school year?		
a9	task duration	How long will the device be used each time (e.g. hrs per project or idea)?		
a10	task ruggedness	How roughly will the device be handled/treated by the users?		
a11	transportation type & amount	How will product be transported & how often (i.e. by hand, on dolly, etc)? How many people desired for transport?		
WHERE: Usage Environment				
e1	surroundings	What type of surroundings will product be used in (e.g. classroom, lab, home use, dorm room, etc.)?		
e3	environment ruggedness	Will product be exposed to any unusual substances or conditions (e.g. water, humidity, caustic environments, etc)?		
e4	space (when in use)	How much space is available for using product (ie Xft x Xft or desk, workbench, lab table, etc)?		
e5	space (storage)	How much space is available for storing product (again Xft x Xft or drawer, small or large cabinet, etc)?		
e6	aesthetics of surroundings	How will product interact w/ the surrounding aesthetics? How "quality" should it look? What feel do you want it to have?		

e7	ventilation available	Is ventilation a concern? If so, how much ventilation is available during product use?		
e9	energy availability	What is the availability of possible energy sources? (e.g. battery, electric AC, human, wind, water)		
e10	noise	How quiet is the surrounding environment (either in dB or a conversational level, shouting level etc)? How quiet should it be?		
e11	materials	Are there specific materials you would want the kit made of or included in it?		
e12	Comments	Any other comments on environment?		
WHO: Customer Characteristics				
c0	user	Who will use the product (students - upper or lower level or grad, professors, technicians, etc)?		
c1	user skills	How familiar is the **average** user with the tasks involved with using this kit? How familiar are they with hand and power tools?		
c3	user tolerance for complexity	What is the most complex device familiar to the user? Must this product be less complex?		
c4	cost expectations: (purchase)	How much would you be willing to pay for a kit and how many would you want for the classes you teach?		
c5	cost expectations: (maintenance)	How much is the user willing to pay/work per semester or year to maintain/repair this product?		

c6	durability expectations	How long does the user expect product to last?		
c7	time expectations: setup & operation	About how much time is the user willing to spend to setup prior to operating/using this product?		
c8	safety expectations	What safety features are you expecting? What dangers must be avoided?		
c9	on site capability	Do you have the ability to fabricate parts on site from component drawings? Is this something that you would find useful for part replacement?		
c10	Product Feature	Now that you have completed the questionnaire, are there any features you would want that have not been mentioned previously?		

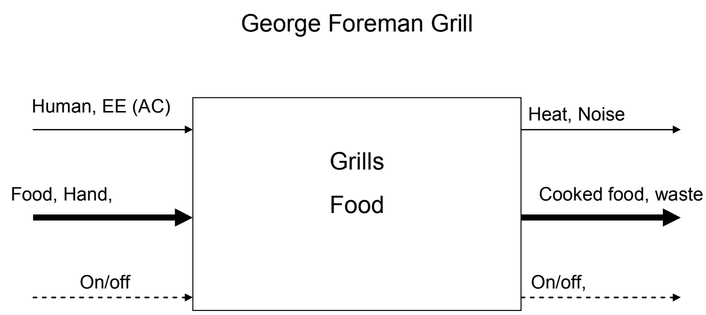
Appendix B: Customer Survey Results

	Number of Subjects					
Customer Requirement	**5**	**4**	**3**	**2**	**1**	**0**
• **Purchase**						
- Cost over $1000		3				
- Cost $500 to $1000		3				
- Cost under $300						
- Cost $300 to $500		4				
- Cost less than 10% per year to maintain		3				
- Cost 10% to 25% per year to maintain		4				
- Cost over 25% per year to maintain						
- Last less than 5 years		0				
- Last 5 to 10 years		7				
- Last over 10 years		1				
• **Select components**						
- Use of different colored parts for different functions			1	1		
• **Setup**						
- Fit on table top		2				
- Fit on a workbench top		6				
- Take less than 10 min to setup	1	3				
- Take less than 20 min to setup	1	2				
- Not require ventilation	2	2				1
- Use less than 10 times per semester		1				
- Use 10 to 20 times per semester		4				
- Use daily to three times a week		4				
• **Connect/Assemble Components**						
- Use for prototyping	1	3				2
Use for demonstration	1	6				

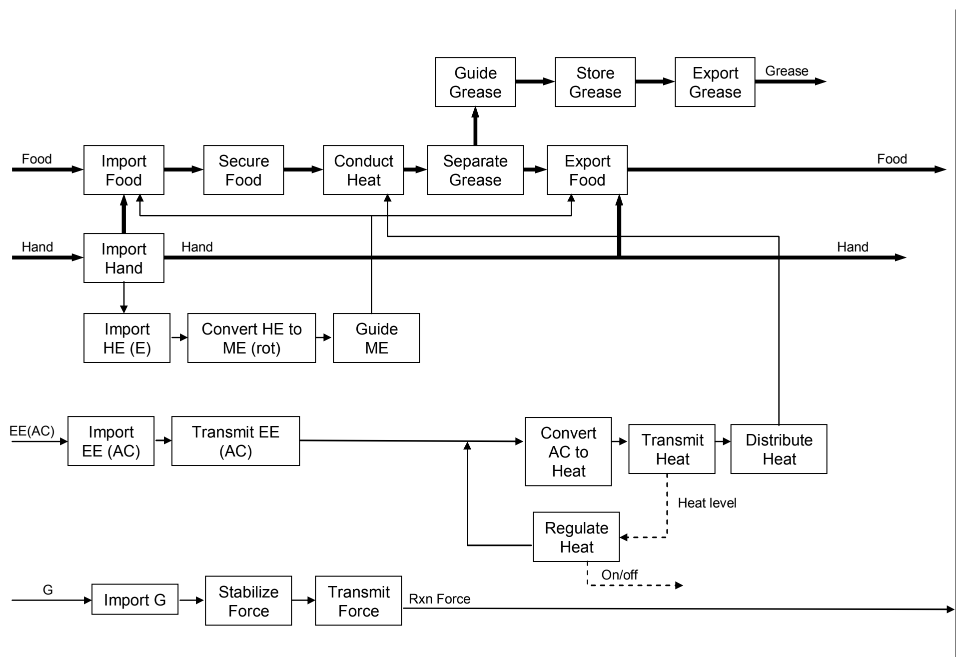
-						
- Use basic hand tools (screwdriver, allen wrench, etc)		7	1			
- Needed tools are included		2				
- No tools needed		1	1			
- Use quick connects	1	2				
- Connect to existing devices/components (COTS)		2				
- Require less than 1 hours to assemble		3				
- Require 1 to 5 hours to assemble		3	1			
- Require more than 5 hours to assemble			1			
- No hammering or spacing requirements	1					
- Should "feel right" during assembly	1	1				
- Have a manual		1				
• **Install/Connect Power/Instrumentation**						
- Use DC from AC/DC power supply	4	6				
- Use hydraulic power			3	1		
- Use DC from Batteries				2	2	2
- Use human power		5	2			
- Use pneumatic power		2	2			
• **Operate**						
- Noise level less than conversational level	1	6	0			1
- Not require ear plugs	1	2	0			0
- Use pneumatic power			1			
- Not crush fingers	1	1				
- Ensure nominal friction not a significant impact		1				
• **Observe/Record Data**						
- Video Recording at over 30 fps	1					
- Provide clear covers (for observation/safety)			1			

- Connect to Computer for Data capture		1	1
• **Transport**			
- One person portable		5	
- Two person portable		1	
- Weigh less than 30 lbs		3	
- Weigh 30 to 50 lbs		1	
- Use at Home		4	
- Use in the classroom		4	2
- Use in a lab		5	3
- Be wheeled	1	4	1
• **Storage**			
- Take up less than 8 cubic feet		5	
- Take up 8 to 25 cubic feet		3	
- Take up more than 25 cubic feet			

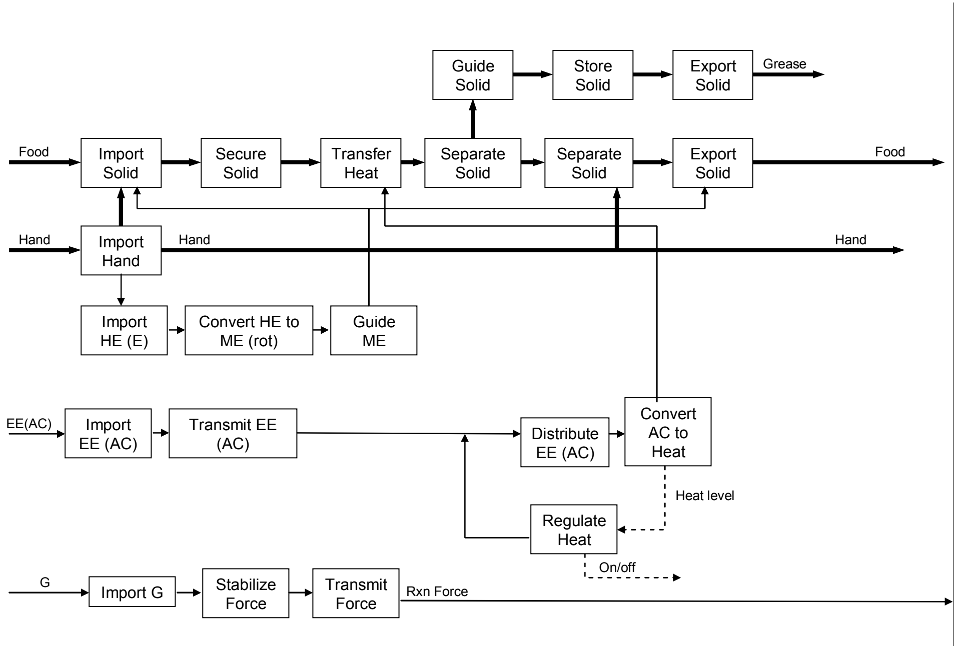
Appendix C: Black Boxes and Functional Models



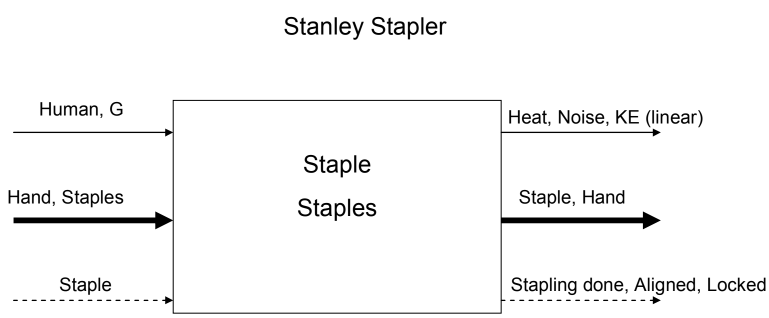
Grill Black Box



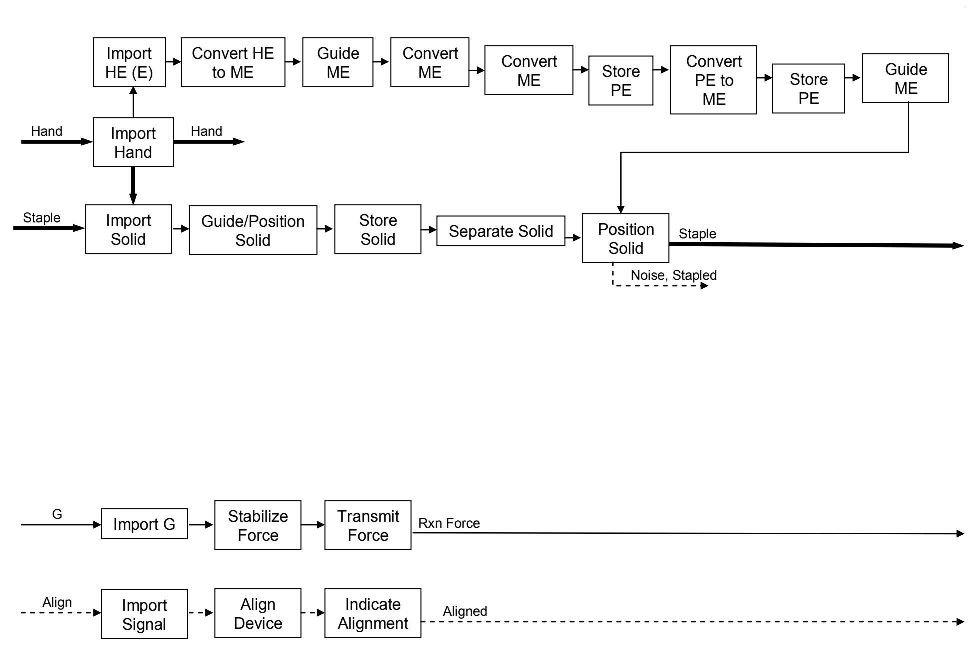
Grill Initial Functional Model



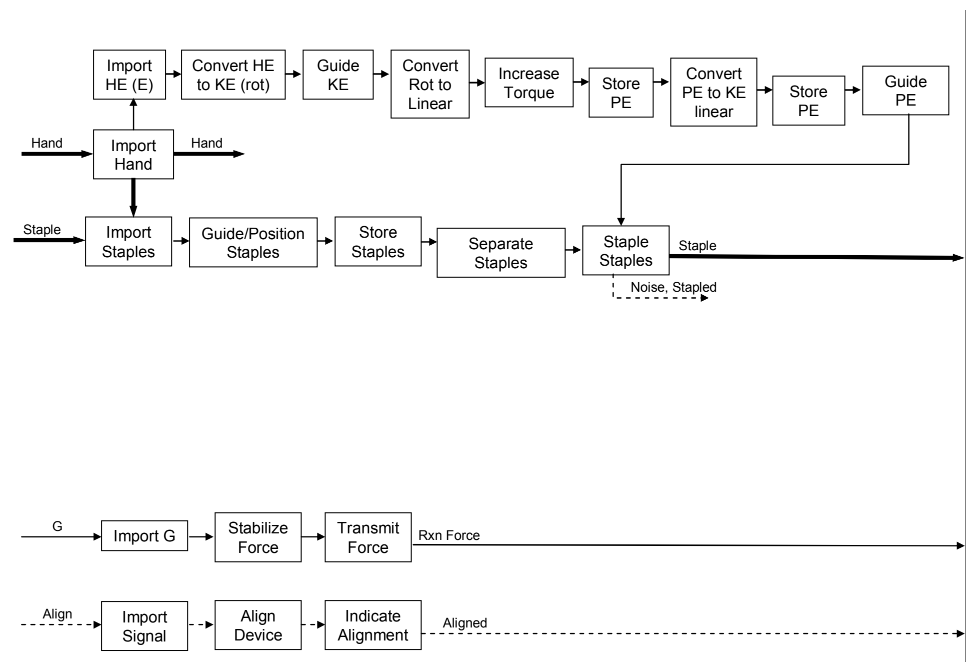
Grill Common Basis Functional Model



Stapler Black Box

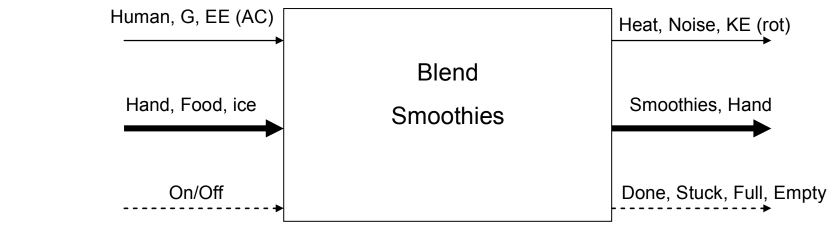


Stapler Initial Functional Model

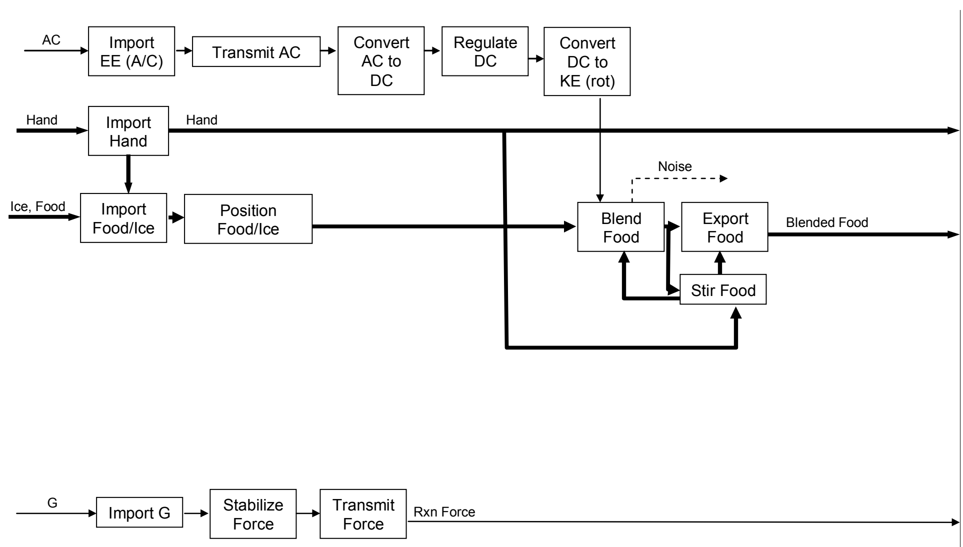


Stapler Common Basis Functional Model

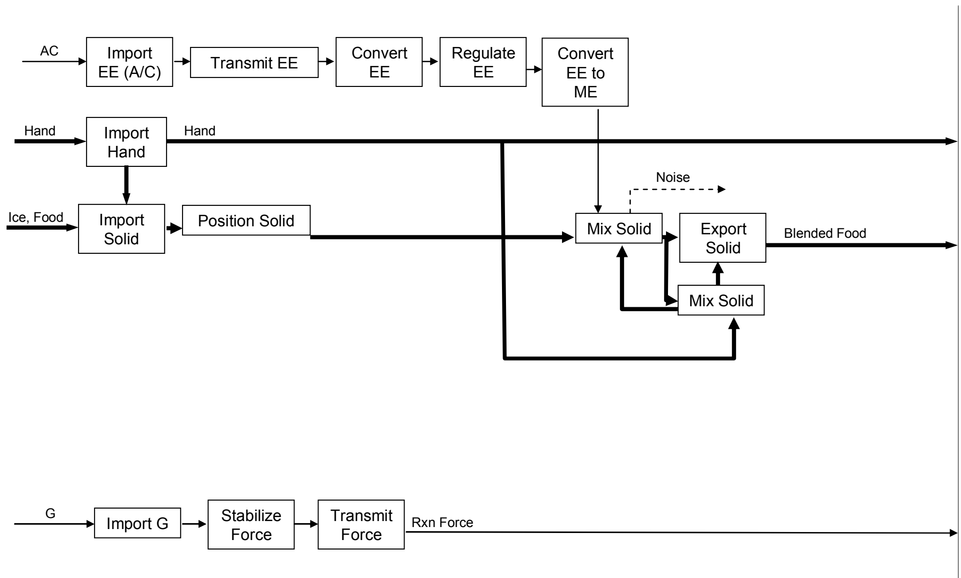
Back to Basics Smoothie Blender



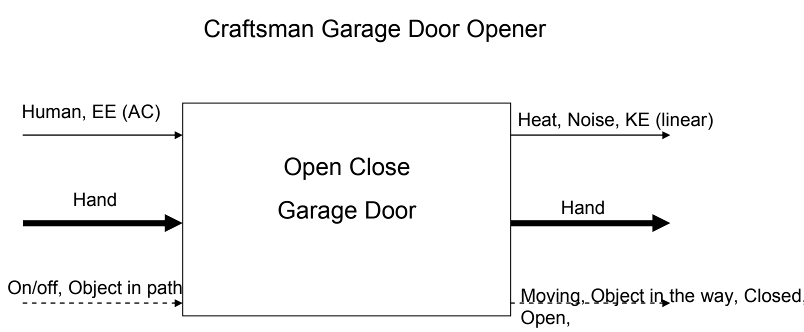
Smoothie Blender Black Box



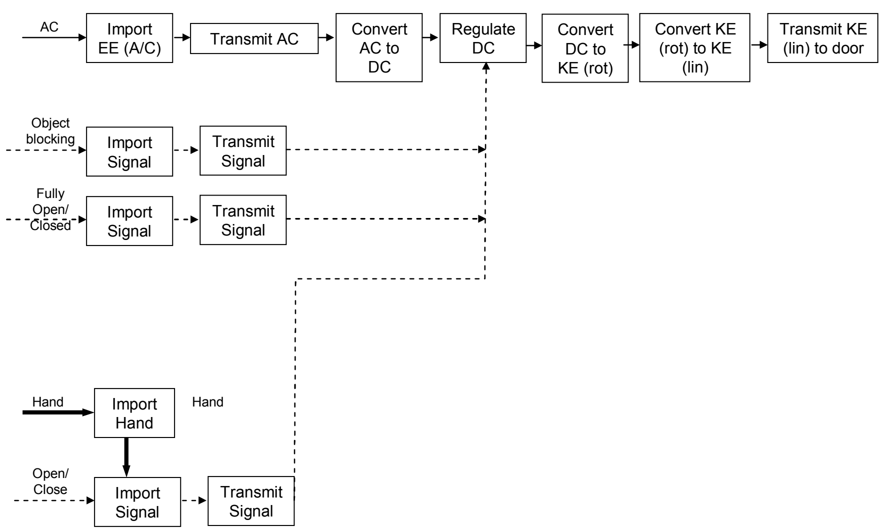
Smoothie Blender Initial Functional Model



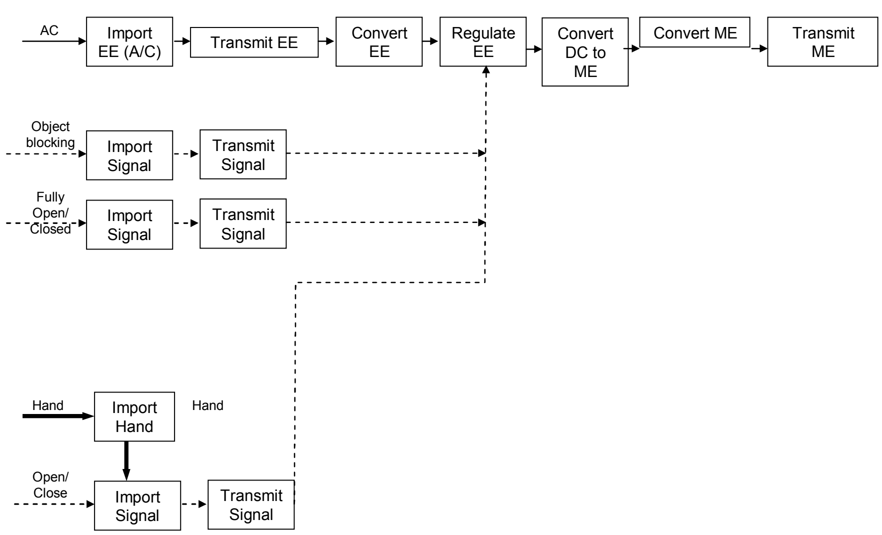
Smoothie Blender Common Basis Functional Model



Garage Door Opener Black Box

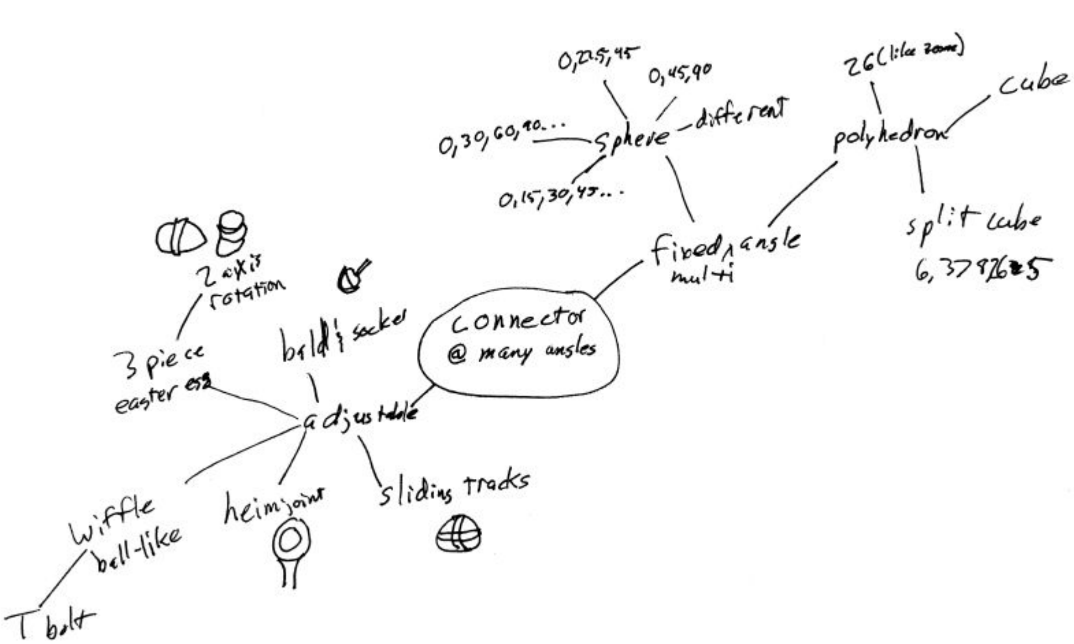


Garage Door Opener Initial Functional Model

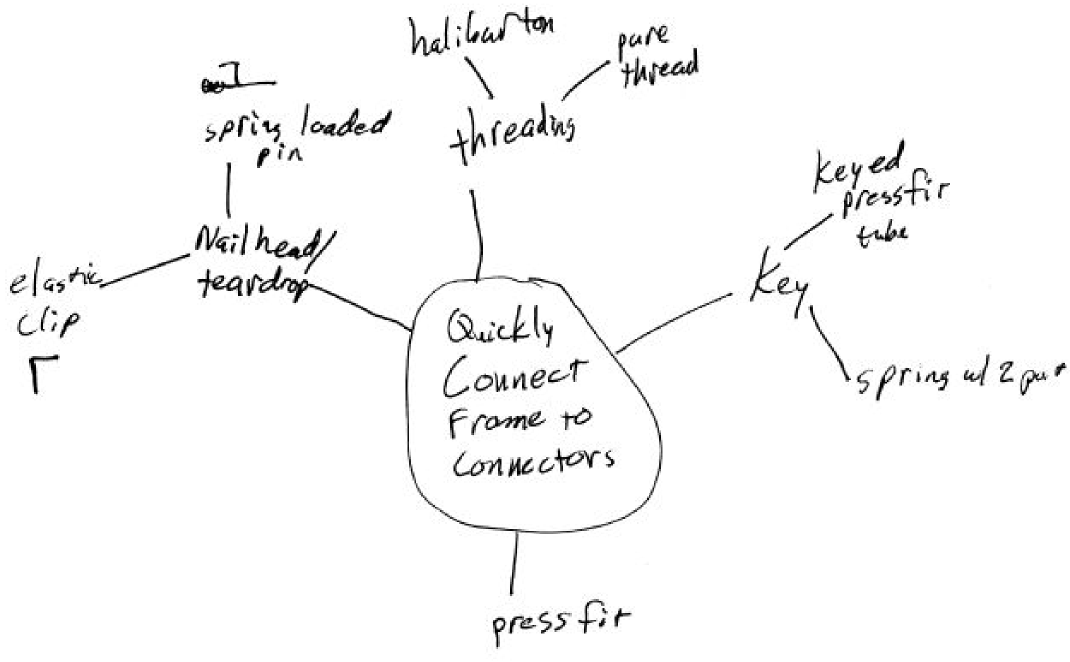


Garage Door Opener Common Basis Functional Model

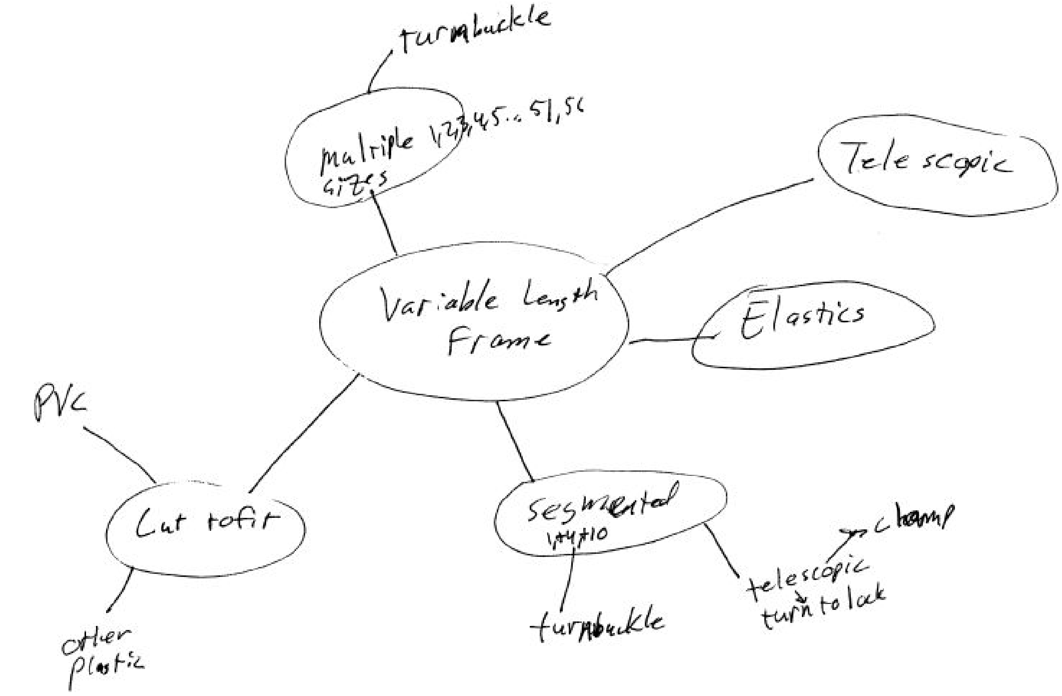
Appendix D: Major Mind Maps



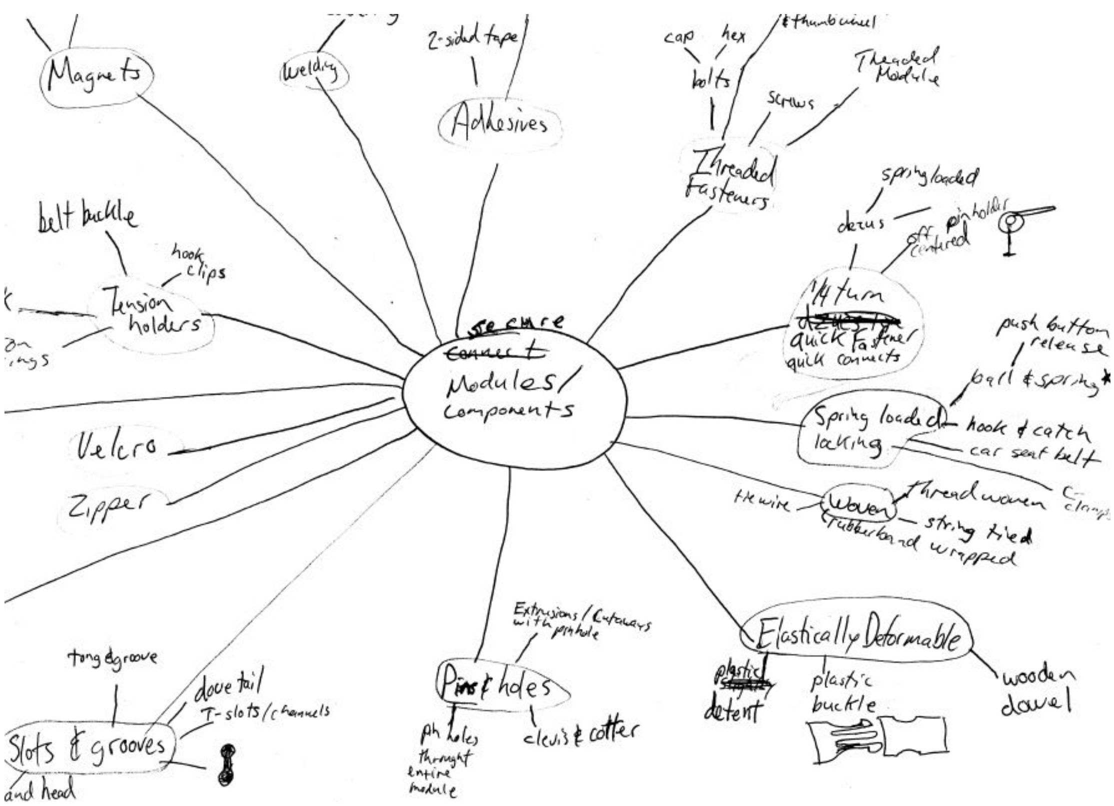
Placing a Connector at Many Different Angles Solutions



Quick Connect Solutions

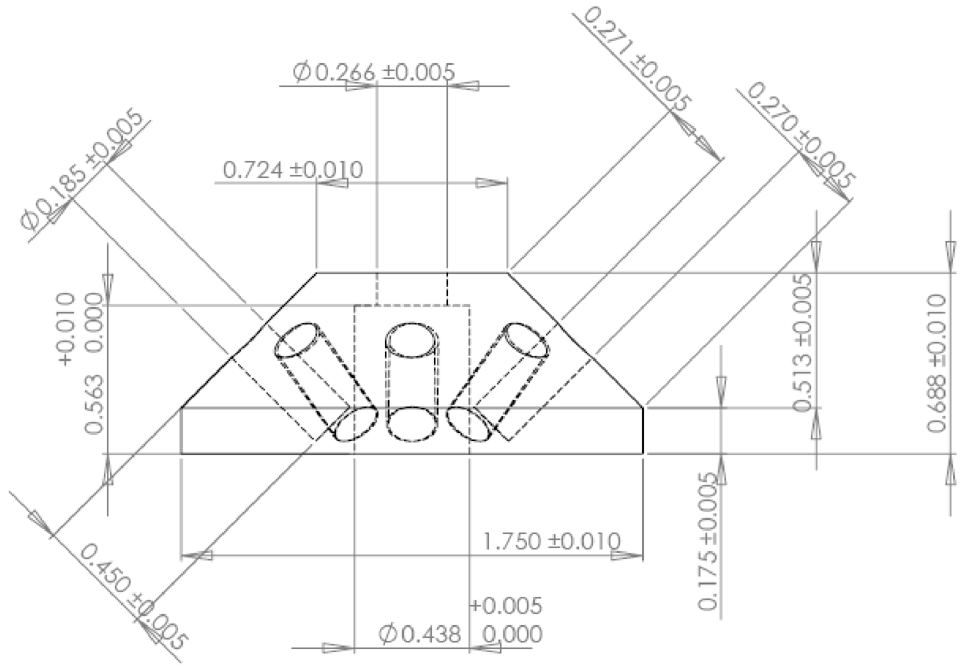


Variable Length Frame Solutions

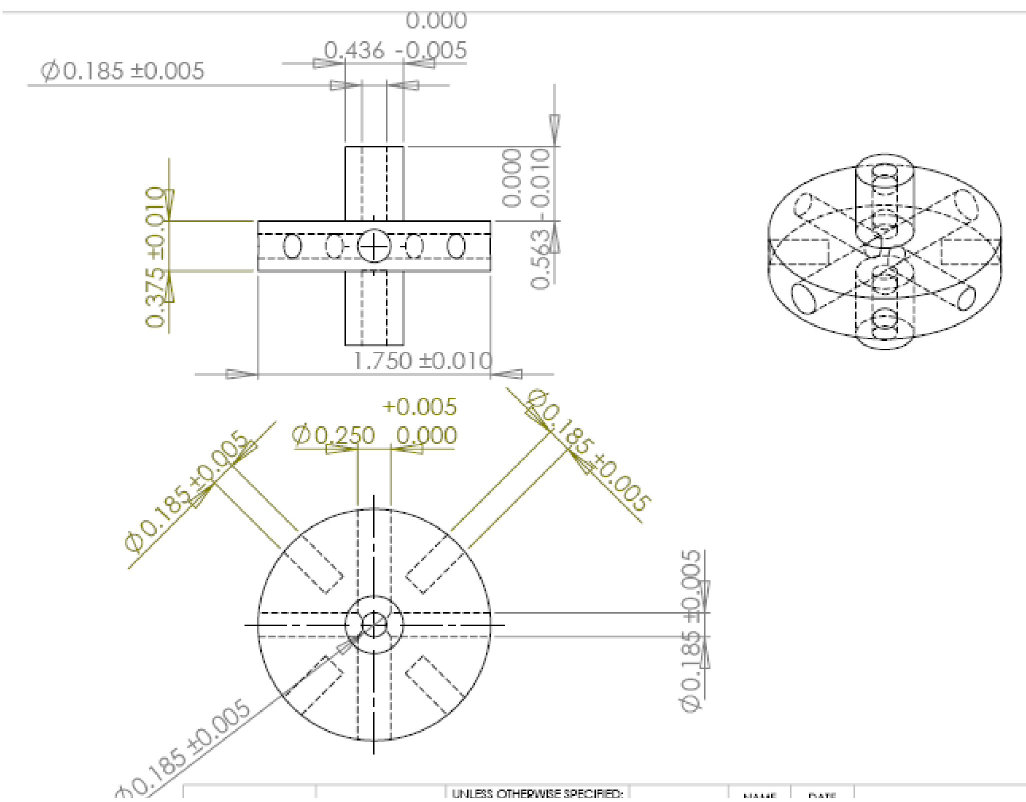


Connecting Modules Together Solutions

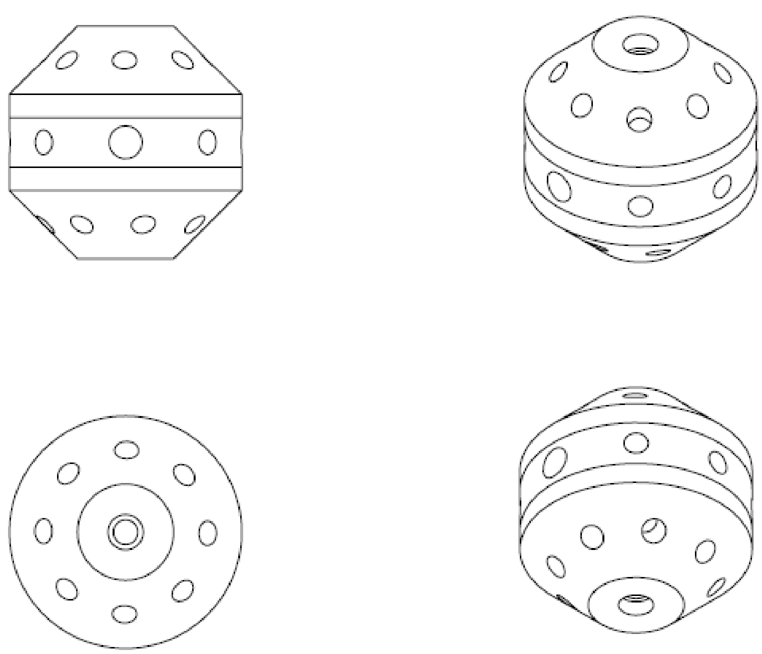
Appendix E: Node Drawings



Top / Bottom Section Drawing



Middle Section Drawing



Assembled Node

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VITA

James Andrew Mikes was born in Arkansas. After completing high school at Catholic School in Little Rock, Arkansas in 1997, he entered the United States Air Force Academy in Colorado Springs, Colorado. He received a Bachelor of Science from the Air Force Academy in 2001. Following his commissioning as a second lieutenant, Lt Mikes spent four years at Eglin Air Force Base as a developmental engineer. In August 2005, he entered the Graduate School at The University of Texas.

This thesis was typed by the author.