MAE 4291 Senior Design Project Report

Design of a Semi-Autonomous Foosball Table

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Project Advisor:
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1 Executive Summary

1.1 Functional Requirements of Design

Our design should function as a standard foosball table with an unobstructed visual of the ball from beneath the table. The table should stand under its weight and all rods and players should be operable.

1.2 Constraints

The table should follow the dimensions and specifications of comparable tournament tables and all components should sum to a cost of less than $500.

1.3 Performance Objectives

The table should score well in the areas of **stability** and **appearance**. This means the table should be structurally sound and not exhibit any excessive wobbling or have any broken/non-functional parts. The table should also be visually appealing and exhibit qualities of normal home furnishings.

1.4 Alternate Designs

As seen in Table 1 there were many alternative design considerations for this project.

Table 1. A summary of different design considerations with our choices bolded.

Situation	Choice A	Choice B
Field Material	**Tempered Glass**	Acrylic
Leg Design	**L-Shape**	Solid beam
Rod Design	Hollow $\frac{5}{8}$"	**Solid $\frac{1}{2}$"**
Goalie rod	**3-count**	1-count
Bumper Design	Ridges	**Holes**
Ball return	Front-facing	**End-facing**
Table material	**Plywood**	Solid oak
Table Coating	Clear coat	**Stain + Clear coat**
Glass support	External Ridges	**Inset shelf between plywood boards**

1.5 Analyses for Decision Making

Our decision process effectively weighed the impact of each choice across the following categories: cost, appearance, manufacturability, weight, strength, durability, and availability. When necessary, outside sources were consulted on topics such as woodworking to ensure effective decision-making and adequate knowledge.

1.6 Industry or Societal Standards

By researching various professional designs, we determined that not much has been standardized across professional tables. However, our table follows a standard layout for the rods and a standard height. The table is 36" above the floor. As standard across US tables, our goalie rods have three players as opposed to international tables which tend to have one goalie.

1.7 Concepts or Coursework Skills Used

Many courses within the MAE department at Cornell were utilized to make a successful design. Those courses are listed below with class number and skills used:

- Mechanical Synthesis, MAE2250 - Manufacturing skills, Fusion360 CAD and engineering drawing making
- Rapid Prototyping, INFO4320 - Prototyping designs
- Statics, MAE2020 - Static simulations, material properties, loading cases
- Mechanics of Materials, MAE3270 - Material properties, loading cases
- Student Project Teams, ENGRG3400 - Design for manufacture, machining skills, 3D printing

1.8 Evaluation of Design Performance

Our table looks and feels like any other foosball table. The design successfully appears as a decorative furnishing while achieving the functionality desired. The table exhibits little to no instabilities during play and shows no signs of wear and tear after several games. The evaluation of its longevity must be determined over a longer period with adequate play frequency, however, tables of equivalent $500 value have shown more wear for similar play.

1.9 Impact on public health, safety, and human welfare, as well as upon current global, cultural, social, environmental, and economic concerns

This design does not interact with stakeholders who are interested in public health, safety, human welfare, or global, cultural, social, and environmental concerns. As noted in the introduction, this table drastically reduces the necessary costs for designing and building a standard Foosball table, as the budget for this project was 500 (compared to upwards of 3000).

1.10 Format of Design

The format of this design is primarily in the form of a 3D CAD model in Fusion360. Designing through computer aided design allowed us to mock up a prototype quickly and make adjustments as needed. The final design was implemented in the form of a physical final product as seen in Figure 1.

Figure 1. The final foosball table. The CAD model aided in understanding the woodworking and joinery before assembly.

1.11 Student Roles

Julian Prieto - Group Coordinator, CAD design lead, Prototyping lead

Katherine Knecht - Machining Lead, Design Coordinator, Consultant Liason

2 Functional Requirements of Design

The main goal of this project was to create a table that could play a normal game of Foosball at tournament-level quality while being able to facilitate a robotic attachment that could be used in place of a human player. In Figure 2, we see an example of a high quality $3000 table. The design features eight rods at specific intervals that hold a total of 26 men above a field that is 120 cm by 68.5 cm. We accomplish what this table does and more with a modest budget of $500.

Figure 2. Image Credit: Valley-Dynamo LP

3 Constraints and Objectives of Design

3.1 Constraints

- Field Size of 48 x 27 inches
- Strength of field material to resist sagging and deformation or failure from impact forces of the ball
- Clear playing field for vision system
- Standard foosball table height (36 inches)
- Emerson Machine shop availability to machine rods
- External ball return due to the fact that the table needed to remain clear and unobstructed for the vision system
- Budget of $500

3.2 Objectives

- Ergonomic handles
- Ergonomic weight of rods
- Replaceable glass field
- High-quality wood and appearance

4 Performance Objectives

In order to evaluate the effectiveness of our tables performance, we've come up with the following metrics: **Stability** and **Appearance**.

4.1 Stability

The overall durability and strength of the table we call the **Stability** of the table. A good measure of this metric involves both qualitative observations of the motion of the table during play and quantitative analysis of the table done through theoretical measures of force done to ensure that the table withstands excessive force. A good quantitative measure of durability over time would be the number of broken components on the table after a long period of frequent play.

4.2 Appearance

The overall **Appearance** of the table refers to the qualitative analysis of the table's overall coordination and visual features. This measure is more subjective than the other one but the features mentioned should distinguish the table from lower-quality tables and share qualities to high-quality furniture.

Figure 2. Stain was used for all wooden features to enhance the appearance of the table.

5 Design Choices

Throughout the design process, many design choices were made to account for ergonomics, manufacturability, assembly and integration ease, as well as budget considerations, material availability, and resource availability. Alternate designs are listed for the table legs, glass security, rods, and handles.

5.1 Table Legs

The table legs were designed with the intent of structural integrity as well as a high quality, elegant appearance. We chose to incorporate L-shaped legs for these very reasons. Made out of solid red oak, the legs support the entire structure of the table and thus must resist buckling under load. (See section 8.4 for this analysis.) Pocket screws were used to hide the joinery and enhance the sleek look while retaining a rigid connection. Not only does this make the table substantially lighter than using solid red oak beams, but it also allows for the possibility of using stepper motors to create a motorized leg leveling system, where the motors could be hidden in the L-shape. (See section 10 for more analysis.)

Figure 3. L-shaped table legs were designed with solid red oak to enhance the stability, appearance, and functionality of the table.

5.2 Glass

What sets this Foosball table design apart from others is its clear glass playing field. From near the beginning of this project, we established that the computer player will track the position and velocity of the ball by using a camera below the playing field. This necessitated some sort of clear field, like acrylic or glass. We chose tempered glass ultimately for its strength, durability, and availability.

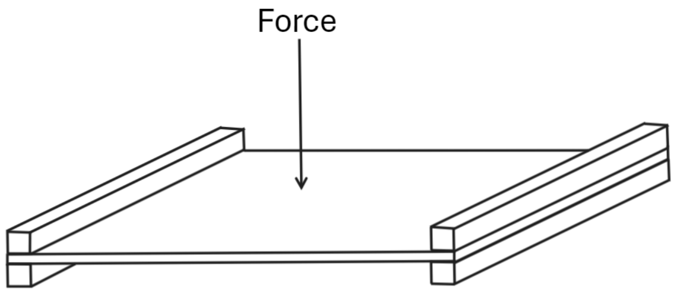


Figure 3. The loading case analyzed to find the max capable load of the glass was the following fixed end beam bending case.

By analyzing the structural load capabilities of our glass in the context of fixed point beam bending (as seen in fig 3), we were able to determine the strength of the glass would be high enough to withstand normal play operation. The equation below describes the equation we used to find the maximum force we could apply to the table before failure which we determined was around 1500N. As an additional precaution, insulation foam was added to cushion the glass and allow slight deformations for any unexpectedly high forces.

$$\sigma_u = \frac{-My}{I}$$

Where:

- σ_u is the ultimate stress of tempered glass (we approximated the strength should at least double that of annealed glass and used 60MPa as an estimate)
- I is the moment of inertia in m^4
- y is the maximum distance from the center of the beam $\frac{1}{8}$" (0.003175 m)
- M is the maximum moment throughout the beam (The applied force times the distance it was applied from the supports)

Figure 4. A top-down view of the table showing off the unique tempered glass field.

5.3 Rods

Typically, Foosball table rods are made out of hollow 5/8” diameter steel rods. This allows for lightweight design and comfortable maneuverability of the players. However, our table features solid 1/2” diameter steel rods because this material was available in the Emerson Manufacturing Shop. Rods were band-sawed and holes were drilled so that players and handles could be installed.

Figure 5. Machining the rods took unique fixturing since all holes drilled had to be colinear for the foosmen to sit together on the rods without twist. Rods were machined in the Emerson Manufacturing Shop.

5.4 Handles

Handles were carved out of a solid rod of red oak. These custom handles fit over the custom 1/2” steel rods, and featured an octagonal grip design for the user to hold on to during play.

Figure 6. Our custom-made handles were carved from a 2" oak dowel and were stained to match the table.

5.5 Ball Return

The ball return is something unique to this table as well. Typical tables include an internal ball return that routes the ball either to the ends or sides of the table. The desired route was to the side of the table where the player stood for ease of access. This made the ball return more complicated however; it could not run under the field else it would block the camera's view of the ball. Thus, an external ball return was necessary.

The ball return was designed to wrap from the short side, where the goal is, to the middle of the long side via some track. One idea was to create a wire metal marble-run style coaster to return the ball. This design choice would require a lot of structural support since a foosball is larger than a marble.

What was designed was a 3D-printed, round shelf that could be screwed into the side of the table. This allowed for stability without concern that the ball would fall out. Its constraints were that it had hold a 33mm diameter ball and fit on a printable bed size of 235 mm x 235 mm.

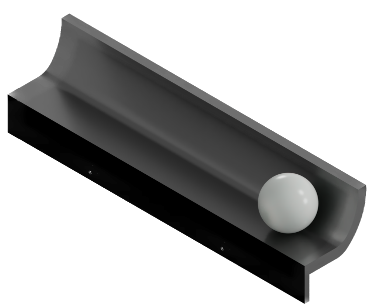


Figure 4. Ball return and ball for scale. Multiple pieces were to be printed and screwed onto the side of the table.

However, this design was not implemented this semester. Instead, a ball basket was designed to catch the ball upon exit of the goal. It screws into the side of the table and features a divet where the ball will sit. More analysis of a convenient ball return will occur next semester.

In addition, a funnel was designed to guide the ball to a hole in the side of the table. The funnel needed to be printable, structural to impact forces of the ball, and successfully guide the ball to an exit hole.

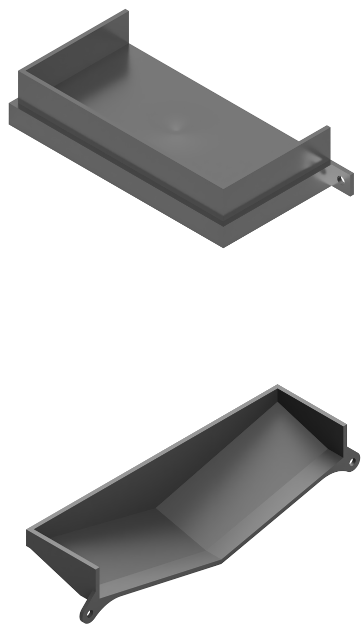


Figure 7. Ball return basket (top) and ball funnel (bottom).

5.6 Foosmen

This design was primarily influenced by the Tornado table counter-balanced foosmen. The center of mass is intentionally made to be as close to the axis of rotation as possible to allow for minimal resistance during rotation and so that rods don't rotate under the weight of the players. The feet of the players is angled in such a way that allows for a tangent kicking plane (purely planar acceleration means the ball stays on the table) and easier contact for control when using the back of the foot.

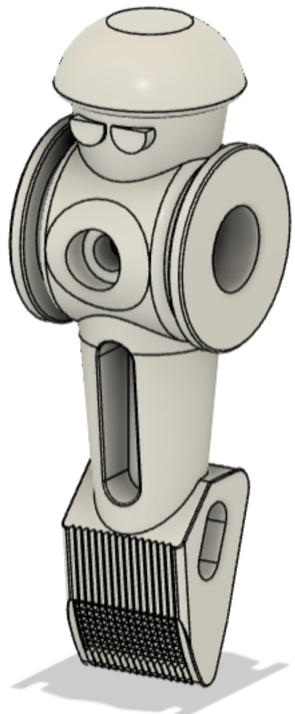


Figure 8. Our foosmen CAD model.

5.7 Glass Support

How the glass would interface with the wood was a vital engineering decision, as this decision needed to ensure maximum stability of the glass, as the glass itself weighed approximately 10.3 pounds.

One option was to create a shelf around the edge of the field and slide the glass in place from above. However, a wide shelf would have been necessary to support the weight of the glass, so instead, the glass was oversized and inset between two boards of oak plywood. A gap of 0.7” was left for a glass of thickness 0.25” to account for the insulation padding of the glass to protect the edges from unnecessary wear and friction forces of the plywood.

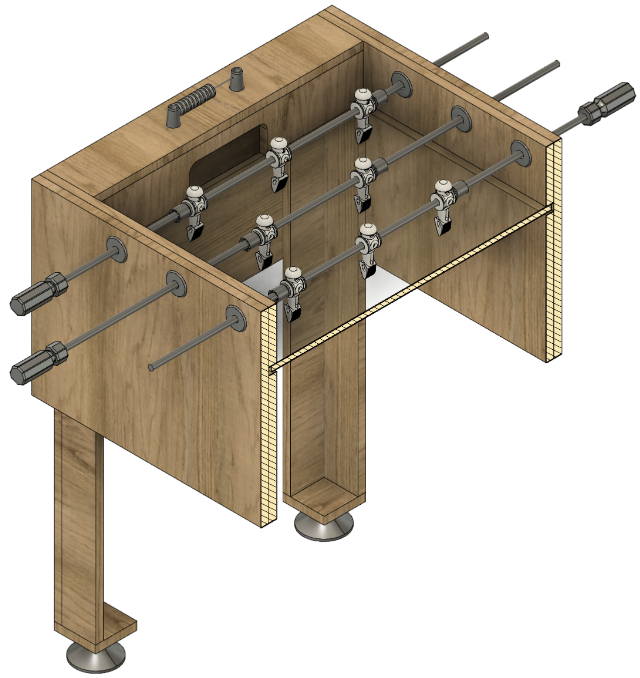


Figure 9. A section view of the table to show that the glass was supported between two pieces of oak plywood.

6 Analyses for Decision Making

Ultimately, this table was to be designed and built in one semester, so many decisions relied on completing a working table by December 15th. A difficult aspect of this project was creating a high-quality table on a low budget with limited tools. The budget affected many of our design decisions.

Additionally, many components of the table were anticipated to undergo distributed or impact loads. For example, where the glass rests, the oak plywood must bear the distributed weight. An example of an impact load is a player applying random forces on the rods and bearings that support the rods, or when the 3D-printed foosmen strike the ball. Stress calculations were performed to ensure materials could perform well under such conditions.

The following questions were asked before making design decisions:

- Is this material readily available? Can we purchase this material at a local store, or somewhere with quick shipping?
- Is this material or item a reasonable cost given our budget? Is there a similar alternative at a cheaper cost?

- Are there resources at Cornell MAE where we could manufacture this part in a timely fashion? If 3D printed, is the material going to result in a high-quality print? Will this fit in the manual mill table size or print bed area?
- Is this material appropriate given the structural loads anticipated? What failure modes are expected, or where is this component most likely to break?

The following Cornell MAE resources were used to complete this project:

- Emerson Manufacturing Shop
- Rapid Prototyping Lab
- Cornell Maker Space

7 Industry or Societal Standards

The dimensions of standard foosball tables were laid out for us in the following table taken from Mohebi's "The Study of Semi-Automated Football Table"

STYLE	Make	Playing area(cm)	3-bar spacing(cm)	Goal width (cm)	Ball wgt(g)
Italian	Garlando	114-120x70.5	18,4	19	17,5-18,5
	Roberto Sport(UCD)	111-118x70.5	16,0	19	17,5
	FABI	120x70	16,8	19	17,5
	FAS	117x70	16,4	19,5	17,5
	Longoni	113x70	16,5	21,5	17,5
	Brighouse/FASNA	108x70	16,2	19,8	17,5
	Sardi	120x69	16,5	19,5	17,5
German	Loewen	119x68.5	16,4	17	20,5
	KCE/TS	118.5x68.5	15,9	18	20,5
French	Bonzini	119x69	17,0	19	14
	Rene Pierre	119.5x69	17,8	20	11
Benlux/Gr	Soccer 2000	116.x69	16,0	19	14,5
	Jupiter	117x68	16,0	19	11,2
	Topper 2000	111x65	16,4	18	15,4
Spanish	Biufca	134x75	n/a	25	28
American	Tornado	120x68.5	16,2	20,5	27
	Sivissidis	119x68.5	18,5	20,5	27

Figure 10. Other Foosball table brands and their varying dimensions.

This gave us a good sense of what size a table might be but also showed us that there was not much standardization present among various foosball tables.

8 Evaluation of Design Performance

Four important factors were considered in the evaluation of the design performance. Of course, the table needed to perform as well or better than a commercial table, but it also needed to remain structural under much heavier loads than a normal table, as well as keep the playing field unobstructed from below. Finally, Fusion360 simulations were conducted to ensure stability of the design.

8.1 Structural Integrity

This project is evaluated in multiple facets. The first is structural integrity. In order to evaluate structural integrity prior to the table being built, stress calculations were performed where maximum loads and forces were expected. Once the table was built, structural integrity was evaluated by applying load to the rods where the player was likely to cause stress, as well as playing multiple games at high speed. (See more on simulations of loads in section 8.4.) Next, the structural integrity of the table itself was tested as we had to rotate it upside down and right side up many times throughout the build process. Despite being moved around significantly, the table remained level and did not shake during games.

8.2 Playability

The second important aspect of design performance was of course playability of the table. Even before actuation is implemented, the table must perform as well or better than commercial tables. The following list is a continuation of the objectives that necessitated a playable table:

- Rods must move freely
- Handles must be comfortable
- Bearings, bumpers, and washers must protect the sides of the table from the rods and foosmen and must not deform, deflect, or fail
- Custom foosmen must be able to maneuver the ball without deforming or failing
- Ball must exit table upon entering either goal at the ends of the field
- Ball entry dish must deposit ball into the field
- Glass must not be easily scratched by player interaction or during a game
- Foosmen must be at the correct vertical height for optimum ball maneuverability
- Table must not shake excessively during play and remain level

To determine that the above criteria was met, foosball games were played with attention to detail on each objective. For example, the foosmen will likely be printed again next semester as the foot could be slightly closer to the glass for maximum speed when hitting the ball.

8.3 Glass Visbility and other Material Factors

What ultimately was a success with the glass aplaying field was its extremely clear visibility. Even if the glass got dirty, it could easily be returned to its clear state with cleaner. The material of the rods was tested in two ways. First, load was applied to the handles where the player might push down. Due to their solid steel structure, the rods returned to their initial state after deflecting. Second, the rods were tested upon completion of the table during games to determine the ergonomics of having heavier rods than standard tables. Despite being heavier, the rods were not difficult to turn and slide back and forth by the player.

8.4 Fusion360 Simulations

What made simulations difficult in Fusion360 is that red oak is not supported in Fusion360's studies due to its orthotropic properties (properties which are different in each axis of the material). This is due to the grain direction of the wood. In order to conduct studies that could model our table as close as possible, simulations were run with the material property of the table set to MDF. The material compressive strength of MDF is 10 MPa as suggested by this source, and red oak has a compressive strength of 16.1 MPa according to this source when compressed parallel to the grain. (The legs of the table were woodworked with the grain in the vertical direction.)

The following images show that for a loading case of 1200 N (equivalent to the weight of two people on top of the table), the legs do not approach buckling in the slightest. The buckling factor is 454.8 in the first case where load is applied directly to the middle of the field. The buckling factor represents the factor by which the loads need to be increased to reach the buckling load; less than 1 indicates the design buckles. Furthermore, since the material assigned has a compressive strength less than that of the material used, the design is even less likely to fail. In this case, one of the feet was constrained in all three axes while the others were only constrained in one or two axes.

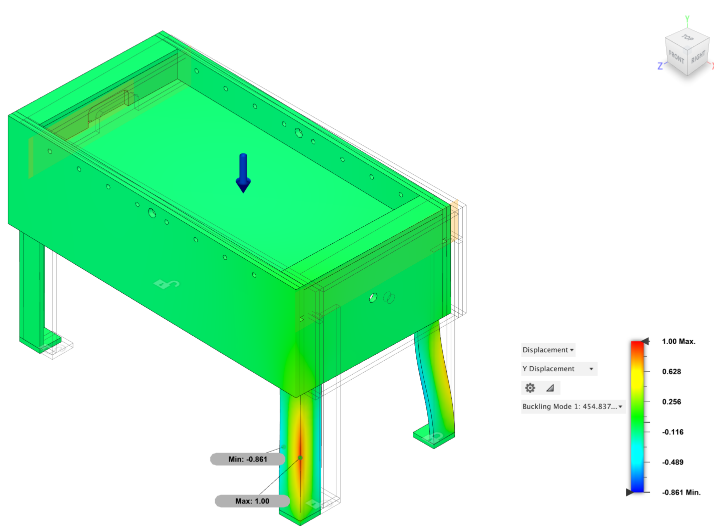


Figure 7. Buckling test: Load of 1200 N applied to the middle of the field.

In the second image, the load is applied to all of the top wood surface. This example simulation is more extreme than the previous since it constrains all feet as fixed to the ground. This is not the case for a real table; in a buckling condition, only one of the legs would be ”fixed” as it buckles but the others would be free to move. As shown in the results, even in this extreme case, with the weight of two people on the top wooden surface of the table and all four feet constrained in all three axes, the table still does not buckle; the buckling factor is 750. This shows the durability of the table design, and more specifically, the legs.

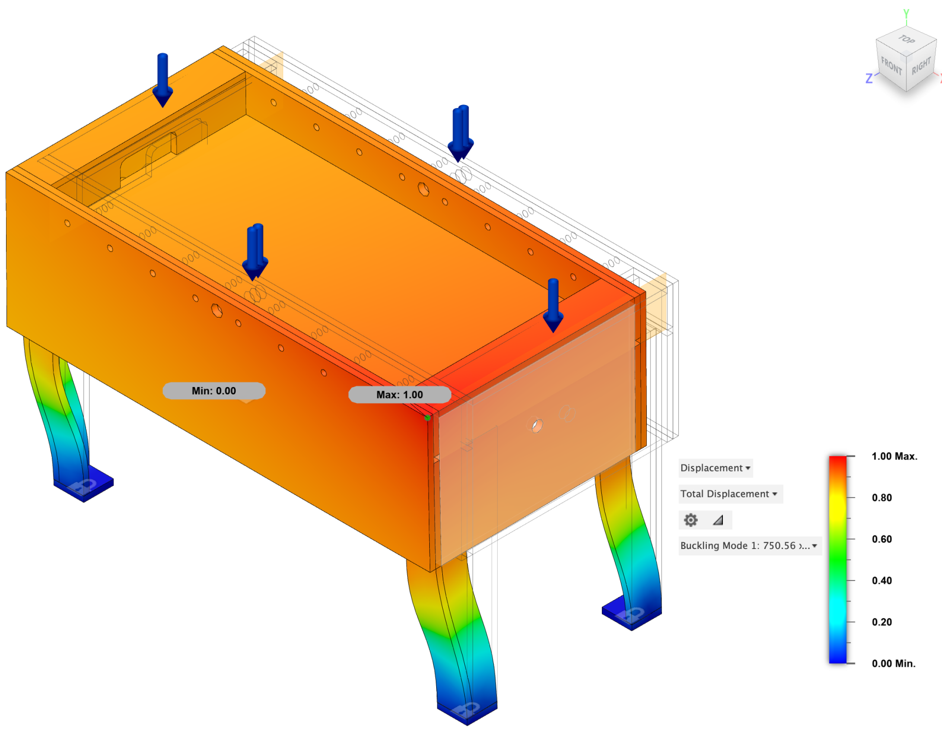
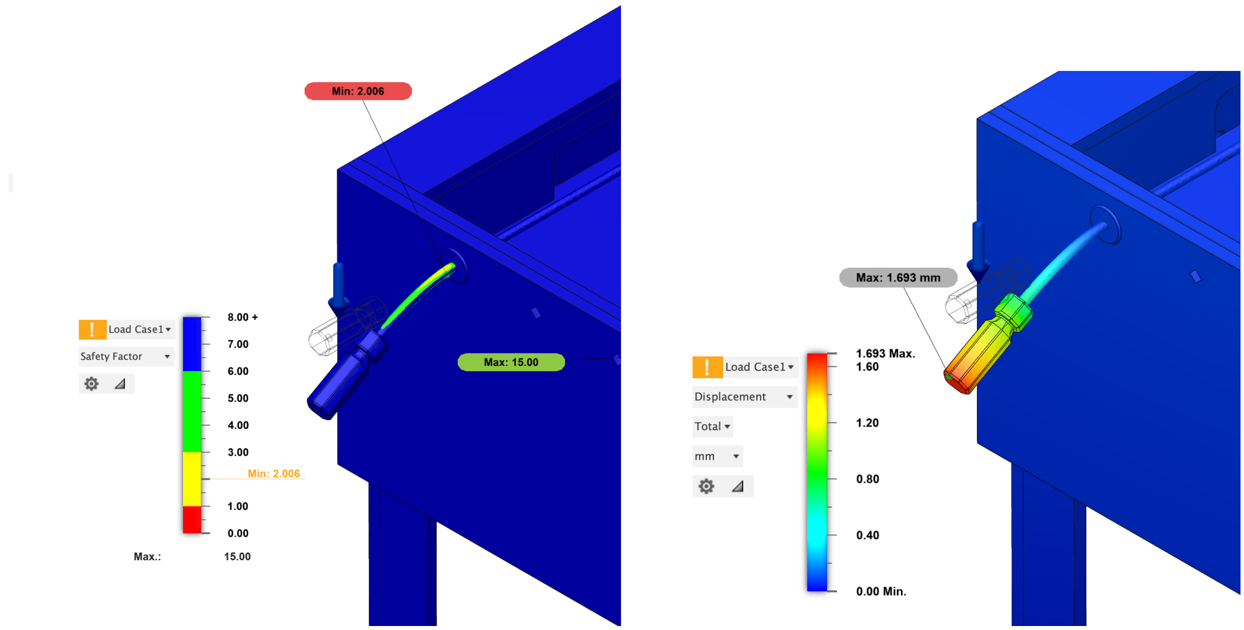


Figure 8. Buckling test: Load of 1200 N applied to the outer wooden top surface of the table and all four feet constrained in all three axes.

With these Fusion360 simulations, it is important to note that rigid contacts are assumed with each component. That being said, the physical model uses four large screws for each leg to secure them to the walls of the table. Thus, buckling will likely not be the first cause of failure for the table; the shearing of the screws would likely occur first.

Additionally, a simulation was run of the bending of the solid steel 1/2” diameter rods. A force of 100N (equivalent to 23 pounds) was pushed onto the end of the handle downward to simulate if a person were to apply all force on a rod during the game. What frequently occurs is constant wiggling of the rods during play, in frustration, or even to intimidate the other player in anticipation. This simulation models the case of excessive force on the rods, even though reaching 23 pounds is an unlikely occurance. The table wood and handles were set to MDF, and the rod was set to Steel AISI 1018 106 HR.



(a) Safety Factor **(b)** Total Displacement

Figure 11. Static Load: Bending Rod Fusion360 Simulation Results

The figure shows 100 N applied to the end of the handle to simulate high loads of a player. This image shows the displacement of the rod under 100N of load. The maximum displacement is 1.7mm (0.067 inches) and the lowest safety factor is 2. However throughout the rest of the rod, the safety factor is higher: between 3 and 8.

9 References

Real Time Ball Tracking

This paper by Janssen, de Best, and van de Molengraft from Eindhoven University of Technology demonstrates the capabilities of a semi-automated foosball prototype. In particular, this paper documents a table with a vision system above the field rather than below.

The Study of a Semi-Automated Foosball Table by Dani Mohebi

This research paper by Mohebi outlines their experience with actuation technologies on a semi-automated foosball table. This paper was referenced as a baseline for our table dimensions and functional goals like anticipated loads from accelerating the ball.

10 Future Work

Next semester, the table will be transformed into a semi-automatic through the implementation of linear actuators and encoded BLDC motors for rod translation and rotation respectively as well as a camera for vision detection of a colorful ball. The camera will sit underneath the glass field for full view, so a mounting mechanism will need to be designed for the camera. The design should not obstruct the player's position in any way.

Additionally, stepper motors could be coupled to the leveling screws by GT2 belts to create motorized-leg levers that would facilitate the table leveling process.

Small adjustments will be made to the foosmen designs as well as implementing another possible ball return that bring the ball back to the player once a goal is scored rather than exiting at the far ends of the table.

11 Acknowledgements

We'd like to thank following people for their contributions to our project

- Professor JJ for his contributions as our advisor and for meeting with us weekly to talk about our project.
- Matt Ulinski for his generous contributions toward our table's budget.
- Sam Knecht for his invaluable consultations regarding woodworking design.
- Alex Eagan and Mateo Guyn for donating the space needed to construct and facilitate the final product.

Appendices

A Bill of Materials and Itemized List of Components

Purchased Components				
Part	No.	Supplier	Quantity	Cost
Red Oak Boards	1042805	Menards	2	80
Oak Plywood 3/4", 4'x8'	796766	Lowes	2	179.56
Wood Finish	91864A018	Lowes	1	25.00
Wood Stain	90128A108	Lowes	1	13.48
Tempered Glass 1/4", 27"x49"	N/A	G and G Glass	1	100.00
Angle Brackets	3632116	Lowes	1 pack	9.16
Binding Post Screws	148274	Lowes	16	16.00
1/4-20 Threaded Inserts	N/A	Amazon	2 packs	7.99
2" OD Oak Rod, 36" Long	96825K86	McMaster Carr	1	52.32
Sum	487.33			

Many components for this table were obtained at no cost from a foosball table that had broken and was no longer usable.

Procured Components		
Part	Supplier	Quantity
1/2" Solid Steel Rods	Emerson Manufacturing Shop	8
Leg levelers	Broken Foosball Table	4
Ball	Broken Foosball Table	1
Foam Insulation	Fluids Laboratory	2 strips

Many components for this table were obtained at no cost by printing through Cornell's **Rapid Prototyping Lab.**

RPL Components		
Part	Material	Quantity
Ball Return	ABS	1 segments
Bumpers	TPU	16
Washers	TPU	16
Bearings	PETG	16
Ball Basket	PLA	2
Ball Entry Dish	PETG	2
Foosmen	ABS	26
Ball Funnel	PETG	2

B Assembly and Integration Order

The assembly order of oak plywood was important because the glass was uniquely sandwiched between boards. Additionally, removing the glass in the case of failure or needed replacement was prioritized.

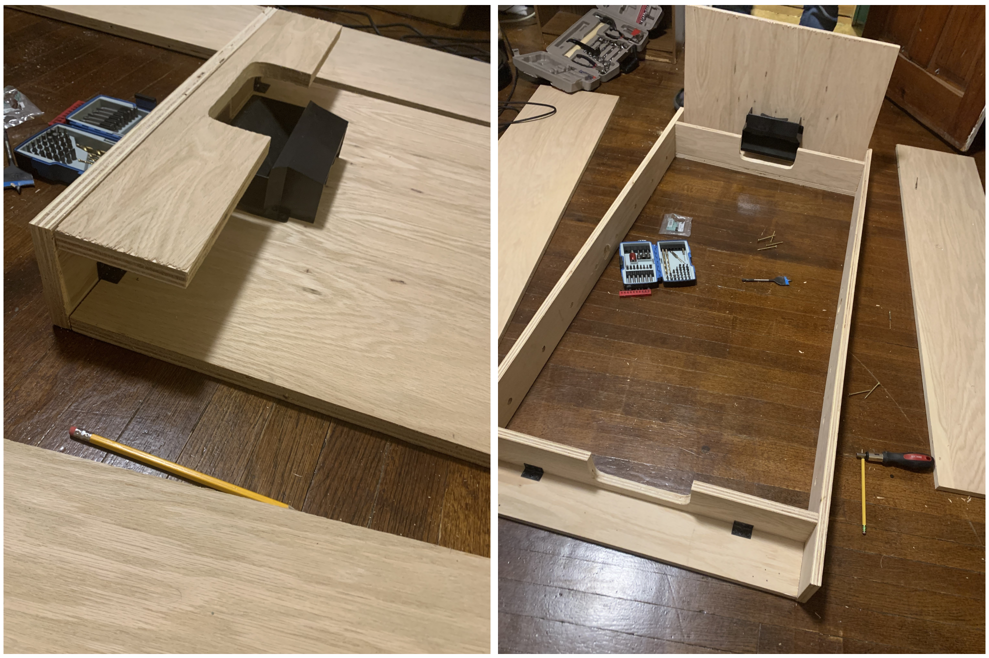


Figure 12. Initial assembly of oak plywood boards

First, the ends of the table were assembled including the goal board, top end boards, and small-side ends. The figures above document this process, in addition to assembling the inner top boards. Wood glue was used for the long sides, and angle brackets were used for the ends of the table for structural support.

Figure 13. Mid-assembly images of table

The figure above on the left shows that the glass was installed before the inner side boards so that those boards could support the glass. This process was thus completed while the table was upside down and the inner side boards could be screwed. Finally, as shown above on the right image, the legs were screwed into place while the table was still upside down, and the leg levelers were added. The use of threaded inserts for the legs allowed for ease of assembly and disassembly since this table will be moved to Upson Hall next semester.

Figure 14. Final assembly images of table

Once the table was flipped back over, the bearings, scoring system, foosmen, bumpers, washers, and ball insert were finally assembled. We were finally able to play our first homemade foosball game.