TruLie Golfer: Final Report

Group A1

24-441 Engineering Design II

7 May 2017

Design Team

Samer Abdelmoty - CAD for initial top plate and clevis assembly design; Manufacture of clevises; Engineering analysis of forces through system and leadscrew calculations as well as required motor torques; FMEA, cost report, and life cycle analysis.
Andrew Chellman - CAD for initial PT2 concepts; manufacture of leadscrew supports, spherical bearing housings, and bottom plate; DFMA redesign of arms; carbon fiber research and construction of hot wire foam cutter; engineering drawings and BOM.
Nadia Florman - CAD for initial arm design, accordion cover; manufacture of spacers for ball joint motor mounts, carbon fiber arm, top plate; shoulder screw calculations, design and manufacturing schedule.
Alyssa Meyer - CAD for bottom plate, FEA, manufacture of arm inserts and motor mounts, carbon fiber arms, top plate, hot wire cutter.
Stephen Scott - Modeling initial design concepts; design and manufacturing of carriage, Proto 1, and Arduino mount; DFMA redesign of supported rail/motor mount system and carriage; inverted arms redesign and test top plate manufacturing; control code for plate location/kinematic design; creation of renders and animations
Alex Woodward - Electronics design; selection and integration of motors, motor drivers, power supply, CPU, firmware and user interface software; manufacture of the carbon fiber arms; customer and market research; poster.

Problem Description and Opportunity

One of the greatest challenges a golfer faces is that of adjusting to their lie. On the practice range every shot is played off of a flat, tightly mown fairway, but on the course the terrain is typically sloped. This can lead to dramatic consequences if the golfer does not adjust accordingly. Currently, golf simulators have no way of accurately simulating this. The goal of our product is to address this shortcoming by creating a robotic golf mat that adjusts its orientation automatically to match what is displayed on the simulator.

Stakeholders:

- Golfers
- Simulator owners and operators, (golf clubs, training facilities, universities)
- Coaches

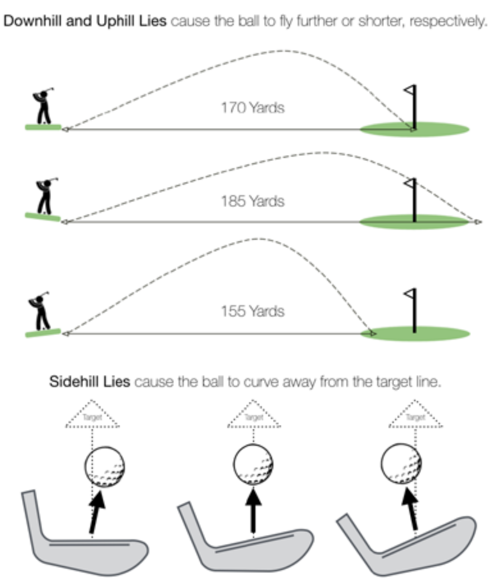
Market:

- No existing product that changes ball height as well as ground angle
- Integrate with simulators to heighten realism

Value Proposition and Design Specifications

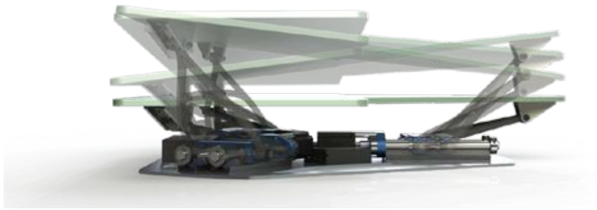
Value Proposition: Golf has become a global sport - of the top six golfers in the world (according to the Official World Golf Rankings) only two are native to the same country. While southern climates facilitate play year-round, the majority of golfers are forced indoors over the winter. To continue practising during the off-season, avid golfers visit sports domes or rent time in golf simulators. As a result of rapid technological advancement over the past decade, the latter option has seen a drastic rise in popularity. To continue to attract new customers, golf simulator companies must continue to innovate, to make the consumer experience as realistic as possible. As illustrated in the figure below, sloped terrain can drastically impact ball flight. TruLie allows simulators to capture this phenomena indoor, and thus provides a more realistic experience for simulator users. We anticipate that TruLie will retail \$3,000 - \$4,000 (since the estimated manufacturing cost is approximately \$1,500). Since simulators range in cost from \$50,000 - \$90,000, this is a small increase in cost for a substantial improvement to the user experience.

The Effect of Sloped Terrain on Ball-Flight



Design Specifications:

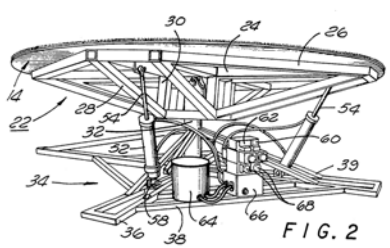
- Range of Articulation: the top plate must be able to travel 8" vertically, and achieve slopes of up to 10 degrees at any height.
- Footprint: the product must fit within a 3' x 3' space on the ground. There must also be space allotted for the golfer and stance mat on one side of the product.
- Forces and deflection: The product must withstand up to 1100 lbs force (the worst-case impact of a golf club) without yielding. Deflection of the top plate during impact should be imperceptible to the user.



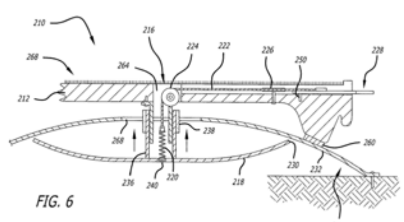
Market and Technology Research

Patents and Related Products

There are several patents for golf mats that aim to simulate sloped terrain, two of which are shown below. The primary difference between our product and these patents is that our mat is designed only for the golf ball, while the patented designs all place the player on the mat. Multiple patents cite issues accommodating the weight of the player on the mat, as well as difficulties scaling their design down to a reasonable size without encountering strength-related problems.



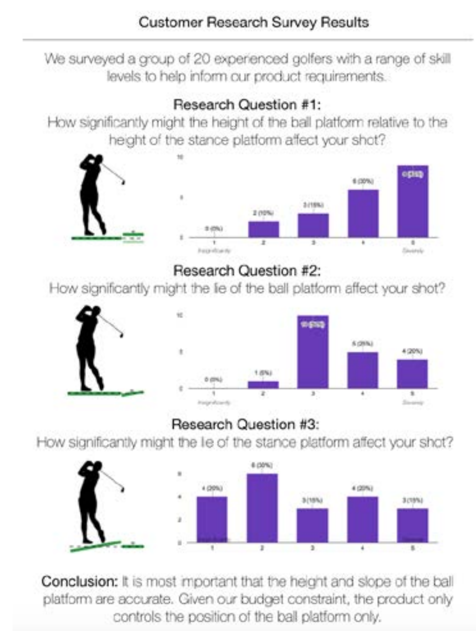
Patent #US5340111 A



Patent #US8496538 B1

Important Notes:

- Cost of a Simulator: $50,000-$90,000
- Average simulator rental cost: $40/hour
- The simulator sensor system tracks the ball with equal proficiency regardless of the top plate position.
- Given the open ended question "what would you liked to see added to or improved about golf simulators?", fifty percent of golfers surveyed specifically mentioned the simulation of sloped lies. Forty percent also mentioned more realistic putting.



Competitor Research

There are currently two products that aim to simulate sloped terrain in practice:

X-Plate Lie Positioning System from X-Golf

Cost: $9,000

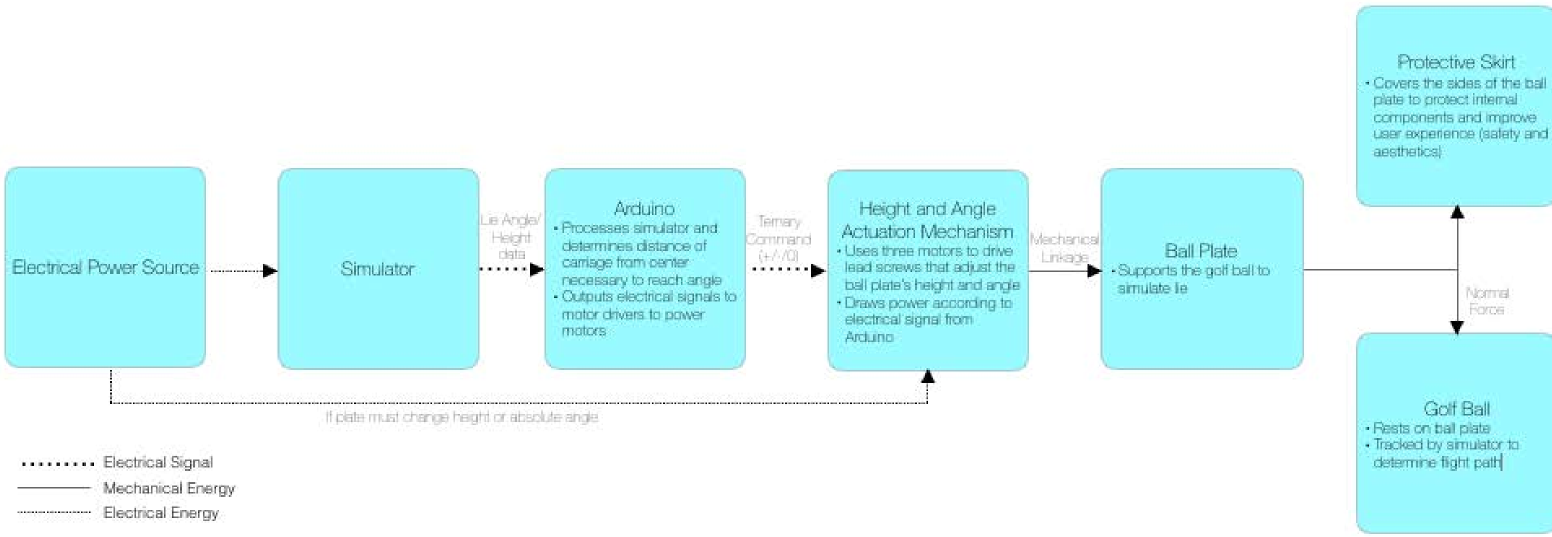
X-Plate is a robotic stance mat intended for use with X-Golf Simulators. The ball plate remains static, while the stance plate automatically adjusts its slope to match what the simulator displays on the screen. This product fails to capture the slope of the earth under the ball, as well as the ball's height relative to the players' feet, which we determined to be most important in simulating varied lies (based on our customer survey). X-Plate is designed for exclusive integration with the X-Golf simulator, and is not available for purchase to non X-Golf simulator owners.

ToughLie 360

Cost: $2,750

ToughLie 360 is an angled golf mat that can be rotated to simulated different hitting slopes. The angle of the mat is fixed, and it must be rotated manually. The product is intended for use at outdoor driving ranges.

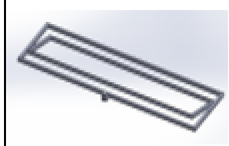
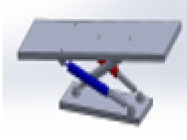
Functional Decomposition



Between the simulator display and the height and angle of the golfing surface of TruLie, computer calculations, motors, and mechanical systems are used to create the most accurate simulated golf experience. The simulator provides the height and angle of the plane of the surface the golfer is supposed to be hitting off of to a complex system of ten equations. When solved, these ten equations output three distances corresponding to distances between the carriage and the motor that is passed on to the arduino. The arduino signals to the motor drivers to power the motors and tells them the number of times to turn in order to move the carriage to the desired spot. Up from the carriage the arms are mechanically connected to the plate with enough degrees of freedom to allow the plate to reach any height or angle within the range of a typical golf course.

Concept Generation and Evaluation*

The design criteria that carry the most weight in our design are stiffness of the system and the ability to achieve the necessary articulation (height and angle of the golfing surface) accurately. The three sliders in a circular pattern was the best design out of our five options; it is able to reach all the necessary angles while also getting very low to the ground.

Criteria	Weight (1-5)	Labyrinth & car lift hybrid			3 Linear Actuators			Adjustable Scissor Lift			Rotating platform with inclining plane			Three Sliders in Circular Pattern**
														
		A*	B	Ave	A	B	Ave	A	B	Ave	A	B	Ave	Group Evaluation
User Experience														
As close to the ground as possible	2	1	1	**1**	2	1	**1.5**	1	1	**1**	0	0	**0**	**2**
Cost	1	1	-1	**0**	-2	0	**-1**	0	1	**0.5**	0	0	**0**	**1**
Lefty-compatible	1	-2	-2	**-2**	2	0	**1**	0	0	**0**	0	0	**0**	**2**
Mat modularity	1	0	2	**1**	0	2	**1**	0	2	**1**	0	1	**0.5**	**2**
Articulation														
Range: X degrees of rotation	5	2	2	**2**	2	2	**2**	-1	0	**-0.5**	0	2	**1**	**2**
Simplicity	4	-2	-2	**-2**	1	1	**1**	0	1	**0.5**	0	1	**0.5**	**2**
Angle accuracy	4	0	2	**1**	0	2	**1**	0	2	**1**	0	1	**0.5**	**2**
Height accuracy	5	0	2	**1**	0	2	**1**	0	2	**1**	0	1	**0.5**	**2**
Stiffness														
No rotation	5	1	-1	**0**	-2	0	**-1**	1	0	**0.5**	2	0	**1**	**2**
No deflection	5	0	0	**0**	-2	1	**-0.5**	0	1	**0.5**	1	1	**1**	**2**
Safety														
Can be stood on (double counting)	1	0	-2	**-1**	0	2	**1**	0	2	**1**	0	1	**0.5**	**1**
Hidden components	2	-2	-1	**-1.5**	2	0	**1**	2	1	**1.5**	2	1	**1.5**	**2**
Ease of use														
Manufacturability	4	0	-1	**-0.5**	2	1	**1.5**	0	1	**0.5**	1	1	**1**	**2**
Ease of modification/repair	3	-2	-1	**-1.5**	2	1	**1.5**	0	1	**0.5**	2	0	**1**	**0**
	Totals:	-2	5	1.5	16	50	33	6	43	24.5	29	36	32.5	78

*A and B indicate groups of 3 team members each that graded the pugh chart together to assure all sides were viewed and then we averaged the groups scores to determine the total scores for each criteria.

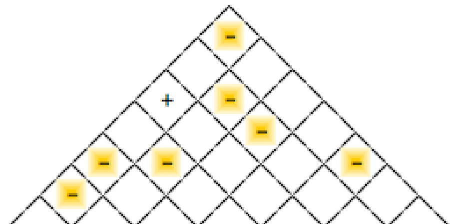
**Highlight indicates best graded design

House of Quality

Relationships	
Strong	●
Moderate	○
Weak	▿

Correlations	
Positive	+
Negative	−
No Correlation	

irection of Improvemer	
Maximize	▲
Target	◇
Minimize	▼



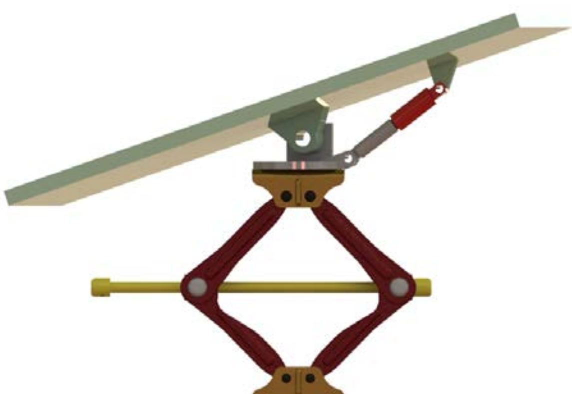
					Column #	1	2	3	4	5	6	7
					Direction of Improvement	▼	▲	▲	▲	▲	▲	
Row #	Weight Chart	Relative Weight	Customer Importance	Maximum Relationship	Functional Requirements / Customer Requirements (Explicit and Implicit)	No Exposed Components	6 of degrees of rotation (+/-)	8 in height achieved	Enough frictio between mat and ball	Motor/Electronics Controlled	Can withstand impacts (bad swings)	Easily Assembled
1		8%	5	9	Product is rigid	▿	○	○			●	
2		8%	5	9	Product moves up and down	▿		●		○	▿	
3		8%	5	9	Safety	●		○			●	
4		3%	2	3	Lefty Compatible	○						
5		7%	4	9	Look Clean/Nice	●				▿		
6		8%	5	9	Has a golf mat	●						▿
7		8%	5	9	Ball doesn't roll off		○		●			
8		8%	5	9	Integrates with simulator		●	○		●		○
9		8%	5	9	Used with all golf clubs		●		▿			
10		8%	5	9	Durability			○		▿	●	▿
11		8%	5	9	Can be repaired						▿	●
12		8%	5	9	Product changes angle		●			●		

The majority of our Customer requirements are equally rated due to the importance of all of them in the design of this project. Being able to reach the necessary heights and angles does not outweigh the importance of having a safe system or the ability of the system to be integrated with a golf simulator.

There are several tradeoffs in our design as shown by the negative signs in the top triangle in the HOQ. The ability to reach the necessary heights and angles create the possibility for components to be exposed despite their possible initial coverings. Some of the other negative signs denote the tradeoff between large angles of the golfing surface and the likeliness of the ball to roll off, the possible weakness of the system at large heights and angles, and the added complexity of assembly as electronics are incorporated.

Our conceptual design meets these criteria as it hits the necessary heights and angles, the grass surface provides enough friction for the ball to not roll off the surface, the system is actuated through electronics (not manually), the system is able to withstand heavy blows, and the system was able to be assembled within one hour by a team of four engineers and disassembled easily to modify components.

Prototype 1



PT1 was an attempt to evaluate one of our early design ideas before we came up with the idea of the three sliders which is now our product design. This prototype was used to evaluate the concept of three separate systems to establish height and angle: a linear actuator to create an angle that would be rotated to hit the two angles associated with a plane and a carjack-like device to reach the necessary heights.

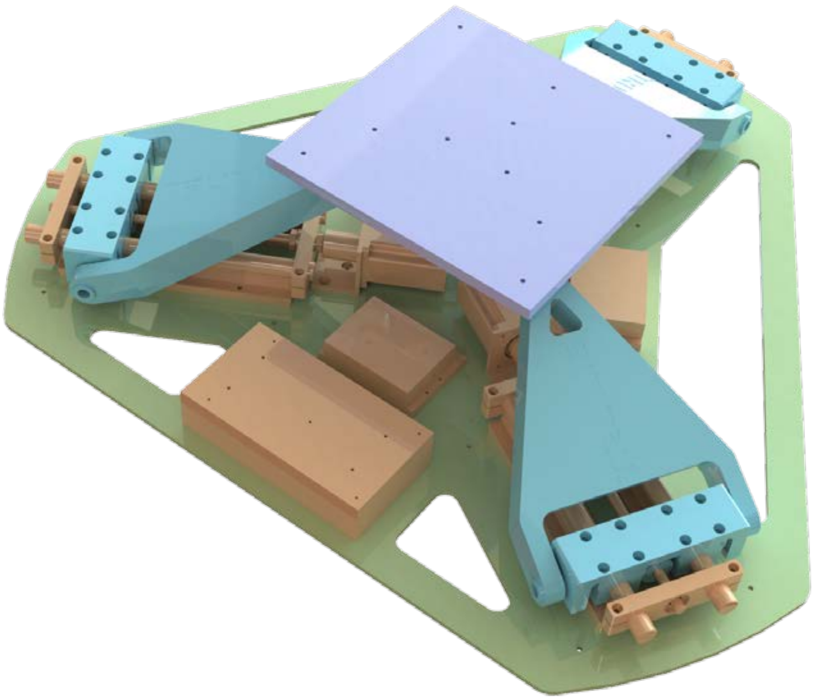
The **manufacturing of the custom parts** of this prototype was done using saws.

The parts used for **standard parts** were purchased from vendors on Amazon.

PT1 was tested for the stability of the golfing surface, the ability to reach angles, and to understand the amount of slop in the system affecting rigidity. We learned that the stacking of systems increased the minimum height of the system (the system would not be close to the ground), there was a lot of slop within the system, and the linear actuator was slow to reach the desired heights.

PT1 showed us that we need to switch our design idea to one that did not contain separate systems and was more stable with less stacking of slop from multiple subsystems.

Prototype 2



The second prototype was treated as both the proof of concept and is mostly the same as the final prototype due to the limited budget associated with the project. The project was able to be assembled successfully and worked.

This prototype achieves all the necessary design requirements such as moving, with accuracy, to all the necessary combinations of heights and angles, and providing a stable surface to hit off of (albeit only in between the clevises, when hit outside that region, the golfing surface is not sturdy).

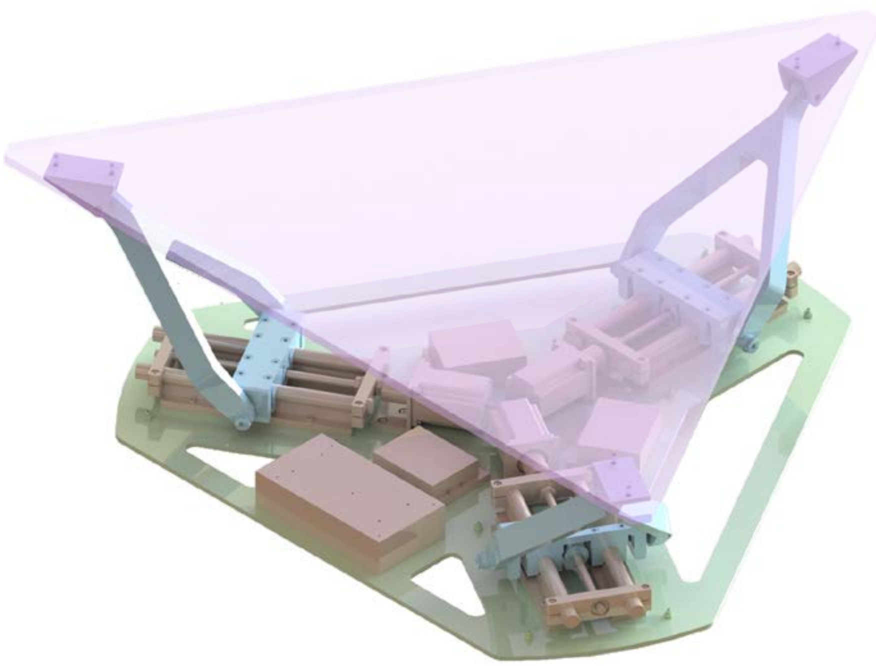
The **manufacturing of the custom parts** of this prototype was done using upright mills (motor mounts), lathes (spacers and bottom of arm tubes), cnc mill (clevises, carriages, clamping lead screw support, top arm tube), and waterjet (bottom plate and spacers), and CFRP (arms).

There were several **vendors** used for **standard parts**. They include McMaster Carr (hardware), Ebay (lead screws, brass nuts), Stepper Online (stepper motors, motor drivers, power supply), and VXB (supported shafts,linear bearings).

PT2 was tested for strength, ability to articulate angles and height, and reusability. We found that although it is able to reach all necessary angles and heights, the system has a tendency to over center at low heights, moves when the golf club does not make contact between the clevises, and the computer code being used is not able to remember zeros when power cycled.

We have decided to include limit switches in our design and change the orientation of the arms so that they point outward instead of inward to increase the area of the golf surface and to remove the system’s ability to overcenter.

Prototype 3



The third, and final prototype is very similar to the second prototype except the arms have been inverted, and limit switched have been added to the product to cut power when the arm carriages get too close to the supported rail clamps.

This prototype achieves all the necessary design requirements such as moving, with accuracy, to all the necessary combinations of heights and angles, and providing a stable hitting surface. The inverted arms create a larger stable hitting surface than their placement in PT2.

The **manufacturing of additional custom parts** of this prototype, those not manufactured during the making of prototype 2, was done using circular saws and drills, this is because the main component made was the hitting surface, which is now much larger.

The only new standard part for this prototype was the kill switches, which were purchased from Amazon.

Like PT2, PT3 was tested for strength, ability to articulate angles and height, and reusability. We found that with the inverted arms, the system is still able to reach all necessary angles and heights, and no longer over centers. The limit switches now eliminate the problem of the computer code not remembering zeros after power cycling; i.e. it will not destroy itself.

Proof of Concept: Functionality Demonstration

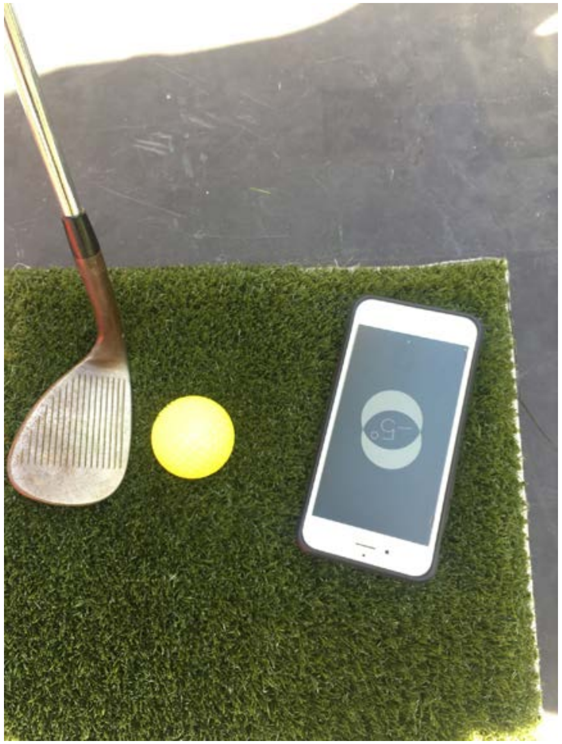
Proof of Concept: PT Tests

Kinematics: Carriage Motion

Set up: Everything below the arms was assembled (motor and rails mounted to bottom plate, lead screw connected and properly housed, and electronics wired). Using our system's UI, the carriages were assigned to move an inch in either direction.
Results: Carriages responded and moved as desired, with all perceived accuracy. However, after a power cycle the system loses track of the carriage positions, potentially leading to running off the rails and damaging parts.
Design Decisions: Final product must incorporate limit switches or use a different computer software to prevent damage to parts and allow system to calibrate upon restarting. A kill switch was also added to shut the system down immediately if necessary.

Kinematics: Range of Motion

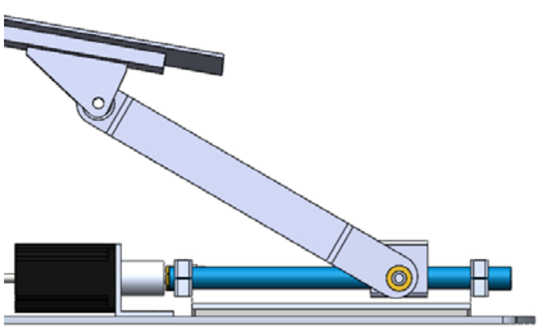
Set up: The system was completely assembled, and coded to reach the maximum and minimum heights (+/- 4 in) as well as steepest angles (+/- 7 deg), and measured to verify.
Results: It was possible for the heights and angles to be achieved. However, upon cycling through various orientations several times, the shoulder bolts began to tighten on the arms, preventing movement.
Design Decisions: Loosen shoulder bolts and use Loctite for the final demo. The connecting joints will be changed for the final product design.

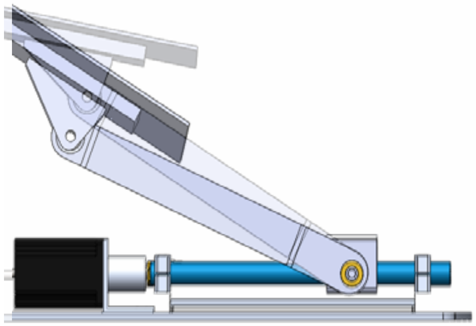


Proof of Concept: PT Tests

Stiffness

Set up: System completely assembled, in its lowest height orientation. Low loads were applied at various points on the top plate.
Results: Upon assembly it was already clear that the corners of the plate deflected up to 0.25 inches. However, there was no perceivable deflection when loaded in the middle of the plate, or in any range between the clevises. Also, at low heights and steep angles, the arm would sometimes over-center.
Design Decisions: To prevent over-centering and improve plate stability, the arms were inverted and a larger plate was used. This also prevents the golfer from accidentally clipping the edge of the small plate and imposing unexpected loading conditions.





Proof of Concept: PT Tests

Strength: Part 1

Set up: System completely assembled. A static load of 100lbs was applied on the top plate.
Results: No perceivable deflection or strength issues.
Design Decisions: None necessary.

Strength: Part 2

Set up: System completely assembled outside. Golf balls were lightly hit off the top plate, initially at max height no angle, then gradually decreasing height and increasing angle, and increasing force of swing.

Results: No perceivable deflection or strength issues. The grass mat sometimes moved as it was hit.

Design Decisions: Better mat fixation technique - switched to a yoga mat shock absorber and turf wrapped around the entire top plate like a canvas.

Note: no failure strength tests were conducted due to limited budget and resulting inability to replace broken components.

Proof of Concept: User Tests

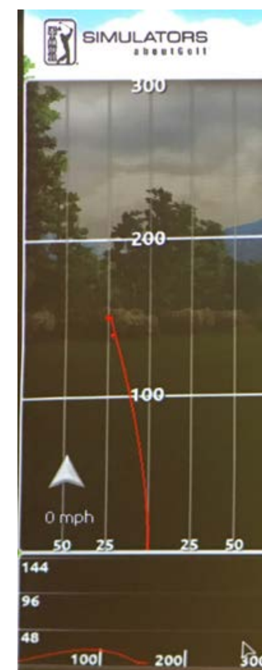
Set up: TruLie completely assembled and moved into the simulator. Three CMU golfers hit off various lies, and provided feedback.

Results:

- No perceptible deflection – felt like hitting off real ground
- Had to adjust to lie to hit straight, ball curved when lie changed – good for practicing
- Would be helpful to also get topography variation under golfer's feet
- *"You can't get this (lie variation), typically, in the simulator, and that's one of the big reasons why people prefer to play outdoors. Once you give them that different lie angle I think more people are definitely willing to substitute this."* – Pat Tan
- *"If you're implementing this in a simulator this is actually better than going to a range outside…this definitely makes practice way more realistic."* – Adrian Del Bosque

Design Decisions: None necessary.

As expected, the ball curves left with an uphill lie.



Engineering Analysis

Applied Forces

Analysis Goals

1. Determine the worst case golf swing the system may experience
2. Analyze the forces this swing implements on the system
3. Determine what variables can be altered to adjust the forces experience

Analysis Methods

To analyze the worst case forces exerted through the system, it was assumed that the golf club head would be swung directly perpendicular to the face of the mat with the same speed as a regular golf swing has upon contact with the ball. The averages of golf head speed and golf head mass for professional golfers were acquired through literature and used to evaluate kinetic energy equations and result in the force distributed to our system. The equations used to evaluate how the energy translates to force are:

$$E = \frac{1}{2}mv^2$$

Where E is kinetic energy, *m* is mass of the golf head, and *v* is the velocity of the golf head upon contact with the surface. The kinetic energy is equivalent to the work experienced in the system so:

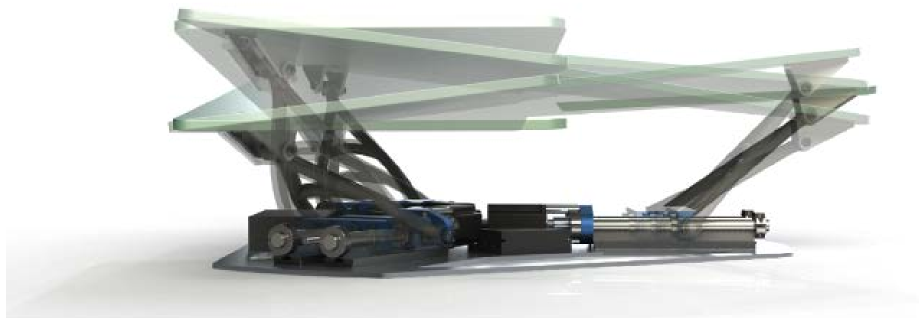
$$W = Fd$$

Where *W* is work, *F* is force and the variable being solved for, and *d* is the distance the club head travels during the impact.

Results

With values plugged in for average club head speed and weight, and assuming a distance of one inch of turf based on what's available for a good price on the market, the system should experience at worst 1,100 lbs of vertical force. The horizontal force is much lower since it relies on friction between the golf head and turf, so it was considerably lower and was ignored**.** This worst case loading result allowed us to move forward in the design process with a much better understanding of the strength required from each component.

Range of Motion



Analysis Goals

1. Determine how different dimensions affect overall performance
2. Determine driving dimensions for design
3. Find a balance between articulation, size, and loading

Analysis Methods

Building on the previous work done to control the system this analysis used MatLab, Excel, and SolidWorks. The matlab script written to determine the carriage positions required to achieve the desired angles and height (previous controls work), was used to explore the relationships between component dimensions and overall range of motion. The results from MatLab were entered into Excel and analyzed to determine the affects individual components had on the assemblies range of motion. After analyzing a FBD of the overall system the forces through the lead screws were also calculated for a worst case vertical loading scenario. SolidWorks was then used to verify that nothing would hit during the system's full range of motion.

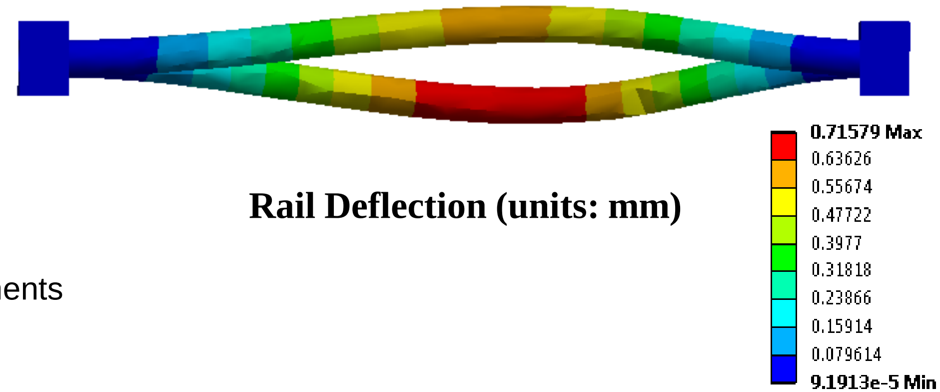
Results

It was found that shorter arms meant steeper angles at their lowest points, more carriage travel would be needed, and at the highest point arms would be closer to the center. (see appendix B) Since there were positives and negatives to long and short arms a variety of arm lengths were tested. It was found that to achieve our range of motion the arms needed to be at least 11” long and with 11” arms we’d need 8.5” of carriage travel. Ultimately 12” arms were used to allow us to go higher if necessary while still keeping loads through the arms reasonable at their lowest point.

Arm length	Min. arm angle (˚)	Required Travel
10.5	8.2	N/A
11	7.8	8.5
12	7.2	6.7

Table 1: Small subset of data obtained during range of motion analysis

FEA



Rail Deflection (units: mm)

Analysis Goals

1. Determine design feasibility and strength requirements
2. Determine areas of concern

Analysis Methods

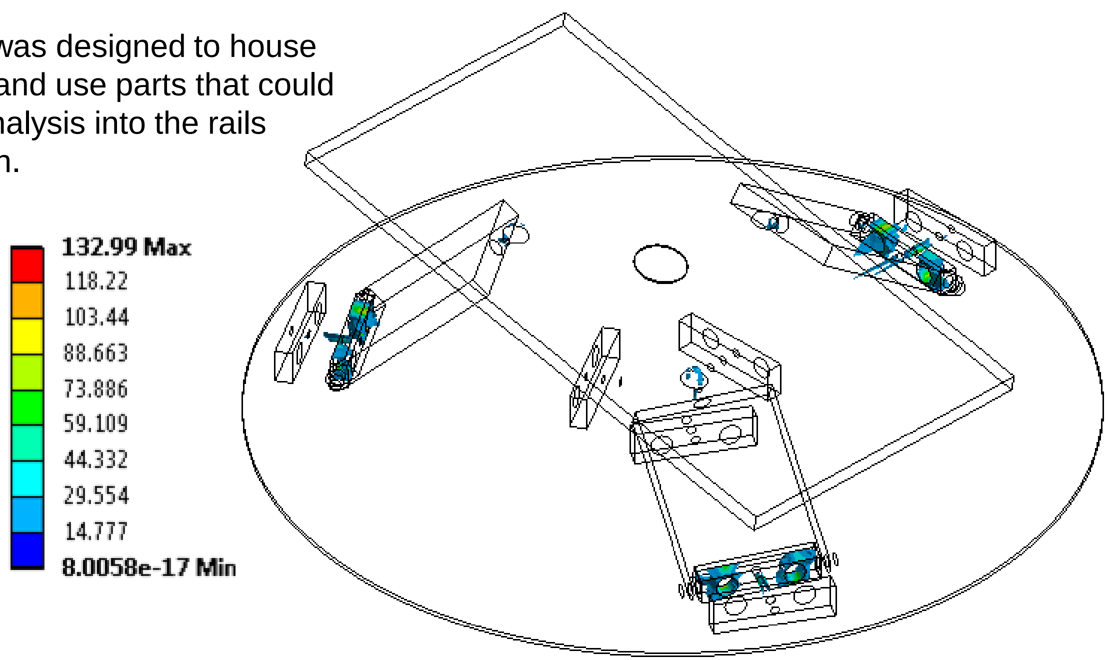
Set up the CAD assembly in ANSYS with the bottom plate fixed and the maximum expected force applied to the top plate. Interfacing parts were under "no separation" to allow movement while maintaining contact for a more accurate simulation.

Results

These tests indicated that the highest stresses were reached at the carriages and rails, while the rest of the assembly experienced relatively low stresses.

After reviewing these results, the carriage was designed to house catalog bearing blocks to minimize friction and use parts that could definitely handle the loads seen. Further analysis into the rails indicated that deflection was also a concern.

While the deflection itself may not seem significant, it will translate into more noticeable deflections at the ends of the plate upon impact. To overcome the deflection and high stress experienced by the rails, the rails were switched out for supported shafts, thus can now support the loads in compression rather than in bending.



Regions of highest stress in the assembly (Units: MPa)

Rails and Carriage

Analysis Goals

1. Determine if unsupported rails are sufficient or if supported rails are necessary
2. Examine the pros and cons of linear bushings vs. linear ball bearings and select an option
3. Choose length and center-to-center spacing of rails

Analysis Methods

FEA data was used to inform the selection of rail type (unsupported or supported). Catalog component characterization and selection was used to tabulate feasible components and weigh the pros and cons of each one. Similarly, tolerance analysis of these components was implemented to characterize the added play in the system due to each component and minimize any slop. Lastly, the calculations relating to range of motion determined rail length and spacing.

Results

Although the deflection from FEA results was less than 1 mm, supported rails were selected to essentially remove all deflection. Because any movement of the rails would be magnified by the geometry of the arms, we elected to use the most rigid option for the rails.

Deciding between bushings and bearings to guide linear motion was mainly driven by compatibility with the supported rails. We found linear ball bearings with slotted undersides to clear the supports, leading us to choose this option. Bearings offer advantages for the final product as well in that they reduce sliding friction, preventing any bogging down of the motors.

The length of the supported rails was determined by range of motion calculations. Center-to-center spacing was a trade off between rigidity and packaging. More distance between rails would help resolve any bending moment in the arms which results from non-vertical loading. However, larger spacing forces the carriages and arms to be very wide, leading to difficult manufacturing and more expensive components. After balancing these concerns, the linear travel was set to be 9.15” and rail spacing to 3.25”.

Lead Screw

Analysis Goals

1. Decide if brakes are necessary to prevent backdriving
2. Analyze the required motor torque to lift a person on the platform

Analysis Methods

For this analysis it was assumed that the lead screw would be supported rigidly from both ends and that the max load through the system would be distributed evenly through each shaft (F_{shaft} ~ 400 lbs). To determine if brakes are necessary the friction between the lead screw and nut was calculated. The equation for this is:

$$f > \frac{L}{\pi D}$$

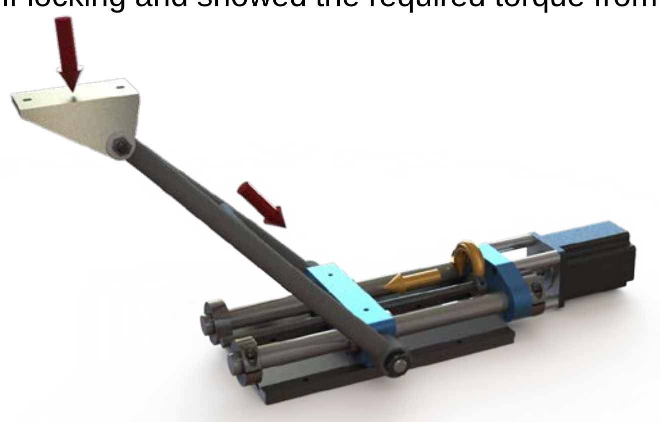
Where *f* is the friction between the nut and the lead screw (.15 for brass nut and steel screw), L is the lead which is the axial distance per one revolution, and D is the diameter of the lead screw. Next the required torque the motors need to raise a person standing on the platform was calculated using the equation below:

$$T_{raise} = \frac{F d_m}{2}\left(\frac{\mu \sec\alpha + \tan\lambda}{1 - \mu \sec\alpha \tan\lambda}\right)$$

Where T_{raise} is the torque from the motor required to lift the platform, *F* is the load on the lead screw which is about 60lbs (Average weight of 180lbs divided by three for each lead screw), d_m is the mean diameter of the lead screw, is the coefficient of friction (0.15 between the brass nut and steel lead screw), l is the lead, and is the lead angle.

Results

With low priced lead screws purchased online, the lead was 2 mm and the diameter was 10mm which led to the friction between the brass nut and steel lead screw of .15 being much larger than the value from the equation of 0.064. This analysis proved that the system is self locking and showed the required torque from each motor is 1.5 Nm.



Motor Selection

Analysis Goals

1. Select the motors.
2. Select the motor drivers and power supply.

Analysis Methods

A static hand-analysis of the system was performed to determine the minimum motor torque required to articulate the top plate in the worst-case orientation (as in section 4.6, above). Next, a CAD interference analysis was used to determine the maximum motor dimensions, based on approximated locations and motor housing dimensions. Cost estimations and analyses were performed to determine the maximum allowable cost of the motors, drivers and power supply. Prospective motors, drivers and power supply combinations were then ranked, based on criteria established through the previous three analyses, to determine the best choice.

Results

Criteria	Requirement	Selected
Driving Torque	> 1.5 Nm	3.1 Nm
Length	< 150 mm	127 mm
Height	< 76.2 mm	60 mm
Total Cost (including drivers and power supply)	< $300	$260

Motor Selected: *OMC-Stepper Nema 24 Dual Shaft - 3.5A - 3.1Nm - 24HS34-3504D*
Driver Selected: *2/4 phase Nema 23 Stepper Motor Driver - 24-50VDC - 1.5A-4.5A - 256 Microstep*
Power Supply Selected: *Switching Power Supply - 350W - 36V - 9.7A - 115V/230V S-350-36*

Arms

Analysis Goals

1. Prevent interference between arms and other components
2. Verify that the arms will not yield to worst-case scenario forces
3. Determine components that interface with the arms and ensure they will not yield
4. Choose a material, design, and manufacturing process that minimize cost

Analysis Methods

To determine whether our goals are achieved by our design, we use the following analysis methods: interference detection, finite element analysis, hand calculations, and material selection.

Results

The interference detection yielded some interferences initially, but in the final model, the arms have cutouts and specific thicknesses in places to ensure that the arm had full range of motion.

Finite element analysis on the entire assembly showed that one of the system's weak locations was at the connection between the arm and the carriage. To verify that the connection point, a shoulder screw, was strong enough some hand calculations were done with the shoulder screw in cantilevered bending.

$$D_{shoulder} = \left(\frac{32 \times F \times l \times FOS}{\pi \sigma_y}\right)^{\frac{1}{3}}$$

$$F = force$$
$$l = \frac{1}{2} length\ of\ shoulder$$
$$\sigma_y = yield\ stress$$
$$FOS = factor\ of\ safety$$

For selecting the arm material there were several materials that had a high Young's Modulus and a low product of price and density. The material selection chart for this can be seen in Appendix B. But many were not ideal in both bending and tension. For this reason the final product would focus more on cost and manufacturability. So the material for the final product would be either medium carbon steel or low alloy steel.

FMEA

Item	Failure Mode	Effects of Failure	S	Cause of Failure	O	Design Control	D	RPN	Recommended Actions
Clevis Assembly	Shearing of bolts	Bolts attaching clevis may shear, top plate becomes unstable or disattached	7	Side of top plate being kicked	4	None	10	6.4	Consider hindged edges with torsional springs
	Shearing of bolts	Shoulder bolt connecting clevis to arm may shear, top plate becomes unstable or disattached	7	Errant swing directly perpendicular to plate	2	None	10	5.6	Look at ball joints driectly attached to top plate instead of machining a custom clevis
	Vibrations	Unrealistic golfing experience	2	Tolerance stack up of machined parts	8	User experience testing	3	4.6	Again choosing correct ball joints to minimize tolarnce stack up from machined clevis and spacers
Arms	Buckling	Arms collapse and system falls	9	Errant swing directly perpendicular to plate	1	Loading tests on arms to see how much force they can handle	1	4.2	Adding extra layers of carbon fiber
Cariage Assembly	Shearing of bolts	Shoulder bolt between carriage and arm may shear, causing arm to slip and top plate to fall	9	Errant swing directly perpendicular to plate	1	None	10	6	Adjusting design so load in bolt connection between the arms and the carriage are axial as oppose to shear
	Nut Failure	System no longer moves with motor rotation, carriage slides to stop and top plate falls	6	Errant swing directly perpendicular to plate	5	None	10	6.4	Consider purchasing a nut of stronger material
	Slidding	System can't support person standing on it	9	Person standing on platform	1	Load top plate to see if a realistic weight will cause backdriving of nut	1	4.2	Purchase lead screw with a lower lead to diameter ratio
	Vibrations	Unrealistic golfing experience	2	Backlash in nut after force applied to system	7	User experience testing	3	4.2	Purchase anti-backlash nuts
Supported Shaft Assembly	Buckling	Carriage no longer can slide across rails and system gets stuck	4	Swings hitting system and causing forces through system	4	Attach weight to center of shaft until noticible deflection occurs	10	5.2	Shift to using shafts with supporting rails
Motor, driver, and power supply	Deformation	Motors are crushed and need to be replaced	2	Motor position that causes extremly shallow arm angles	5	None	10	4.8	Add limit switches to carriage motion to assure arms don't crush the motors
	Over Heating	Electronics damaged and need replacing	3	Rapid use of the system	4	Place thermocouple near high heat areas and power off supply when too hot	3	3.4	Place additional fans on components to mitigate the risk of over heating
	Vibrations	Electronics damaged and need replacing	3	Repetion of swings hitting system	7	None	10	6	Use shock mounts to protect from motor vibration
Entire Assembly	Deformation	Saftey hazard for user and potential breaking of motor and and other moving components	10	Placing of object or human part in interior of system	3	Limit switches below the top plate to assure if person reaches in the system shuts down	7	6.6	Adding accordian type cover on extreior of top plate to assure moving components of the system are covered

Solved Failure Modes

From the FMEA table on the previous slide, there were certain failure modes with enough risk and potential damage to the system that creating a solution for them was pivotal to a successful system. The following list is a summary of the failure modes and the way in which they're risk is alleviated:

- The risk of the arms crushing the motor's at certain angles was mitigated through applying limit switches on the carriage so that if the motor behaves in an unexpected manner the limit switches will trigger as they near the end of their safe position and shut the motor actuation down.
- The risk of excessive deflection within the shaft assembly was mitigated through using shafts with supporting rails.
- The risk of major vibrations of the motors was mitigated by changing their mounting method to ensure proper shaft to lead screw alignment.
- The risk of shoulder bolt shear in the carriage assembly was mitigated by replacing the shoulder bolts with threaded studs to increase strength.
- The risk of arm buckling was mitigated by replacing the carbon fiber arms with welded steel arms to increase strength and provide a much larger factor of safety under the expected loads of the system.
- The risk of user interference or danger occurring from operation of the lie board was mitigated by placing an accordion type connecting surface between the platform of the user and the lie board. This assures that none of the system interior is exposed while user experience is maintained.

Component and Material Selection

Material Selection

The majority of all custom components are 6061 aluminum because this material is very easy to machine and is light while still being stiff and cheap. Magnesium alloys such as AZ31B were considered but ultimately their increased cost outweighed their potential for weight savings. Machinability is a major concern since the carriage, rail and clamps all require pretty extensive CNC milling operations. This eliminates most steel alloys as potential options. All components will ultimately be T6 tempered but the clevis stock will be purchased at a T4 temper so it can be bent without cracking then brought up to a T6 temper.

The arms will be made of 4130 steel because of the ease with which it can be bent and welded. This method of bending then welding is how a tube frame chassis is made. So we can outsource this part of production. Due to our relatively low quantity this will reduce the price of the product since specialty machines won't need to be purchased.

The grass turf on top of TruLie was selected after testing out multiple samples. The selected turf doesn't lose its fluff or spray debris everywhere after a swing and also includes a rubber bottom that significantly reduces the force through TruLie.

Purchased Part Selection

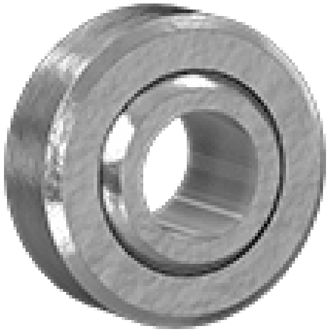
Open Bearings

- Fits selected 20mm supported shafts
- Each bearing supports 305 lbs giving the carriage a FOS of ~2
- Retaining rings allow for easy assembly and disassembly

Vibration Dampening Bushings

- Can better withstand the shock loading from a tomahawk type swing
- Reduce shock loads through system due to their compliance
- Prevent audible noise from “fat” swing
- Each bushing supports 800 lbs giving them a FOS of ~1.6

Purchased Part Selection



Ball Joint

- PTFE linear means lubrication isn't required
- Each joint can withstand 10,500 lbs giving them a FOS > 10
- Precision manufacturing of the joint allows them to be press fit into arms

Leadscrew bearing

- Double row construction means only one is needed
- Using an angular contact bearing eliminates the need for thrust and ball bearings
- Necessity to preload bearing is already accomplished by lead screw retaining nut

Bill of Materials - Complete

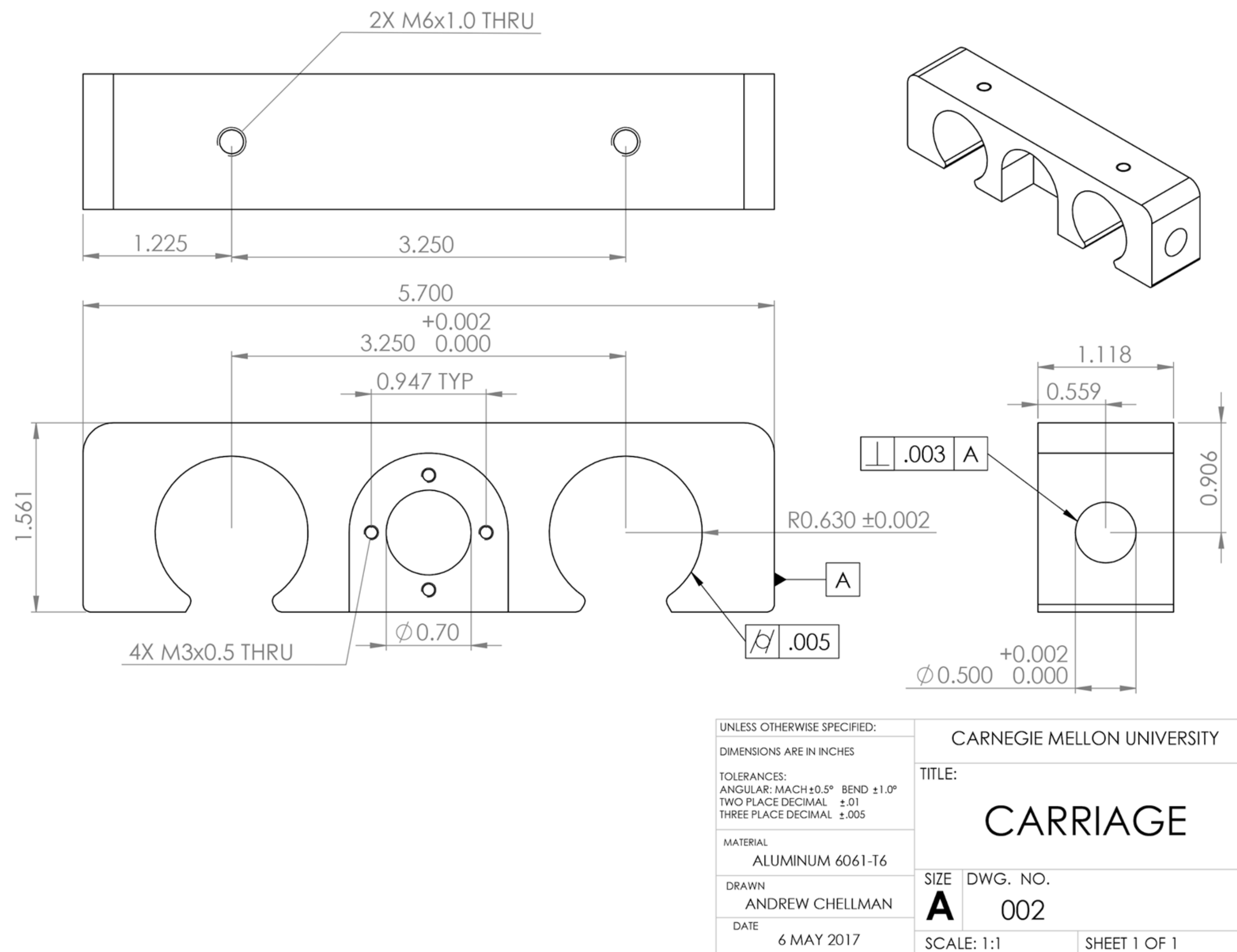
Custom Component	Description	Quantity
Bottom plate	Integrates all components	1
Rail support	Attaches rail to bottom plate	6
Rail support spacer	Placed between bottom plate and rail support	6
Motor mount	Attaches motors to bottom plate	3
Carriage	Slides along rails	3
Arm	Connects carriages to clevises	3
Clevis	Mounts to top plate	3
Top plate	Serves as ball platform and integrates clevises	1
Electronics enclosure	Protects control board	1
Catalogue Component		
Rail	Allows carriages to slide	6
Leadscrew	Controls linear position of carriage	3
Flange nut	Interface between carriages and leadscrews	3
Trapezoidal thread nut	Holds leadscrew captive relative to motor mount	3
Shaft collar	Keep motor mount attached; prevent carriage over travel	12
Linear ball bearing	Interface between carriages and rails	6
Damping bushing	Interface between arms and carriages	6
Motor	Drives leadscrew to actuate motion	3
Resilient coupling	Interface between motors and leadscrews	3
Stepper driver	Controls motors	3
Power supply	Supplies power	1
Controller (PCB)	Takes input and signals the drivers to actuate motion	1
Spherical Bearing	Interface between arms and clevises	3
Turf	Provides accurate surface for use	1
Misc. hardware	Screws, nuts, washers	NA

Bill of Materials - Custom Components

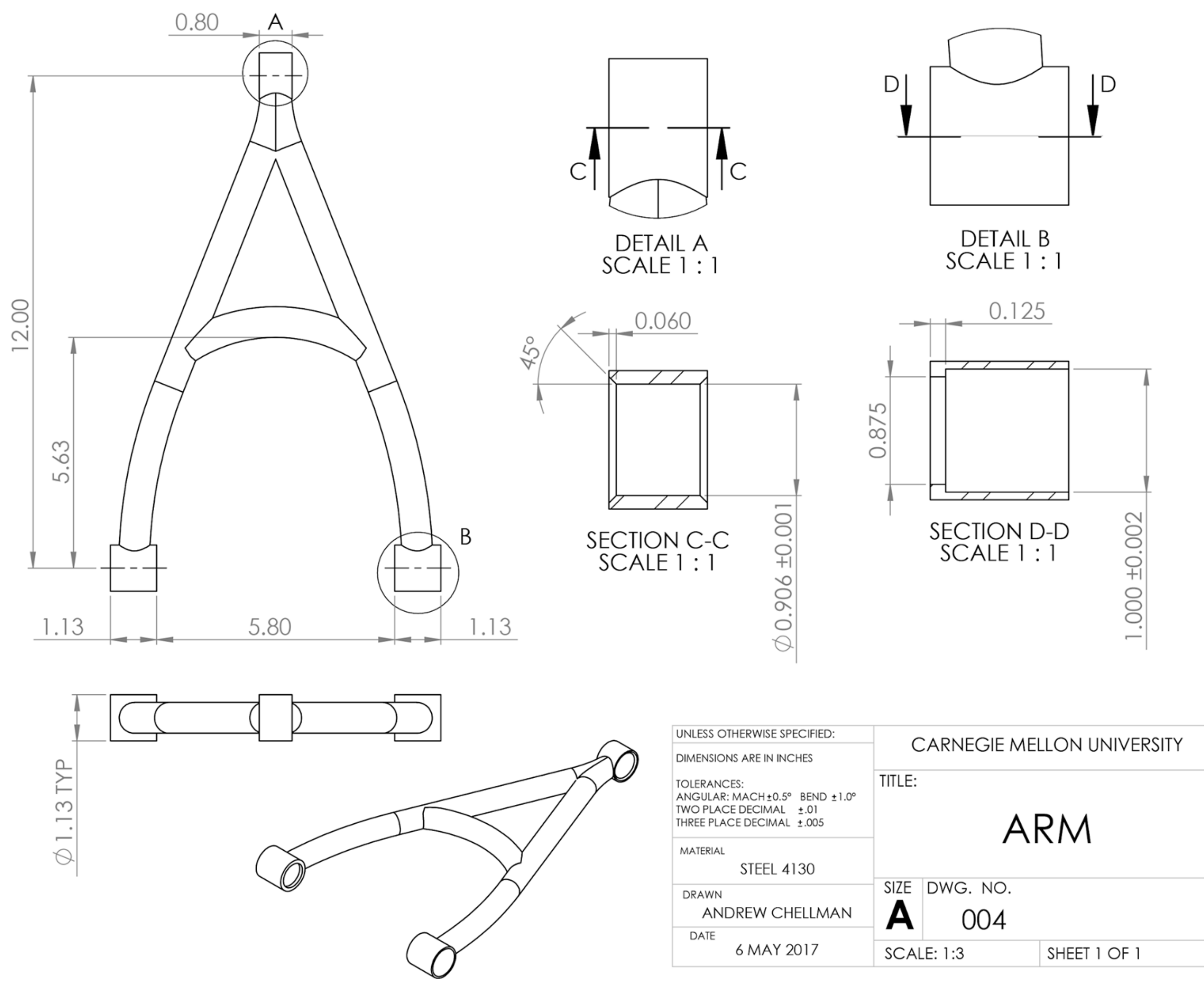
- Bottom plate (QTY 1)
  - Aluminum sheet
- Rail support (QTY 6)
  - Aluminum extrusion
- Rail support spacer (QTY 6)
  - Aluminum sheet
- Motor mount (QTY 3)
  - Aluminum bar
- Carriage (QTY 3)
  - Aluminum bar
- Arm (QTY 3)
  - Steel tube
- Clevis (QTY 3)
  - Aluminum sheet
- Top plate (QTY 1)
  - Aluminum sheet

Additional material and manufacturing data are including in the following slides.

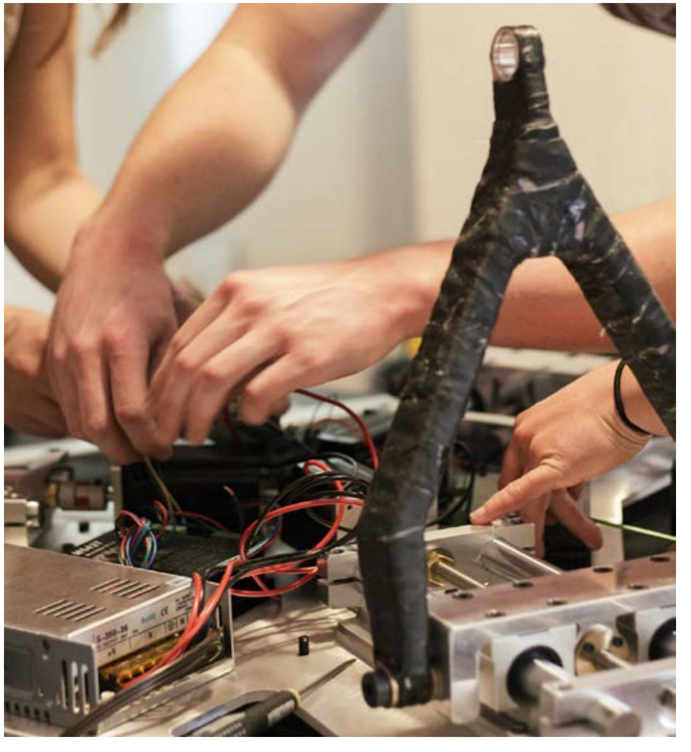
Bill of Materials - Carriage Drawing



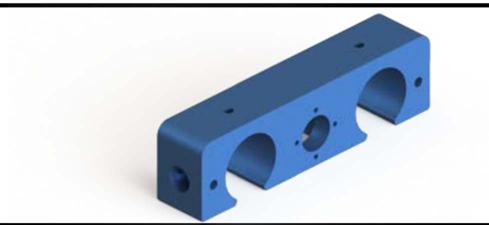
Bill of Materials - Arm Drawing



Manufacturing and Assembly Techniques

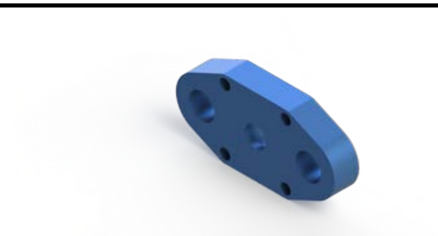


Manufacturing Methods



Carriage

- CNC Machined from solid block
- Done in 4 setups with 2 tapped holes



Rail Clamp

- Waterjet oversized for CNC post machining
- Done in 1 setup and requires no hole tapping

Clevises

- Waterjet from top and bottom plate excess
- Bent into shape

See appendix

Bottom and Top Plate

- Waterjet and tapped

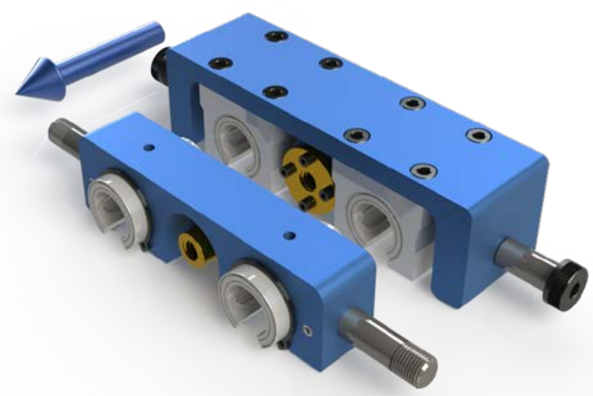
Supported Rails

- Purchased then support is cut to length

**arms will be outsourced to a Protolabs for manufacturing*

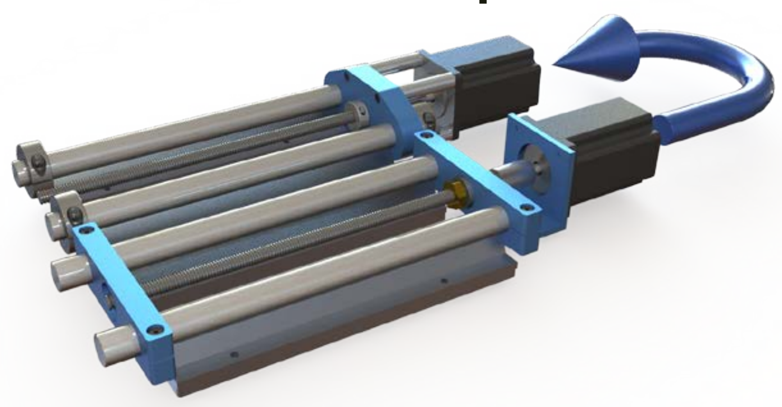
DFMA Redesign

Carriage



- Integrated bearing mount
  - Eliminates slop from cheap bearing block
  - Allows for a thinner part design which reduces cost
- Shoulder screws replaced with studs
  - Increase strength where arm connects to carriage
  - Eliminates the need to tap for shoulder bolts

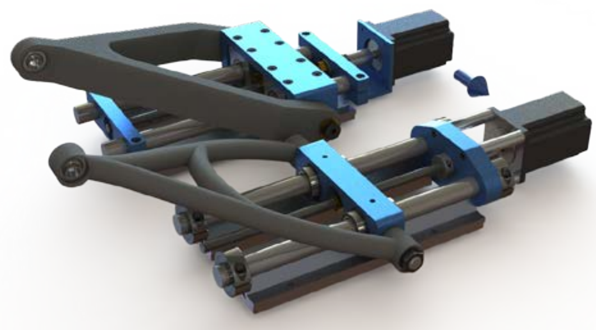
Rail Clamps



- Single rail clamp design
  - Improves assembly process
  - Eliminates a custom component
  - Can be machined in 1 setup
  - Has no tapped holes
- Motor mounts integrated into rail clamp
  - Eliminate a custom component
  - Ensure proper alignment between motor and lead screw
- Use of clamping shaft collars
  - Simplifies design of rail clamp
  - Eliminates the need to loctite lead screw retaining nut

DFMA Redesign

Arm



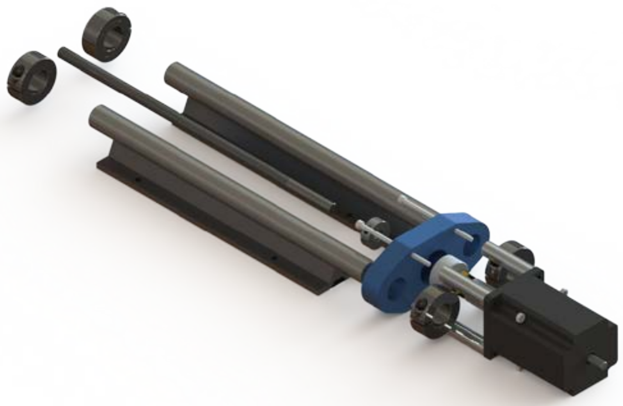
- Tube structure
  - CNC bent
  - Welded
- Significantly cheaper than CNC machining
- Due to quantity (~10,000) stamped sheet metal isn't cheaper because of die costs

Clevis

- Waterjet then bent into shape
- Cheaper than machining
- Can be waterjet out of bottom plate excess

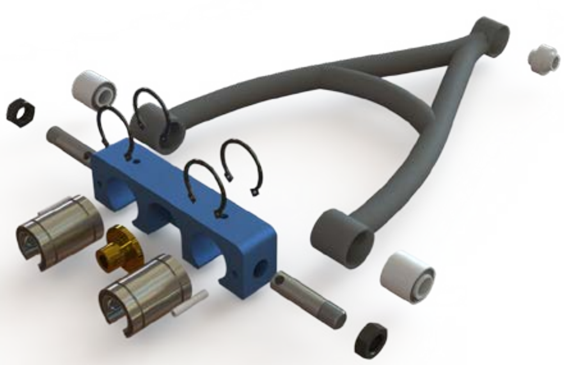
Assembly Process for Subsystems

Rails and Motors



1. Double row angular contact bearing is press fit into rail clamp
2. Motor mounting screws and spacers are put on rail clamp
3. Rail clamp is slid onto the two rails and clamped in place by the two shaft collars
4. Lead screw is inserted and shaft collar is attached
5. Lead screw nut is attached and tightened
6. Motor coupling is attached and butted against leadscrew nut
7. Motor is attached with coupling
8. Rails are attached to bottom plate

Carriages and Arms



1. Spherical bearing and vibration dampening bushings pressed into arm
2. Open bearings pressed into carriage
3. C-clips attached to open bearings
4. Leadscrew nut attached to carriage
5. Arm brought into position
6. Studs inserted
7. Spring pins inserted into studs
8. Nuts attached to retain arms

Assembly Process

1. Attach all three rail and motor subassemblies
2. Attach all electronics (controller, PSU, motor driver…)
3. Test electronic system
4. Attach carriage and arm subassemblies
5. While top plate is held over bottom plate attach arms to clevises on top plate
6. Perform range of motion check
7. Check all fasteners
8. Attach accordion cover

Cost Charts

Custom Parts

Water Jetting		Per System	Total
Part: Top Plate	Quantity	1	10000
	Material Cost	$82.72	$827,200.00
	Production	$15.24	$152,400.00
	Total	$97.96	$979,600.00

CNC		Per System	Total
Part: Rail Support Block	Quantity	6	60000
	Material Cost	$16.04	$160,400.00
	Production	$16.97	$169,700.00
	Total	$33.01	$330,100.00

Water Jetting		Per System	Total
Part: Bottom Plate	Quantity	1	10000
	Material Cost	$41.03	$410,300.00
	Production	$2.61	$26,100.00
	Total	$43.64	$436,400.00

CNC Bending then Welded		Per System	Total
Part: Arms*	Quantity	3	30000
	Material Cost	$30.21	$302,100.00
	Production	$51.26	$512,600.00
	Total	$81.47	$814,700.00

* Arms will be produced externally by Protolabs

Water Jetting then Bending		Per System	Total
Part: Clevis	Quantity	3	30000
	Material Cost	$9.03	$90,300.00
	Production	$0.27	$2,700.00
	Total	$9.30	$93,000.00

CNC		Per System	Total
Part: Rail Support Block	Quantity	3	30000
	Material Cost	$20.44	$204,400.00
	Production	$19.97	$199,700.00
	Total	$40.41	$404,100.00

Labor	Hours (Per System)	Hourly Rate	Total Price
CNC Set Up and Postprocessing	2	$12.50	$250,000.00
Waterjetting Set Up and Postprocessing	1	$12.50	$125,000.00
Assembly	1	$12.50	$125,000.00
		Total =	**$500,000.00**

Catalog Parts

Catalog Component	Supplier	Unit Price	Quantity	Total Price
Supported Rails	VXB	$7.99	6	$47.94
Steel Leadscrew	Mcmaster Carr	$31.54	3	$94.62
Flange nut	MTD	$4.56	3	$13.68
Trapezoidal thread nut	RCmall	$3.75	3	$11.25
Shaft collar	Grainger	$6.16	12	$73.92
Linear ball bearing	VXB	$30.00	6	$180.00
Damping bushing	Mcmaster Carr	$8.93	6	$53.58
Motor	NEMA	$36.00	3	$108.00
Resilient coupling	VXB	$7.77	3	$23.31
Stepper driver	Leadshine	$37.32	3	$111.96
Power supply	Mouser Electronics	$44.80	1	$44.80
Controller (PCB)	Jameco Electronics	$21.49	1	$21.49
Steel Spherical Bearing	Pegasus Auto Racing Supply	$27.99	3	$83.97
Turf	Rukket Sports	$63.99	1	$63.99
Misc. hardware	Mcmaster Carr	$25.00	1	$25.00
			Total =	**$957.51**

Cost Justifications

Total Units to be Produced will be 10,000. The justification for this quantity is that there are currently 28,000 listed PGA professional golfers in the US, and of those professional golfers we assume the top 10% to compete enough year around to want or already have at home golf simulators. We then assume that with the 1,281 NCAA certified colleges in the country, around 1,000 will have a golf program and therefore a golf simulator. We then assume that with the 4,400 private and 15,000 public golf clubs in the US, that at least a quarter would be interested in placing TruLie within their golf simulators.

Total fixed Cost for Production is roughly $3,500,000. This value was derived from the cost of purchasing a waterjet system at roughly $100,000 (the variable cost to do all waterjetting externally for 10,000 units exceeds this cost significantly) and three CNC Machines at roughly $30,000 each. The cost of overhead, land, labor, and utilities for the total operation were then estimated at $3,300,000 for the year needed for production.

Variable Cost Example Calculation:

Item: Bottom Plate

Dimensions: 37” x 33” x .25” Cost of Material: $0.87 / lb Cost = Volume * Density * Cost of Material

Cost of Material total = $26.03 Delivery and Production Cost = $15.00 Total Cost For Material = $41.03

Cost of Process:

Outer Length of Plate = 103” = 261.62 cm Cost per cm cut[1] = $0.01 Machining Cost Total = $2.61

Total Variable Cost for one Bottom Plate = $43.64

[1] Process cost estimates gathered from FSAE cost report tables

Total Cost Per System:

Fixed Costs	$3,500,000
Variable Costs	$12,633,000.00
Total Cost	$16,133,000
Cost Per System	**$1,613**

Life Cycle Analysis

	Production Items that compose your product			Use Items consumed during the use phase (e.g.: electricity)
	Item 1	*Item 2*	*Item 3*	*Item 1*
Item Purchased	Aluminum	Turf for mat	Steel	Electricity
(a) Best match economic sector # and name Confidence that sector represents item (low/high)†	Ferrous and nonferrous metal production. High Confidence	Plastic, Rubber, and Nonmetallic mineral products. Low Confidence	Ferrous and nonferrous metal production. High Confidence	Lighting, Electrical Components, Batteries. Low Confidence
(b) Reference unit (e.g.: 1 kg or 1 kWh)	4.5 kg	4.6 kg	2.3 kg	3.2 kWh
(c) Units consumed per product life	1	1	1	1
(d) Cost per unit ($2002)	2.51	0.62	2.33	0.989
(e) Lifetime cost =(d)×(e) ($2002)	2.51	0.62	2.33	0.989
(f) Economy-wide mtCO2e released per $1M of output for sector (b)	1,360	191	2,030	8,820
(g) Implied mtCO2e per product life =(g) ×(f)/$1M	0.0034	0.0001	0.0047	0.0087

Product Life Cycle

The major inputs to our products life cycle are aluminum, steel, artificial turf, and electricity.

The major output to our product life cycle is greenhouse gas emissions. To properly evaluate our system's outputs, it is important to consider the role Distribution plays in the $mtCO_2e$ calculation. As precise understanding of location and distribution means for acquiring our materials and delivering our systems is not yet understood, we made a liberal assumption that the distribution emissions cost will be about a quarter of the emissions cost for each of our major inputs. Based off of the calculations from our LCA, and the fact that we will be producing roughly 10,000 systems, the total amount of metric tons of carbon dioxide equivalent we will produce is:

Item Purchased	Aluminum	Artificial Turf	Steel	Electricity
Implied mtCO2e per product life	0.0034	0.0001	0.0047	0.0087
mtCO2e from Distribution	0.00085	0.00003	0.00118	0.00218
Total mtCO2e	42.67	1.48	59.12	109.04
			Final mtCO2e =	**212.31**

The lessons learnec ;e can have a significant effect on the environment and choosing materials with their entire life cycle in mind as oppose to just their use is a major factor in producing sustainable designs. We realized that although initially the variation between steel and aluminum was very small in terms of their environmental impact, when scaled up to the 10,000 systems we will produce this variation grows significantly. Having that in mind we elected to only use steel for our arms, which is the component in the system that requires the most strength.

Conclusion

Design Specifications To accurately simulate the majority of lies that a golfer experiences on the course, the product must must be able to travel 8” vertically, and achieve slopes of up to 10 degrees at any height. At any position, the product must be able to withstand up to 1,100 lbf impact. Deflection of the top plate under normal use should be imperceptible to the user. The product lifetime must exceed eight years with very limited maintenance required from the owner. It must also occupy at most a 3’ by 3’ area on the simulator floor.

Competitors TruLie has only one primary competitor: X-Plate. From a user standpoint, X-Plate is a suboptimal product because it fails to capture the most important aspects of uneven lies. Additionally, X-Plate is designed for exclusive use with X-Golf simulators and X-Golf does not have a significant share in the golf simulator market. As a result, TruLie has almost no competition.

Competitive Advantage At the moment, there does not exist a product that inputs simulator data and changes the lie of the hitting surface. We have a very competitive advantage.

Profitability We think that this product has a lot of opportunity to be profitable. With golf simulator prices ranging from $60,000 to $90,0000, and as their use continues to grow, companies will continue to make them as representative of a real golf game as possible. Given the final estimated cost to produce one product as $1,613, we should be able to sell the product at a competitive price while still having a decent profit margin.

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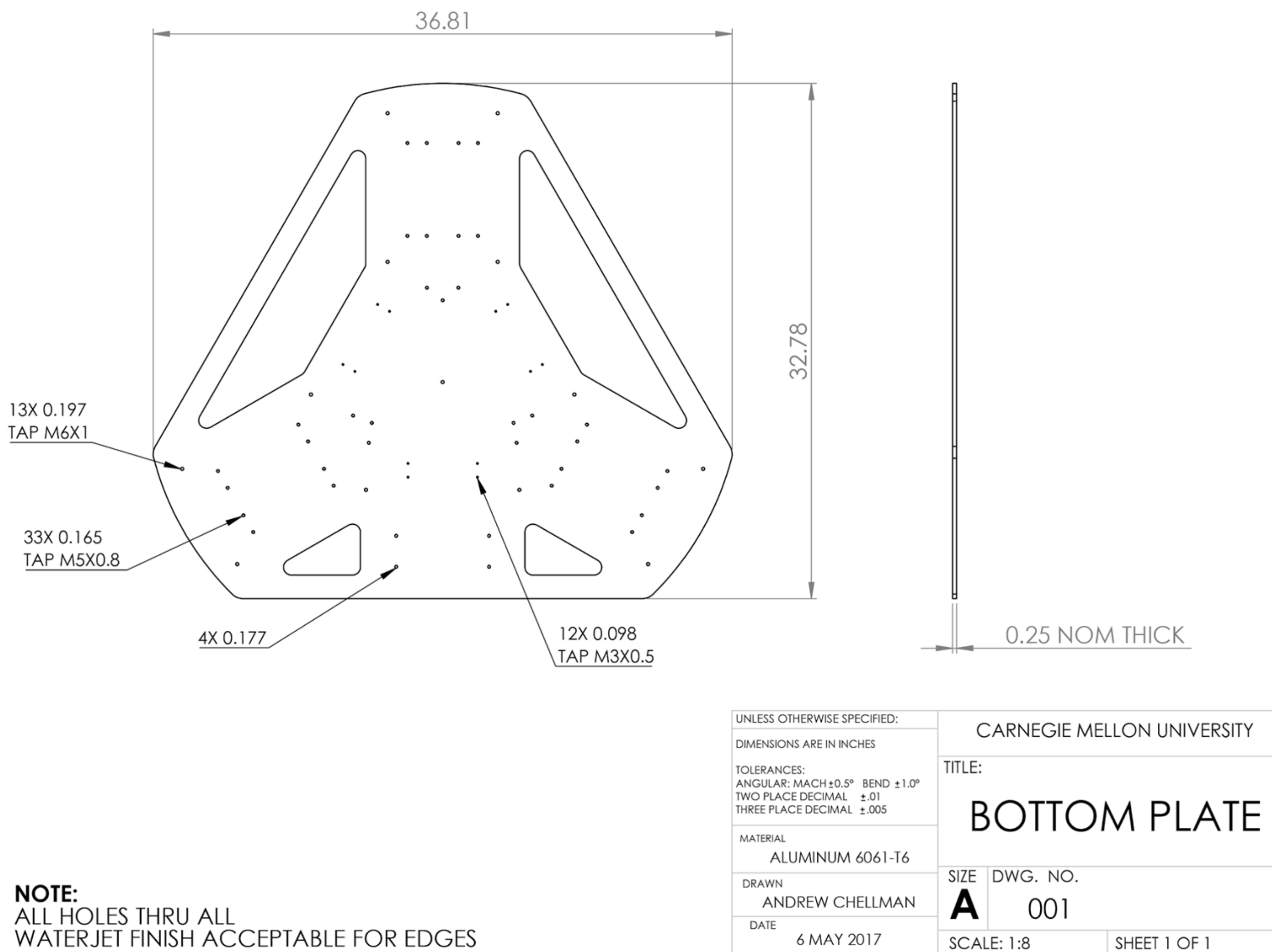
XGolf America Inc. *XPlate Variable Lie Positioning*. 2012. 28 January 2017. <http://www.xgolfsimulator.com/x-plate-variable-lie>.

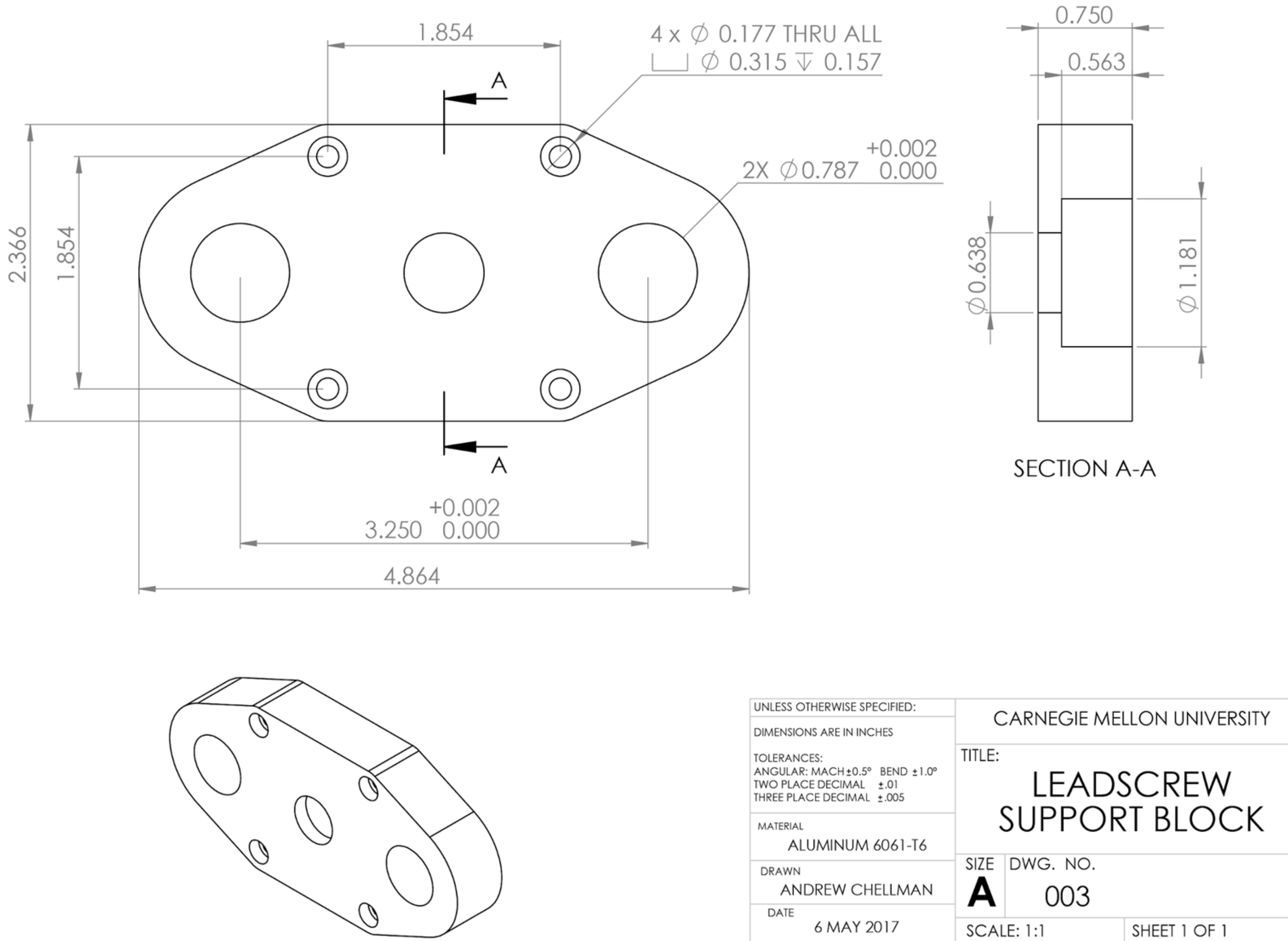
Appendix I: Notes for Future Teams

- Definitely take the time to choose a good project suitable for this class, and make sure everybody is on board. Having something we all believed in for the duration of the project helped with motivation.
- Set aside meeting times with your team (a good one is when other groups are meeting with the professor and TA's because everybody has to be free then.) If it turns out you don't need to meet you can always cancel, which is still easier than planning meetings every time.
- Take budget into consideration early on. McMaster is great for finding parts, but sometimes they can be found elsewhere for much cheaper.
- We got some help with manufacturing from outside companies, which was really helpful.
- Keep in mind from the very beginning that your final product is not the same as the prototype you demo.
- Give yourself a LOT of time to troubleshoot and manufacture; don't put things off till the last second because it will almost always take longer than you expect.

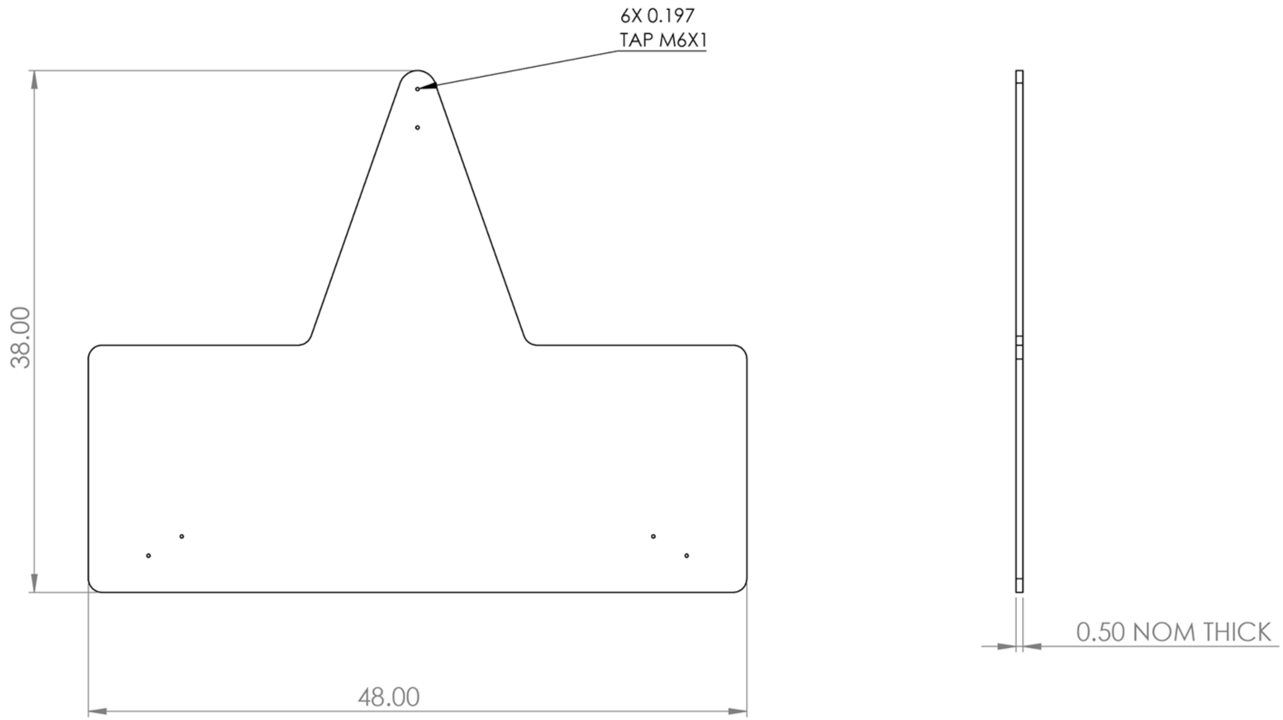
Appendix II: CAD Drawings



Appendix II: CAD Drawings



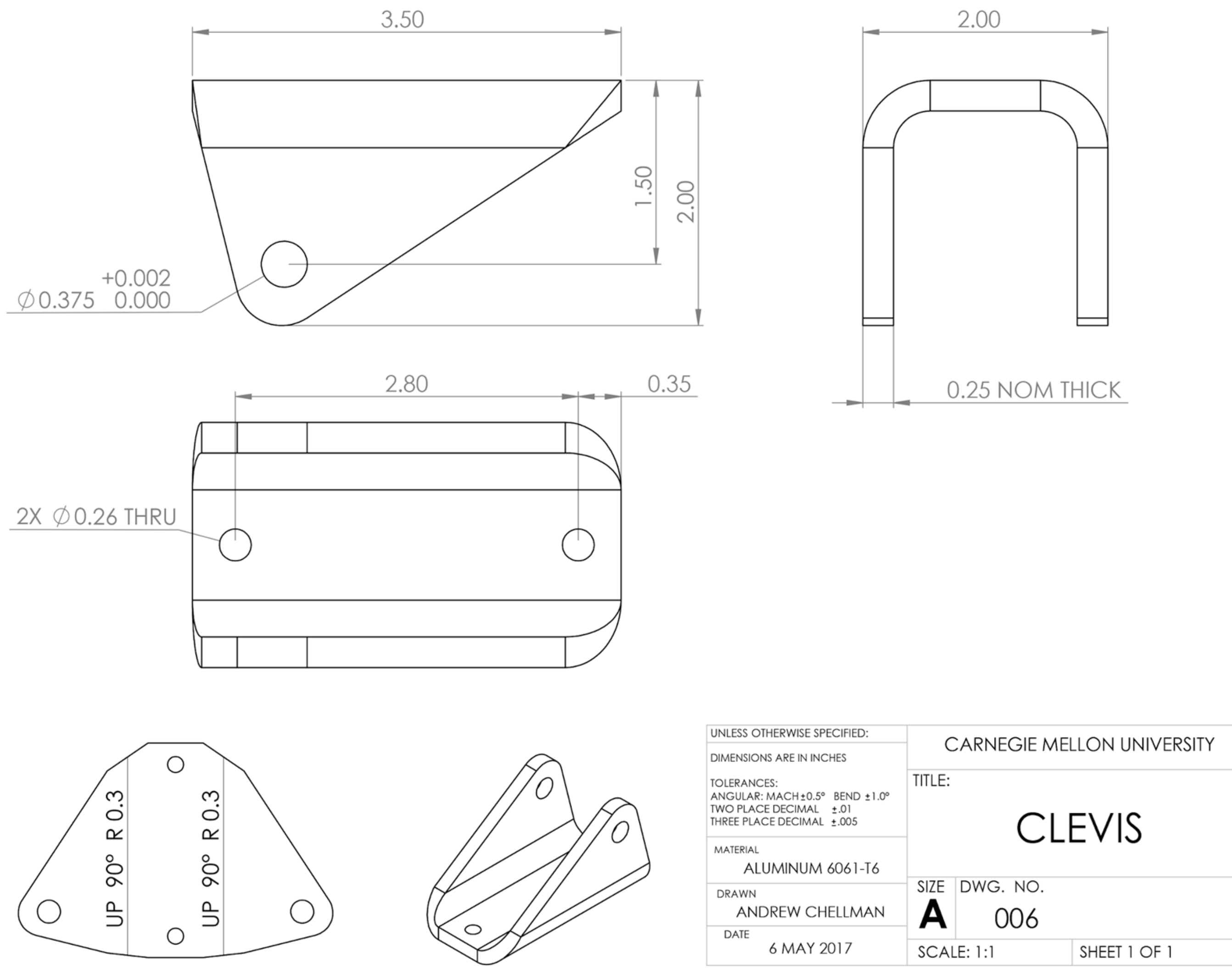
Appendix II: CAD Drawings



NOTE:
ALL HOLES THRU ALL
WATERJET FINISH ACCEPTABLE FOR EDGES

UNLESS OTHERWISE SPECIFIED:	CARNEGIE MELLON UNIVERSITY
DIMENSIONS ARE IN INCHES TOLERANCES: ANGULAR: MACH ±0.5° BEND ±1.0° TWO PLACE DECIMAL ±.01 THREE PLACE DECIMAL ±.005	TITLE: BOTTOM PLATE
MATERIAL ALUMINUM 6061-T6	
DRAWN ANDREW CHELLMAN	SIZE A / DWG. NO. 005
DATE 6 MAY 2017	SCALE: 1:10 / SHEET 1 OF 1

Appendix II: CAD Drawings



Appendix III: Report Distribution

- Alex: Design Specifications and Research, Engineering Analysis (Motor Selection), and Conclusion
- Alyssa: Proof of Concept, Engineering Analysis (FEA), and Appendix I
- Andrew: Engineering Analysis (Rails and Carriage), BOM, and Appendix II
- Nadia: Conceptual Design, Engineering Analysis (Arms), and Conclusion
- Samer: Engineering Analysis (Lead screw selection & Applied Forces), FMEA, Cost Report, and Life Cycle
- Stephen: Component and Material Selection, Manufacturing and Assembly techniques, and Engineering Analysis (Range of Motion)