Final Design Report

KDT Design Group
Robot Crawling Device and Tee Table

Sponsored by: Hot Stix Golf
Academic Advisor: Lee McFarland

Trauman, Colvin, Fantz
12/6/2010

Statement of Disclaimer

Since this project is a result of a class assignment, it has been graded and accepted as fulfillment of the course requirements. Acceptance does not imply technical accuracy or reliability. Any use of information in this report is done at the risk of the user. These risks may include catastrophic failure of the device or infringement of patent or copyright laws. California Polytechnic State University at San Luis Obispo and its staff cannot be held liable for any use or misuse of the project.

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1. Executive Summary

In keeping with the California Polytechnic State University motto of "Learn by Doing", this project was performed by Mechanical Engineering students Todd Trauman, Kyle Colvin, and David Fantz as their senior project. Starting in Winter 2010 quarter and reaching completion with the end of Fall 2010 quarter, this project provided these students with experience in application of a formal engineering design process including solving open-ended problems, developing project schedules, and working with an engineering team.

As golf becomes a more frequently enjoyed activity, equipment manufacturers such as Hot Stix Golf require updated testing mechanisms to actively compete in their respective markets. One such testing device is a golfing robot nicknamed the "Iron Byron". Two issues were asked to be addressed for the senior project. First, the robot was practically immobile unless taken apart and moved with a forklift. The request from Hot Stix was to mobilize the robot so that it could easily be transported with minimal use of external help. Secondly, the initial tee-table was both poorly-designed and missing altogether. The new tee-table needed to be vibration-isolated from the robot and able to accurately traverse and record position in three dimensions.

The designs for the project were entirely original and were based on a conglomeration of many ideas developed while researching existing technologies. After a Preliminary Design Review, a final design was selected and various modifications were made along the route to completion. The final design, its modifications, and the complete design process is described in detail in the following report.

2. Introduction

The overall goal of this project is twofold: to design and build a transport mechanism for a uniquely shaped golf swing test robot, and to design and build a three-dimensional traversing tee table to be used for more accurate testing of golf clubs.

Preliminary research shows that the unusual shape of the robot frame as well as its heavy weight requires a specially designed lifting and moving device aside from traditional moving methods. Also, while there are many available multi-purpose traversing tables, the design requirements of our project will most likely require a unique design that applies specifically to the robot's range of motion and precision. Our sponsor, Hot Stix Golf, and possibly other current users of this golf robot model are interested in improving the mobility of their devices and the accuracy of their tests.

3. Background

Due to the golf robot's large weight, many companies that use the robot typically keep their testing devices in relatively permanent locations. This often requires building an expensive testing site around the robot, such as a warehouse or indoor driving range. When moving of the robot is necessary, dismantling and the use of heavy moving equipment such as forklifts is found to be exceptionally tedious and time consuming. A more convenient solution for transportation is desired.

A disadvantage of the current tee table used is that it is physically attached to the robot frame. The quick downswing of the robot in combination with its weight causes considerable vibration of the golf ball before impact. This vibration decreases the repeatability of testing conditions and reduces the precision of results. Users of the golf robot not only want to eliminate this vibration but would also like a method to move the ball to an exact location on the club face, allowing for "face mapping" at designated distances away from the clubface center.

As mentioned, preliminary research has been done to find existing solutions as well as possible modifications to existing devices. Because of the design constraints, including the need for the transport device to work on turf-like terrain, there are limited devices readily available that will work as a solution. One device sold by Vestile Manufacturing Corporation, mimics a warehouse pallet jack and utilizes off-road wheels and a sturdy frame, but would require an excessive amount of permanent modifications to either itself of the golf robot. A second idea, discovered when visiting the Callaway R&D department in Carlsbad, CA, involves four separate wheels that are permanently attached with small individual mounts

and are simply pressed into place utilizing leverage with a long rod. A third device, the most realistic of the three, includes a motorized dolly built to drag around heavy boat trailers. Because of its convenient design and feasibility in accomplishing the desired goals, more detail on this device is in following sections.

Solutions for the tee table have been researched in parallel with the transportation device. One current user of the robot uses an old milling machine table with CNC readouts, but this setup requires that the robot be lifted several feet off the ground. Callaway R&D employs small metallic tracks developed by Mitutoyo Co. which provide hand-adjusted digital readouts that satisfy similar requirements of this project.

While these and several other devices prove to be sufficient for their existing users, no single one will be so for this project, and as such, further details of those designs are omitted here.

4. Objective

The first stage of the project required that we design and build a mechanical device that will lift and transport a 900lb robot. Our background research showed us that the design will most likely be completely original, yet utilize commonly available parts found at online manufacturers. The second part of the project required that we design and build an adjustable mechanical tee table system that isolates vibration from the robot and displays the ball's location in three dimensions for accurate golf club testing.

In parallel with the physical testing of the devices, we also used SolidWorks to perform Finite Element Analysis (FEA) to help determine weaknesses in the designs and prevent future failures. Once the FEA model had been developed, we used it to show how the device responds under expected and abnormal loads (ie. the user stepping on the robot when being transported).

A project timeline created in Microsoft Project is shown in Appendix B with major and minor deadlines. Because there is a consumer desire to get the robot mobile as soon as possible, the transportation device and the tee-table were to be completed in sequence, as depicted in the Gantt chart. This is described in more detail in following sections.

House of Quality engineering requirement sheets for both the transport device and the tee-table can be found in Appendix A. A list of engineering requirements for both parts can be found in Tables 1 and 2 below.

Table 1. Technical engineering requirements for transport device

Spec. #	Parameter Description	Requirement or Target	Tolerance	Risk
1	Ease of Use	1 Person Operation	Max	L
2	Use of Wheels	4 or Less	Max	L
3	Total Wheel Surface Area	30" in^2	±6" in^2	L
4	Compact Storage	6'x6'	±1'	M
5	Cost	< $1,000	±$300	M
6	Lifting Capability	> 2000 lbs	+500 lbs	L
7	Distance	500 Yards	+1000 Yards	L

Table 2. Technical engineering requirements for tee table

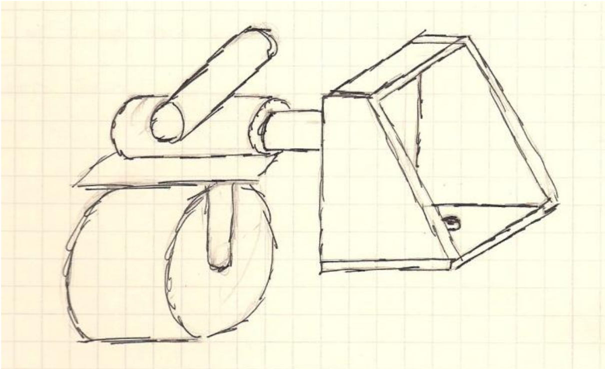
Spec. #	Parameter Description	Requirement or Target	Tolerance	Risk
1	Cost	< $1,000	±$300	M
2	Weight	< 100 lbs	±50 lbs	L
3	Travel along stance	2'	Max	L
4	Perpendicular travel	1'	+6"	L
5	Vertical Travel	6"	+4"	L
6	Feedback	Digital Readout to 0.001"	±0.001	H
7	Attachment	While in transport	Max	M
8	Ease of Use	1 Person Operation	Max	L
9	Vibration Isolation	Zero Effect from Robot	Max	M

The above table is a representation of the technical requirements for our project. There are three levels of risk, (H)igh, (M)edium, and (L)ow for reaching these goals. For the transport device, the highest risk item (ie. most difficult) is to keep the cost of the device under the requirement which is related to the tee tables highest risk item, the digital readout system. This is because digital readouts are expensive to purchase and may significantly increase the overall cost of the design.

5. Descriptions and Sketches of Preliminary Transport Device Concepts

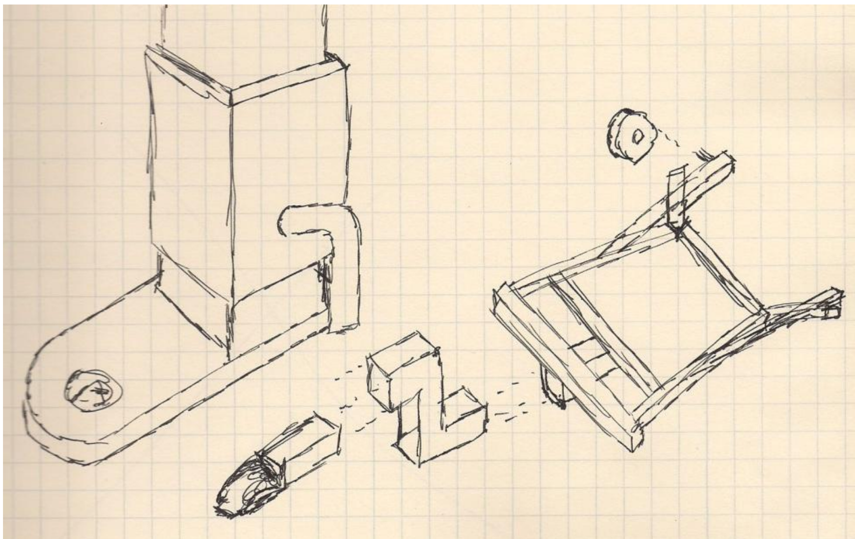
Top concepts for the transport device are described and shown below. Because the projects are to be completed in series, concept generation and idea selection for the transport device is shown first followed by tee-table concepts.

1. Four permanent wheels leveraged and pinned into place while lifting device off its feet. One wheel is chain driven with motor and steered from behind.

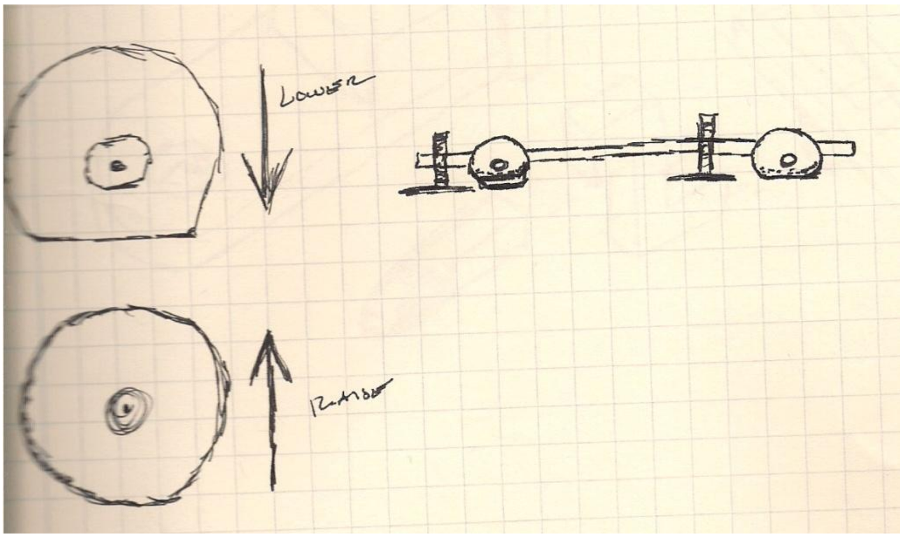


2. Three wheels with one wheel used to drive and steer the device. Two front wheels are leveraged and pinned into place. This design utilizes the same type of device as shown above.

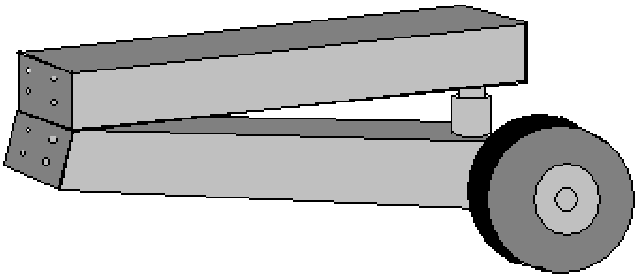
3. Two permanent wheels on robot with removable trailer hitch mounted to front. An electric trailer dolly will be used to move around the robot. Feet manually raised.



4. Four large permanent wheels off to the sides of the robot with one wheel chain driven and steered at one wheel. Wheels will be inflated and deflated to lift and lower the device off of its feet.



5. Four wheels on swing arms with hydraulic jacks to lift and lower the device onto the wheels with one wheel driven, steered from behind.



6. Motorized all-terrain pallet jack

5.1. Process for Top Concept Selection

To determine the best design concept, a decision matrix was used to do a side by side comparison based on several design factors. To decide the weight factors of the design criteria below, each area was compared against each other to determine which was the most important. Then weight factors were assigned to the criteria based on what was deemed most important. This resulted in 'feasibility' as the most important design criteria with 'storage size' in second place and so on. The decision matrix containing the comparisons can be found in Table 3. Below are the design criteria with their associated weights:

1. **Ease of use**. A combination of the total time, man power and the overall effort required to operate. A high score in this area indicates a very easy to use design. (Weight: 15%)
2. **Cost.** Cost of any frequent maintenance or repairs (batteries etc.). High score indicates very low cost. (Weight: 10%)
3. **Feasibility.** A measure of our confidence in our ability to meet the requirements with a particular concept including the difficulty to implement a given design. High score here indicates very feasible and easy to implement solution. (Weight: 25%)
4. **Size.** This also includes stored or packed size. A high score in this section indicates a low storage size. (Weight: 20%)

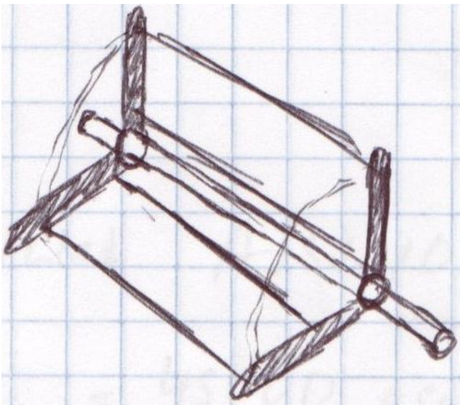
5. **Performance.** This is a measure of how effectively the design will meet the requirements. A high performance score indicates very fast and efficient design. (Weight: 15%)
6. **Life and maintenance.** How long will it last before it needs repairs and how costly will the repairs be? A high score here indicates a long lasting design with little maintenance or repairs. (Weight: 15%)

Table 3. Decision matrix for transportation device. The winning concept is number three, highlighted above.

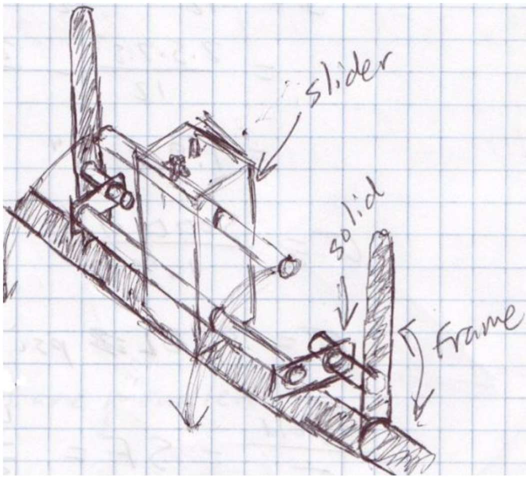
	Criteria →	Feasibility	Storage Size	Performance	Ease of Use	Total Cost	Lifespan	Total
Concepts	Weight →	0.25	0.2	0.15	0.15	0.15	0.1	1
	1	0.65	0.9	0.7	0.6	0.8	0.7	0.7275
	2	0.55	0.85	0.65	0.7	0.75	0.7	0.6925
	3	0.95	0.75	0.8	0.8	0.55	0.8	0.79
	4	0.85	0.85	0.7	0.6	0.8	0.6	0.7575
	5	0.45	0.9	0.7	0.6	0.45	0.65	0.62
	6	0.85	0.45	0.75	0.75	0.5	0.8	0.6825

6. Descriptions and Sketches of Preliminary Transport Device Concepts

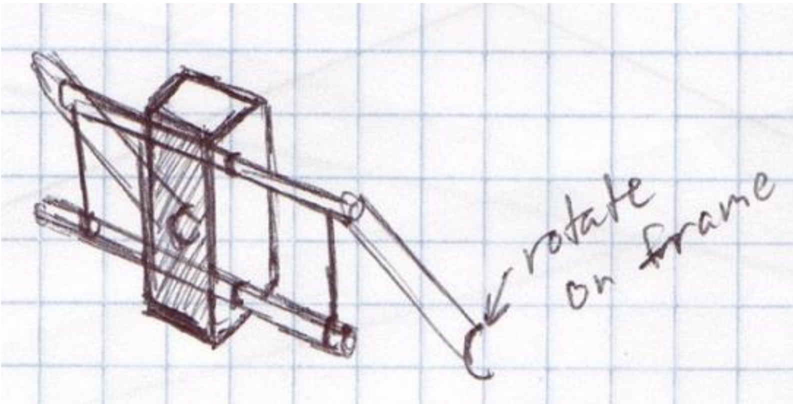
1. Tee table box is flipped around on the sliders and hinges are placed at the base of the arms to allow the tee table to swing out in front of the robot.



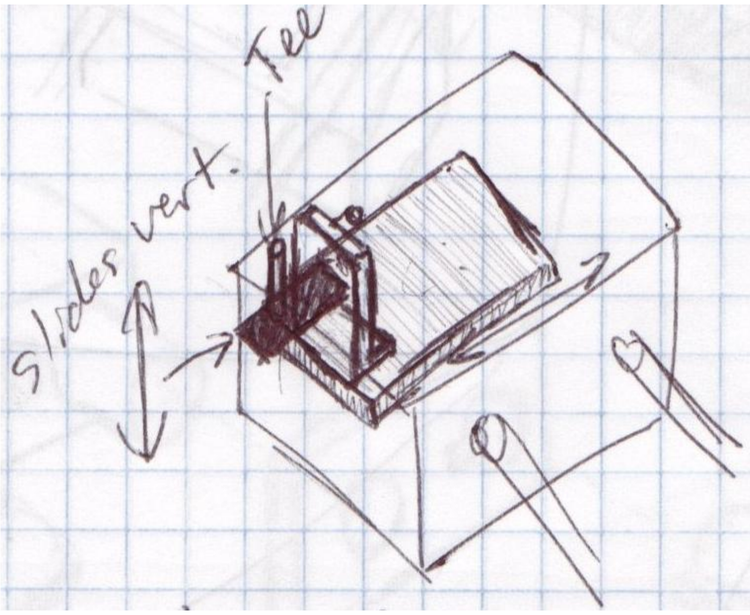
2. Place hinge off the tube to allow further extension from robot and reduce modification to the frame.



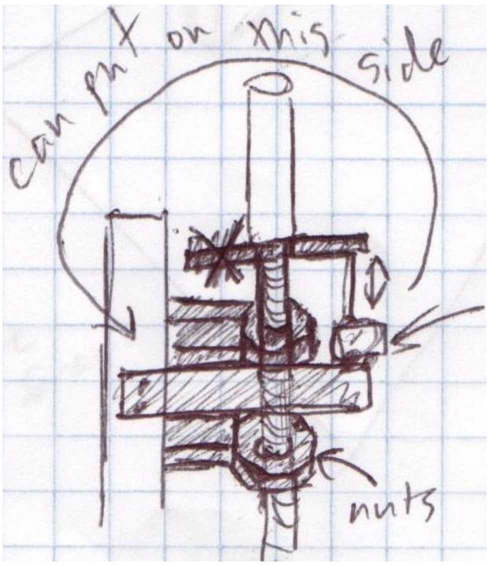
3. Two bar linkage allowing even further extension from the robot and keeping the tee table box facing the same direction.



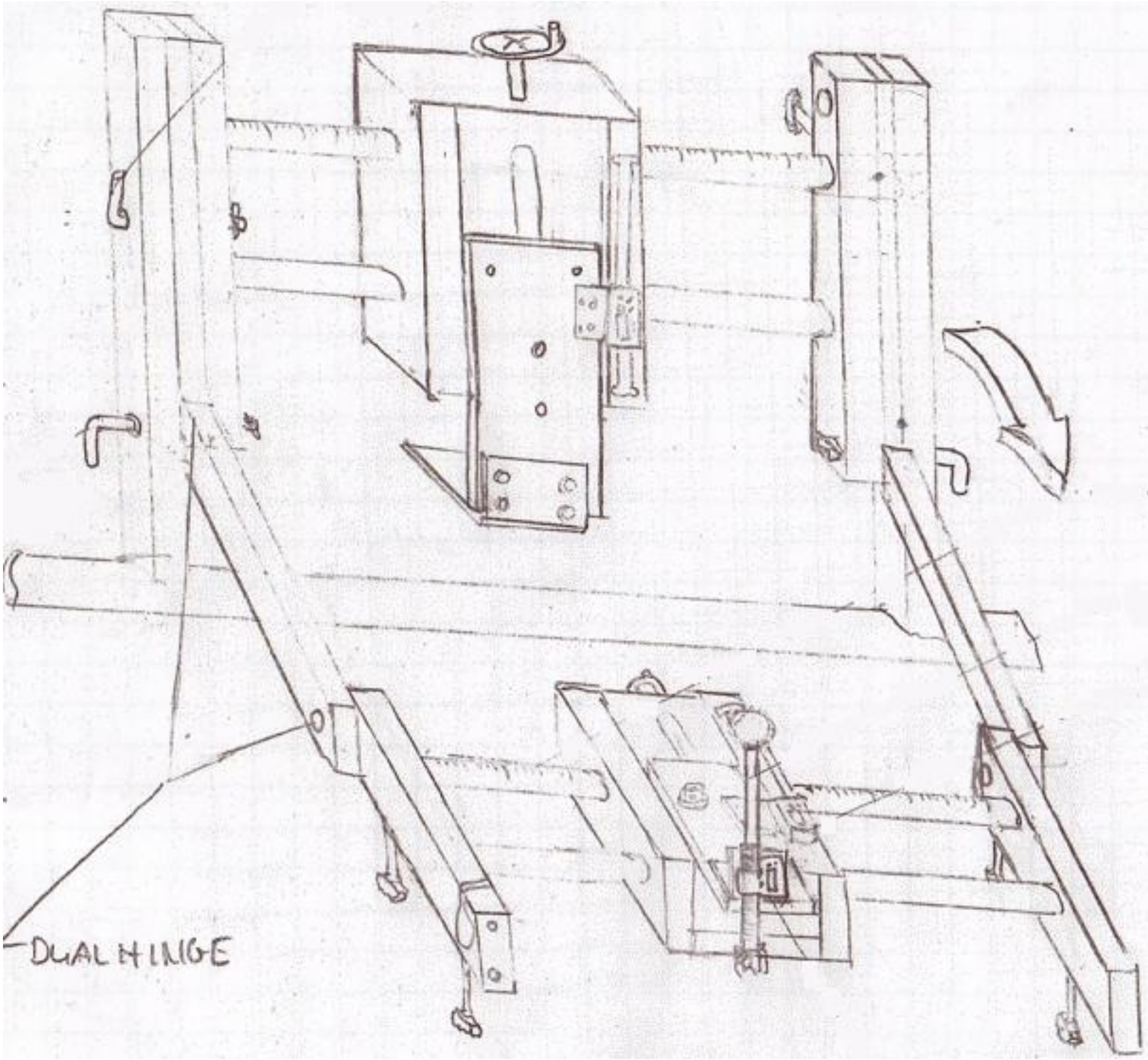
4. L-shaped bracket used for vertical adjustment of the tee.



5. Concept for measuring vertical adjustment on tee table box.



6. Complete design concept for extending tee table with removable pins to isolate vibration from golf robot.



6.1. Process for Top Concept Selection

The mechanics of the tee table top concept was not formally decided upon. The general idea of the dual hinge was easily the most feasible and functional idea and was chosen unanimously. Construction and necessary modifications of the robot began before all components of the design were finalized, which we found to be an effective technique due to time constraints. The final design, including the arms and the third-axis design is discussed in a following section.

7. Method of Approach

While the majority of tasks, such as research and conceptualization, were performed as a team, some tasks needed to be split up for two reasons: first, to finish them in a timely manner, and second, to take advantage of each team member's specific strengths. Kyle typically did most of the quick hand calculations, led brainstorming and other problem solving sessions, and was involved with manufacturing. David was typically in charge of SolidWorks modelling and FEA analysis of each concept, and purchasing of parts. Todd led the manufacturing processes, including machining, fastening and aesthetics. Such tasks that only required one person, such as recording meeting minutes, were assigned on a rotating basis each week. A Gantt chart is supplied in Appendix B that gives a timeline of the project and includes several hard dates of reports and other status updates as required by our advisor.

8. Description of Final Device Concepts

Our final concept can be seen in Figure 1. It involves attaching two wheels on the backside of the robot and lifting the front with a special dolly that utilizes a trailer coupler. The dolly is a purchasable item, but the rest needed fabrication. The wheels on the rear of the robot have internal roller bearings that fit on 0.75" diameter fixed axles. The axles fit through 2.5" x 2.5" x .25" square tubing that extends from the base frame of the robot and over the All-Thread rod used for the feet posts. Because the frame of the robot is built of smaller 2" x 2" square tubing, the larger tubing used to make the transport device allowed for certain sections of the square tubing to be cut out so it can slide over the robot frame while still maintaining its rigidity. This also eliminates the need for additional welding. These attachments and wheels will be mounted with bolts and are completely removable should the user so desire.

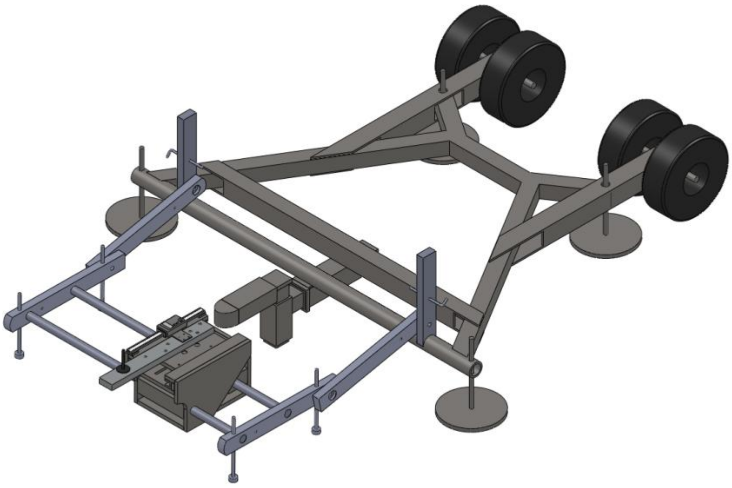


Figure 1. Final Design Concept

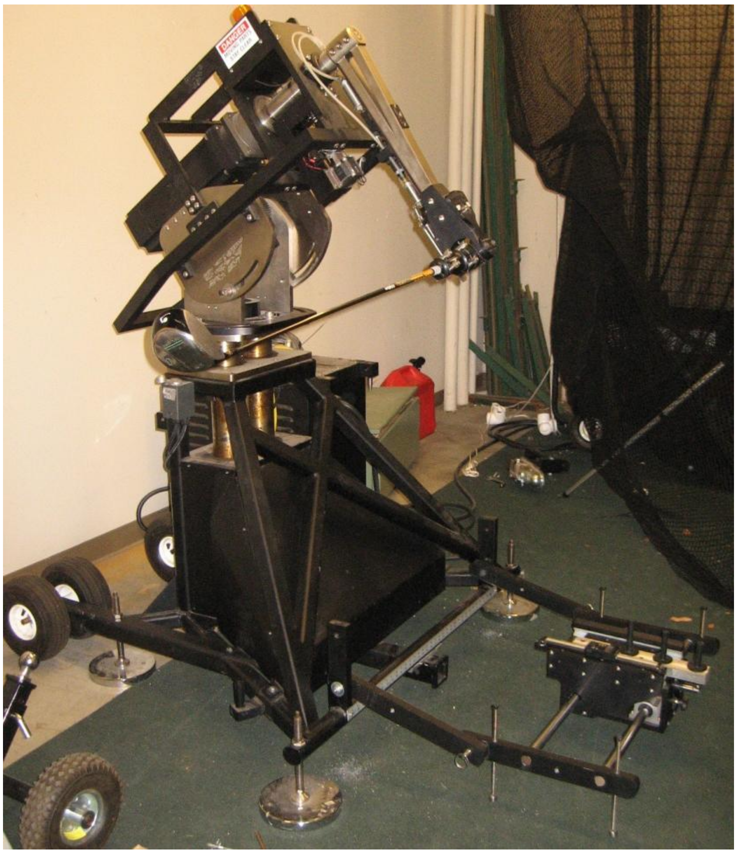


Figure 2. Complete transport device and tee table unfolded.

To attach the dolly to the robot, a trailer hitch receiver was mounted under the robot frame. A modified adjustable drop hitch with a trailer coupler can be slid into the receiver and secured with a standard pin. When the robot is in operation, this hitch can be removed to allow the tee table to sit in front. The trailer ball on the dolly can fit in the coupler and be

used to pull the robot around. The dolly will eventually be motorized and lift the front of the robot off the ground in one of three ways; using leverage, with a trailer tongue jack mounted to the hitch, or a lifting system incorporated into the dolly. The full system can be seen in Figure 2 above with the wheel system shown in Figure 3 below.

Figure 3. Transport wheels and frame.

The tee table design utilizes several components from the original robot tee table. The stainless steel rods that allow for horizontal travel were reused, as was the box that slides along them. The vertical posts were part of the original robot and were used again as securing points when the tee table is in its upright position. When not in use, the tee table is folded up and pinned so that it is not in the way when moving the robot. When ready, the tee table can be unfolded.

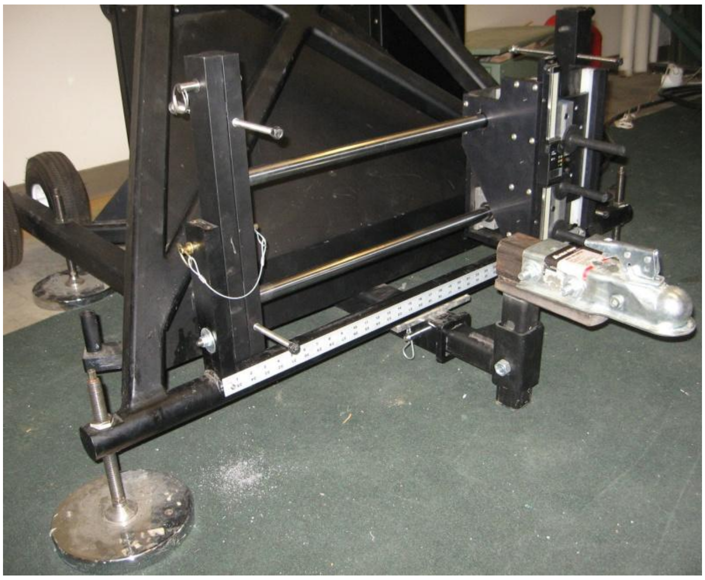


Figure 4. Folded tee table with hitch inserted.

The main design tee table design concentrated around two design considerations: first that the tee table is traceable in three dimensions, and second, that it is isolated from all vibration induced by the robot. The first consideration has three different methods to measure position. The horizontal axis (along the golfer's stance) is viewed by pressing a button on the side of the tee table that illuminates a laser pointer. This pointer shines on a steel measuring stick mounted to the robot frame and is accurate to 1/32".

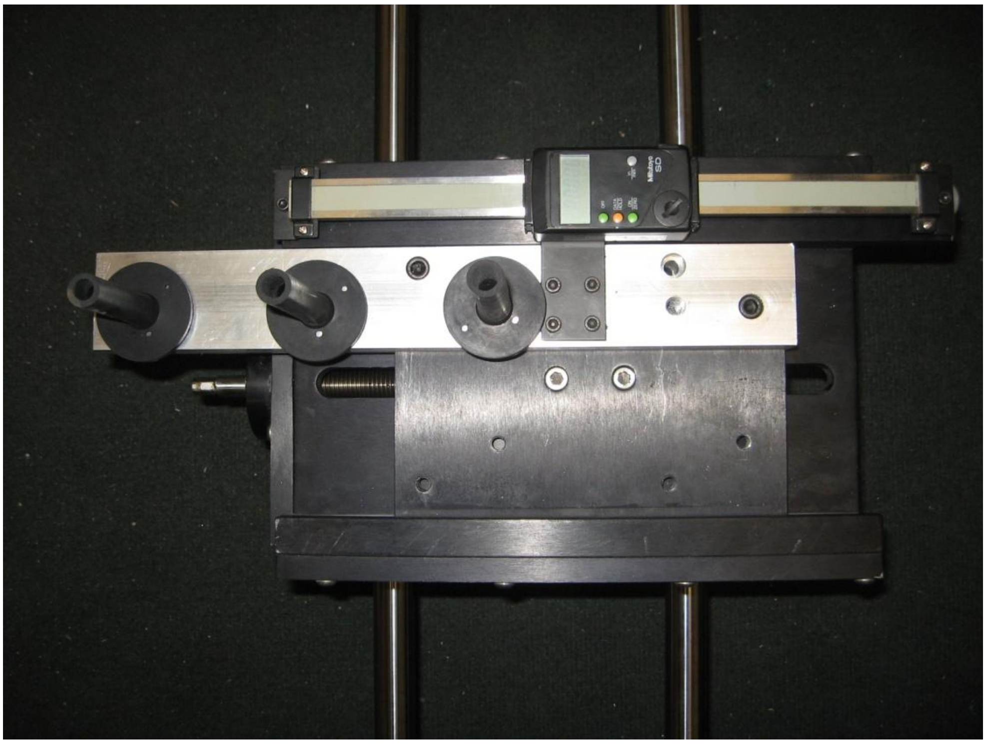


Figure 5. Second axis using Mitutoyo slider accurate to 1/1000".

The second axis (perpendicular to the golfer's stance) is measured by an attached Mitutoyo slider that moves when a knob on the far side of the tee table is turned. This axis, being more important when face-mapping is sensitive to 1/1000". The third axis, also important to face-mapping, uses four exchangeable tees of different heights that were cut based on four-desired heights on the club face typically used for testing. If the user desired more precise measurement along the vertical axis, the four feet posts can be raised or lowered appropriately. The second design consideration, vibration isolation, was achieved using a simple removable pin in the second hinge joint. After the tee table is lowered and placed to an appropriate horizontal location, the pin can be removed, completely detaching the tee table from the frame of the robot, eliminating all induced vibration.

9. Construction and Testing

As planned, construction of the transportation device preceded the tee table construction. It began with thorough three-view drawings of all components, including the extensions arms, the supporting bar, axles, and hitch connection designs.

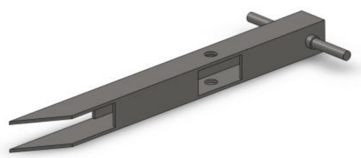


Figure 6. Rear axle extension for transport device showing milled slots in square tubing.

The square tubing was purchased in three four foot sections and cut to appropriate lengths with a steel chop-saw. Because the square tubing was 2 ½" x 2 ½", milling slots out of the sides and ends allowed the pieces to slip over the 2" x 2" existing tubing on the robot frame. Holes were drilled for 1.25" axles. The axles were turned down on both sides to ¾" for the wheels hubs to press against. These drawings and detailed designs, along with SolidWorks files, can be requested if needed. The wheels and extensions required very little robot modification.

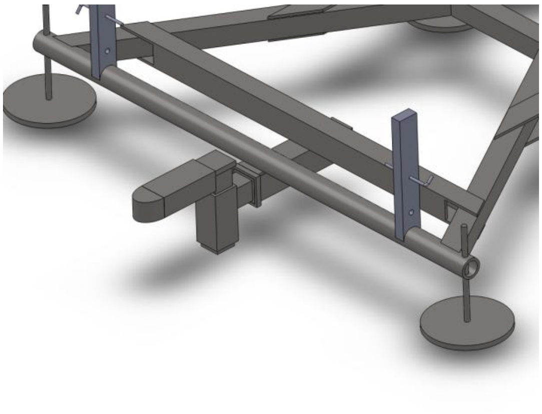


Figure 7. Hitch couple and cross support bar.

The hitch section, however, required several hours of modification to the bottom half of the robot. Black steel plates on the robot, mostly aesthetic in purpose, needed to removed and cut to allow the steel cross member to be installed. The hitch receiver tube was welded to the cross support bar and the hitch coupler was bolted to the drop hitch.

The tee table required much less physical machining, while needing higher precision tolerances. Because we do not expect high cycle loading and desire a lightweight design, basic aluminium 1" x 2" stock was selected for all components.

Figure 9. Inner Hinge

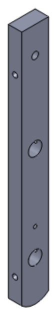


Figure 8. Outer Hinge

The inner and outer hinges are shown above. Neither required machining outside of through holes, tapping, and counterbores. The holes for the stainless steel rods did need to be accurately placed though, because the rods needed to be perfectly parallel or the carriage would jam and not slide.

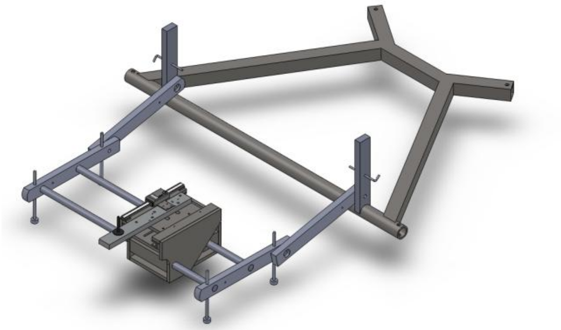


Figure 10. Final tee table assembly.

The component attached the tee table carriage is also made of aluminium, with several tapped holes along its length. These holes give crude tee placement in the horizontal plane perpendicular to the golfer's stance, while a knob on the far side allows for more fine adjustment.

While we were able to manually move the tee table around, physical limitations of the device were not discovered because the actual robot was not functional at the time of completion. That is, actual face mapping and data acquisition was not a part of our project, and the assumptions we made about accuracies, while warranted, are not proven.

10. Conclusions and Future Design Considerations

There are several design considerations that would make these devices more effective. Considering the transport device, if the robot ever needed to be moved for a longer distance than around a shop, a motorized dolly would be the most practical solution. Products are available on the market today, such as the EZ-Tug or the ParkIt360, that would require no modifications to the robot or our project. Knobs on the top of the feet posts would also be useful because currently a socket wrench is necessary to move them into the correct position.

The tee table has the most room for improvement. Only one of the three axes has a digital readout, which means a user needs to physically record position data of the golf ball. If the tee table had digital Mitutoyo scales with USB attachments, data logging would be much easier and less time consuming. Also, though they were intended, no levelling scale was ever attached to the tee table. With four feet posts, precise levelling is completely possible, but without the appropriate hardware the three axis system may not translate the ball in one direction only.

11. Appendices

11.1. A (1) – House of Quality, Tee Table

11.2. A (2) – House of Quality, Transport Device

11.3. B – Gantt Chart

11.4. C (1) – Bill of Materials, Transport Device

11.5. C (2) – Bill of Materials, Tee Table

Appendix A (1)
KDT Design Group
Phase 1-Transport Device

Engineering Requirements (HOWS)

Benchmarks

Customer (Step #1) Requirements (Whats)

Customer Requirements (Step #2)

Customer Requirements (Whats)	Weighting (1 to 5)	3000lbs Capacity	Operates on Grass	3 MPH	Operated by 1 Person	Use 1 Golf Cart Battery	> 4 Golf Cart Wheels	> $1000	Moves 500 Yards on Single Charge	Fit's Within 5'x5'	5' Braking Distance	Life of 5 Years	Carries Charging System							
Motorized	3	1	1	9	1	1			3			1								
Off Road Terrain	4		9				3													
Easy to Use	3				9															
Golf Cart Batteries	4								9			3	9							
Golf Cart Wheels	4	9	9	1			9													
Aesthetically Pleasing	2																			
Easy to Clean	1																			
Compact	3									9										
Lift and Lower Robot	5	9			9															
Durable	4											9								
Travel Few Hundred Yards	4	3	3	3					9											
Cost Effective	3							9												
Brakes	2		3								9									
Good Travel Pace	3		1	9																
Operated by One Person	4				9															
Units																				
Targets																				
Benchmark #1																				
Benchmark #2																				
Benchmark #3																				
Importance Scoring		96	96	70	111	3	48	27	81	27	18	51	36	0	0	0	0	0	0	0
Importance Rating (%)		86	86	63	100	3	43	24	73	24	16	46	32	0	0	0	0	0	0	0

● = 9	Strong Correlation
○ = 3	Medium Correlation
Δ = 1	Small Correlation
Blank	No Correlation

Appendix A (2)
KDT Design Group
Phase 1-Tee Table

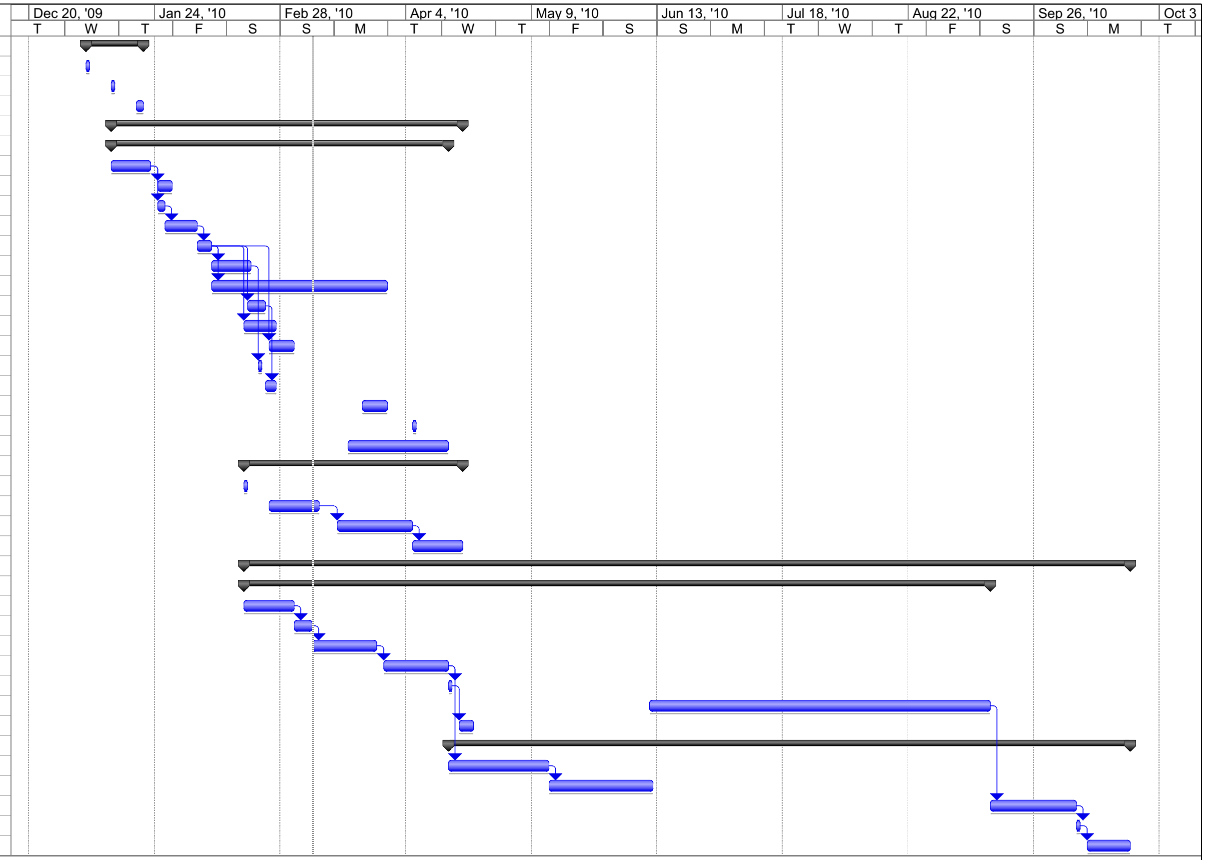
Engineering Requirements (HOWS)

Benchmarks

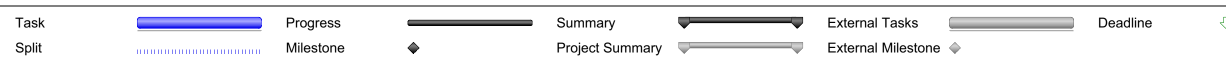
Customer (Step #1) Requirements (Whats) / Customer Requirements (Step #2)	Weighting (1 to 5)	Feedback to .001"	Stationary on Grass	Digital Readout	Separated from Robot	Ability to Attach to Robot	>100 lbs	> $1000	Fit's Within 3'x3'	Life of 5 Years	Manually Adjusted									
Accurate	5	9	3	3																
Easy to Adjust	4	3		3							9									
Translates in 3D	5			1							3									
Stable	4		9		9	1														
Lightweight	3						9													
Transportable with Robot	3					9														
Easy to Clean	1									1										
Compact	3								9											
Simple Design	3							3		3	1									
Durable	4									9										
Easy to Read Output	4	3		9																
Cost Effective	3							9												
Units																				
Targets																				
Benchmark #1																				
Benchmark #2																				
Benchmark #3																				
Importance Scoring		69	51	68	36	31	27	36	27	46	54	0	0	0	0	0	0	0	0	0
Importance Rating (%)		100	74	99	52	45	39	52	39	67	78	0	0	0	0	0	0	0	0	0

● = 9	Strong Correlation
○ = 3	Medium Correlation
Δ = 1	Small Correlation
Blank	No Correlation

ID	Task Name	Duration	Start	Finish	Predecessors
1	**Team Forming**	**12 days**	**Tue 1/5/10**	**Wed 1/20/10**	
2	Meet teams	1 day	Tue 1/5/10	Tue 1/5/10	
3	letter of intro to sponsor	1 day	Tue 1/12/10	Tue 1/12/10	
4	team bonging assignment	2 days	Tue 1/19/10	Wed 1/20/10	
5	**Crawler**	**70 days**	**Tue 1/12/10**	**Mon 4/19/10**	
6	**Design**	**68 days**	**Tue 1/12/10**	**Thu 4/15/10**	
7	research	9 days	Tue 1/12/10	Fri 1/22/10	
8	requirements	4 days	Mon 1/25/10	Thu 1/28/10	7
9	project proposal	2 days	Mon 1/25/10	Tue 1/26/10	7
10	idea generation	7 days	Wed 1/27/10	Thu 2/4/10	9
11	idea selection	2 days	Fri 2/5/10	Mon 2/8/10	10
12	design analysis	9 days	Tue 2/9/10	Fri 2/19/10	11
13	modeling	35 days	Tue 2/9/10	Mon 3/29/10	11
14	safety considerations	3 days	Fri 2/19/10	Tue 2/23/10	11
15	sponsor evaluation/design modification	7 days	Thu 2/18/10	Fri 2/26/10	11
16	design report	5 days	Thu 2/25/10	Wed 3/3/10	11
17	design presentation	1 day	Mon 2/22/10	Mon 2/22/10	12
18	cost analysis	3 days	Wed 2/24/10	Fri 2/26/10	14
19	spring break	5 days	Tue 3/23/10	Mon 3/29/10	
20	critical design review	1 day	Tue 4/6/10	Tue 4/6/10	
21	final design report	20 days	Fri 3/19/10	Thu 4/15/10	
22	**Build**	**43 days**	**Thu 2/18/10**	**Mon 4/19/10**	
23	design review	1 day	Thu 2/18/10	Thu 2/18/10	
24	purchase parts	10 days	Thu 2/25/10	Wed 3/10/10	
25	build device	15 days	Tue 3/16/10	Mon 4/5/10	24
26	troubleshoot/modify	10 days	Tue 4/6/10	Mon 4/19/10	25
27	**Tee Table**	**177 days**	**Thu 2/18/10**	**Fri 10/22/10**	
28	**Design**	**148 days**	**Thu 2/18/10**	**Mon 9/13/10**	
29	idea generation	10 days	Thu 2/18/10	Wed 3/3/10	
30	idea selection	3 days	Thu 3/4/10	Mon 3/8/10	29
31	analysis	14 days	Tue 3/9/10	Fri 3/26/10	30
32	modeling	14 days	Mon 3/29/10	Thu 4/15/10	31
33	sponsor evaluation	1 day	Fri 4/16/10	Fri 4/16/10	32
34	SummerBreak	67 days	Fri 6/11/10	Mon 9/13/10	
35	project update report	4 days	Mon 4/19/10	Thu 4/22/10	33
36	**Build**	**136 days**	**Fri 4/16/10**	**Fri 10/22/10**	
37	purchase parts	20 days	Fri 4/16/10	Thu 5/13/10	32
38	assemble	21 days	Fri 5/14/10	Fri 6/11/10	37
39	trouble shoot modify	18 days	Tue 9/14/10	Thu 10/7/10	34
40	final assembly completed	1 day	Fri 10/8/10	Fri 10/8/10	39
41	testing	10 days	Mon 10/11/10	Fri 10/22/10	40



Project: Revised Gantt Chart 1
Date: Tue 3/9/10



Appendix C

Indented Bill of Material (BOM)
Robot Transportation System

Assembly Level	Part Number	Description	Vendor	Qty	Individual Cost	Total Cost
		Lvl0 Lvl1 Lvl2 Lvl3 Lvl4				
0	100000	Final Assy	------	1		
1	101000	├── Towing Assembly	------	1	207.27	207.27
2	102000	├── Receiver	Northern Tool	1	22.99	22.99
2	102001	├── Cross Bar	------	1	24.16	24.16
3	103000	└── ASTM A500 Gr. B 2.5"x2.5" .25" wall steel tubing	McCarthy Steel	4 ft	6.04	24.16
2	102002	├── Hitch Assembly	------	1	67.98	67.98
3	103001	├── Drop Hitch	Northern Tool	1	49.99	49.99
3	103002	└── Trailer Coupler	Northern Tool	1	17.99	17.99
2	102003	└── Pins	------	2		
1	101001	├── Rolling Assembly	------	1	160.88	160.88
2	102004	└── Back Wheel Extension	------	2	80.44	160.88
3	103003	├── ASTM A500 Gr. B 2.5"x2.5" .25" wall steel tubing	McCarthy Steel	3 ft	6.04	18.12
3	103004	├── AISI 1144 cold finished 1" diameter steel round	McCarthy Steel	1 ft	2.94	2.94
3	103005	├── Wheels	McMaster Carr	2	18.39	36.78
3	103006	└── Tires	McMaster Carr	2	11.3	22.6
1	101002	├── Bolts	------			
1	101003	└── Trailer Dolly	Northern Tool	1	67.99	67.99
	Total			**17**		436.14

Appendix D

Indented Bill of Material (BOM)
Tee Table

Assembly Level	Part Number	Description	Vendor	Qty	Individual Cost	Total Cost
		Lvl0 Lvl1 Lvl2 Lvl3 Lvl4				
0	100000	Final Assy	------	1		
1	101000	└── Folding Assembly	------	1		
2	102000	├── Arms	------	1		
3	103000	├── 1"x2" Aluminum		6 ft	56.5	56.50
3	103001	├── Threaded Swivel Feet		4	3.46	13.84
3	103002	├── Set Screw		1 pack	1.25	1.25
3	103003	├── Hinge Bolt		2	3.55	7.10
3	103004	├── Clevis Pin		4	0.85	3.40
3	103005	└── Nylon Washer		1 pack	1.25	1.25
2	102002	└── Tee Box	------	1		0.00
3	103009	├── Linear Scale		1		provided
3	103011	├── Rubber Tees		1 pack	5.65	5.65
3	103012	├── All Thread		1 pack	9.08	9.08
3	103013	Adjustment Handle		4	2.45	9.80
3	103014	└── Bi-Axial Level		1	9.99	9.99
	Total			**20**		**117.86**