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Re-Configurable Putting Green

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RE-CONFIGURABLE PUTTING GREEN

by

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&
Team Fore

Thesis submitted in partial fulfillment
of the requirements for the degree
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In the Department of Mechanical and Aerospace Engineering

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Re-configurable Putting Green
Prototype Development Report

May 4, 2012

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Executive Summary:

This report discusses the design of a prototype transformable putting green that can be programmed to recreate the topography of any putting green. The goal of the design was to give a realistic putting experience with real topography in an indoor environment. This report discusses the design of a pair of 4’x4’ module prototypes; a commercial implementation of this design would utilize a number of modules to create putting greens on a more realistic scale (example 12’x32’). The design of a full size transformable putting green necessitates a topographical range of up to 30”. After initial concepts and preliminary designs it was determined that the budget was insufficient for a putting green with a full topographical range of 30”. To reduce cost while still providing a proof of concept, the design scope was reduced to a smaller topographical range. This design presents a 4’x8’ prototype consisting of two 4’x4’ modules each with a topographical range of 6” across their width.

The prototype uses an array of linear actuators to create the topography. The actuators are mounted vertically in a frame and are placed in a square grid array. Each module contains a 6x6 array of actuators (or 36 actuators per module) with 8 inch spacing between the centers of each actuator. Each of the linear actuators has a vertical range of 6”. The actuators are attached to a subsurface to carry the loads between the actuators and to create a uniform surface. The primary purpose of the subsurface is to create a smoothly contoured putting surface that simulates the smooth curves of a putting green. Attached to the subsurface is an artificial turf that creates a seamless, realistic putting surface.

Each module is controlled by a microcontroller. The microcontroller dictates the steps for all the stepper motors in each of the linear actuators. The use of stepper motors on the linear actuators gives precise control over the resolution of the putting surface. The micro-controllers are governed by a computer controlling function which dictates the steps of the motors. Power to the stepper motors is supplied by a computer power supply that runs on a standard 110 volt AC circuit. However, a 220 volt AC circuit can be used for larger module arrays.

Each 4’x4’ module is self-contained and can be moved via castor wheels mounted on the base of each module. The electronic control interface between each module and the computer USB connection. Each of the prototype modules is 4’x4’x10” tall and weighs 250lbs. The cost to produce two modules with an included 10% over-run protection is $5,409.44
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1. Introduction

Golfing is a recreational activity enjoyed by millions. The most difficult aspect of golfing is putting and the only way to improve is frequent practice. However, in places where space is limited or in climates where year round golfing is not possible, the ability to putt year round is very attractive. The transformable putting green was designed to fill that role.

The prototype design is based on an array of actuator modules set in an aluminum T-slot frame. Each actuator in the array can be individually controlled to form different topographies. The actuators are driven by stepper motors that receive steps through the motor controllers. Each actuator assembly has an individual motor controller that receives step signals from the microcontroller. In a commercial application the microcontrollers will be connected to a computer terminal where the user may select the desired topography and the desired hole location. Once a green topography is selected the data is interpreted from topography data into step values and sent to the microcontrollers which then dictate the steps to the individual actuators to reproduce the desired topography. An array of 36 actuators on an 8” spacing makes up one 4’x4’ module. Because the prototype is designed to be modular, it is possible to create a custom size green without having to change the design of the prototype and thereby avoid having to build a custom green for each customer.

The modularity of this design also caters to tight spaces by allowing only the necessary parts of the green to be reproduced. The part of the green that is necessary for a putt is the lane between the hole and the ball. Once a desired putt has been selected by the user, the computer will determine the area of the green that will be required for the putt. The width of this putting lane is determined by how many modules make up the width of the re-configurable putting green.

Many requirements were derived from what the initial design dictated as will be explained later in this paper. Tests, analysis, and trade studies provide a detailed account of the design process as well as the components that were chosen based on these results.

2. Background

Some may say that a re-configurable putting green is unnecessary due to locations with warm climates where year round golfing is readily available. But what about the places where weather does not permit year round golfing, or locations where space is expensive due to large populations? In both these cases there is a need for a compact putting green that can change its’ topography to allow for year round practice on a variety of putting greens.

The idea for this project came from the customer’s visit to Japan. Japan has a population of 127 million people [1] and a total land space of 142 thousand square miles [2], which is approximately 900 people per square mile. In such a crowded place the customer came up with an idea to provide a way for putting practice that was economical and space efficient. With this new technology, the putting green could be installed at various locations: a golf course club house, an apartment building, at a school athletic center, etc. The modularity of this design provides for a very large range of possibilities. The
design was created to provide a putting green surface that simulates any putting green the user wants. This makes the opportunity of year round putting practice available to more people in more locations.

3. Statement of Problem

The design question was formulated from analyzing the design objective and the design need. How will we provide an indoor putting green surface for year round practice in limited space while using new technology and staying within our given budget? The putting green must simulate challenges presented by actual green topographies and provides indoor putting practice where in other circumstances this would be impossible.

It was originally found that an extreme putting green had a maximum elevation difference of about 1” per linear foot (see Appendix C). This would mean that over an average green size of 30’x30’ an elevation difference of 30” would be needed. Therefore, the original design started out with two layers of actuators for fine and course adjustment in order to meet the 30” elevation difference. However, because of cost concerns as well as considering that this prototype is mainly going to be used to show the proof of concept, the scope of the project was limited to just the fine adjustment actuators giving an elevation difference of 6” for each module of 4’ length.

With the invention of this new putting technology, there are assumptions that go along with the design process. During the design process the following assumptions were made: indoor use, installed on a flat surface, and installed in a controlled environment. These assumptions provide the knowledge that weather will not be a factor in the maintenance of the modules. The maintenance was determined with these assumptions in place. They also guarantee that calculations made are correct when assumed that the putting green is installed on a flat surface. The surface it is installed on determines angles of force that occur within the modules.

There are some factors that affect the design of the reconfigurable putting green. The design needs to be modular for transportation, installation, and custom sizes. This affects the electrical components of the design by making it critical that all the components work together on a modular basis. The green topographies also affect the design. The largest slope of actual green topographies needs to be simulated with the reconfigurable putting green. This goes to affect the mechanical components of the project.

4. Hardware

4.1 Overview

The design will be explained from the top down. The putting surface is where the user will stand and putt. Beneath the putting surface is a sub-surface intended to give the putting surface support and stability throughout. The sub-surface is attached to the tops of the actuators by way of a custom
interface. This interface is known in this report as the actuator tops. The actuator tops are mounted on an ACME threaded lead screw which is driven by a motor beneath it.

4.2 Putting Surface

The putting surface is the artificial turf that serves as the main interface with the user. The design of this project was such that the putting surface could be chosen strictly on the basis of realism and durability; it contributes nothing to the structural integrity of the project. One of the qualities needed in the putting surface is that it be able to bend. In order to conform to the contours of a putting green topography, which is outlined by the actuators and subsurface beneath it the surface must be flexible and be able to bend with the adjustments in elevation.

A large number of artificial turf products are available, but very few simulate an actual putting green grass surface in a convincing way. The chosen product for this design is Birdie Ball Turf [see Appendix A for specifications]. The product fulfills its design requirement in the following ways. First, the “grass” side of the turf simulates the look, feel, and rolling resistance of real grass. Second, the turf has a high density foam-rubber backing on it. This foam backing gives the turf a realistic feel when it is stepped on by depressing slightly like a real grass surface would.

4.3 Subsurface

Using linear actuators for the height adjustment of the putting surface there is a need to provide support for the putting green material between the locations of the actuators. The subsurface needs the capabilities to allow the actuators to move to the needed topographical positions while being able to support the putting surface and the required 300lbs per 4 square feet. Several possible materials were considered in order to meet the needs explained above. The trade study in Table 2 demonstrates the top materials considered.
Table 1: Subsurface trade study in order to compare materials against each other

<table>
<thead>
<tr>
<th>Material type</th>
<th>Pros</th>
<th>Cons</th>
<th>Cost</th>
</tr>
</thead>
<tbody>
<tr>
<td>Trampoline Fabric</td>
<td>-Good Strength</td>
<td>-(May) Need To Be Layered</td>
<td>~$60</td>
</tr>
<tr>
<td></td>
<td>-Good Flexibility</td>
<td></td>
<td></td>
</tr>
<tr>
<td>3/16&quot; Neoprene &amp; 19 Gauge Hardware Cloth Composite</td>
<td>-Good Strength</td>
<td>-Too Flexible</td>
<td>~$250</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>1/8&quot; Perforated Aluminum Plate</td>
<td>-Good Strength</td>
<td>-Too Stiff</td>
<td>~200</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>3/8&quot; Polystyrene &amp; 19 Gauge Hardware Cloth Composite</td>
<td>-Good Flexibility</td>
<td>-Too weak</td>
<td>~60</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>1/2&quot; Anti-Fatigue Mat</td>
<td>-High Strength</td>
<td>-Too Flexible</td>
<td>~$180</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Bidirectional 12 Gauge Metal Mesh</td>
<td>-Good Flexibility</td>
<td>-Too Weak</td>
<td>~$80</td>
</tr>
</tbody>
</table>

As can be seen from the trade study the only material that meets all the requirements is the trampoline fabric. The plan is to use a fabric weave of polypropylene, commonly used in the manufacturing of trampolines, in two layers in order to get the strength we need in all directions. Each layer of fabric has a bidirectional weave as can be seen in figure 2.

![Figure 2: Polypropylene weave, commonly used in the manufacturing of trampolines.](image)

The two layers will be oriented with one at a 0°/90° directional weave and the second to form a 45°/135° in order to create a support material to span the distances between the actuator tops and
carry the weight in all directions. This polypropylene material layer will provide support needed between the actuators while still allowing the topographical changes needed for the putting green surface.

Figure 3 demonstrates the layout of the complete putting surface configuration.

![Figure 3: Layout of putting surface configuration (cup attachment varied).](image)

The green surface on top will be adhered to the 2-ply weave of trampoline fabric. Also shown in figure 3 is the cup that will be installed in the surface. There will be one full piece of this surface configuration cut to the size of the complete modular layout in order to avoid seams in the putting surface.

In order to access the modular motor assemblies for maintenance and service the surface must be capable of being removed from the linear actuators. The means devised for this attachment is to use button and socket assemblies that will allow the repeated installation and removal of the sub layer by simply snapping them on and off. This will allow for easy access to service components and also enable the separation of the modules for transportation.

### 4.4 Actuator Tops

The linear actuator top is a component that transfers loads from the putting surface to the ACME threads of the linear actuator and the base plate. The design of the component needed to allow the surface to maintain a smooth contour when the actuator array was set to more extreme contours. The best way to transmit a load effectively is to have a large area over which the load can be spread. However, the best way to maintain a smooth contour is to have small flexible actuator feet. The best way to combine these two characteristics is a tapered profile.
The design of the actuator top, as portrayed in figure 4, was aided by basic tests run with a 3x3 actuator model. The purpose of these tests was qualitative more than quantitative. The results of the tests confirmed the ideas stated in the previous paragraph. First, for the design loads to be transmitted from the subsurface to the actuators, a pad of some sort was needed to spread out the point load from the actuators. Second, the actuator tops need to be flexible enough so they gave a smooth contour when the actuators were set at maximum deflection. The best way to combine these two test observations is to create a funnel shaped actuator pad. To reduce project costs it was decided to purchase the actuator feet off the shelf.

The closest off the shelf product is a drill mounted sanding pad backer. The design of the pad backer has the key features needed for the actuator feet [3]. The pad backer accomplishes the design need of the actuator foot at a much lower cost than building a custom actuator foot. The chosen pad backer has a diameter of 3”.

The pad backer has the female side of the metal snap that hold the subsurface in place mounted in the center of the side in contact with the subsurface. The steel shaft that is threaded into the bottom of the backer pad rotates in a sleeve bearing in the top of the ACME threads.

4.5 Actuator Assembly

4.5.1 Motor

There are multiple requirements in the selection of the motors to drive the linear actuators. Most importantly the motors must have a torque rating sufficient to drive the surface to the desired contours. The next requirement is the speed of the motors. The motors must be able to reach a speed that will complete any surface transformation within the allotted time frame of 30 seconds. Without an external means to determine the height of the linear actuator, the motor must be able to turn through a desired angle. The last requirements are the power required to drive the motor and the cost of the motor.
The motors need to have a sufficient torque in order to spin the ACME thread rod, to raise the adapter foot and to overcome the tension created by the subsurface. Calculations have shown that the motors will need to have a torque of .98 kg-cm (see Appendix B).

The speed of the motor needed is dependent upon the pitch of the ACME thread rod that is used. With the designed thread pitch of 1/10 the motor would need to spin at 120rpm in order to move through the 6” of adjustability in 30 seconds.

By using a stepper motor the angle that the motor is rotated through can easily be controlled with the use of an open loop control system that sends the desired amount of steps the motor is required to move through in order to achieve the desired position.

The cost and power consumption of the motors are as minimized as possible without compromising any of the other requirements set forth by the motors.

The motor that was chosen (figure 5) is the SY42STH46-1206A stepper motor with a torque of 3.17 kg-cm, max rotational speed of 600rpm, power consumption of 4.8watts and a cost of $14. This meets all of the set requirements for the motor.

4.5.2 Lead Screw and Collar

As was mentioned in the previous section, an ACME threaded lead screw is to be used with a thread pitch of 1/10. The diameter of the lead screw is to be 3/4”. This is to create a large enough friction as to produce a holding torque able to take the required load when the motor is off. Also the large diameter is needed in order to drill into the actuator tops to be attached.

The collar that the lead screw will pass through in order to raise and lower the putting surface will be an oil filled bearing grade bronze collar (Part #8931K89 on McMaster.com). This will reduce on the maintenance costs of the actuator assembly. The oil filled bronze will suffice as the only lubrication needed for the lead screw. The collar is to be mounted on the steel plate and will take the bulk of the load and transfer it from the lead screw to the steel plate itself. (For more details see drawing package)

4.5.3 Heat Dissipation

Because we are going to have 36 actuators in every 16 square feet, each module of 4 feet by 4 feet, there was concern of overheating the actuators. To address this concern a quick calculation was done in
order to evaluate the need of some sort of cooling. According to the sales technician the motor is not to exceed a temperature of 80°C. Assuming the underside of the module falls in the realm of free convection, we take a tabulated value for the convection coefficient [4] to match our calculated convection coefficient in the range of 2-25 W/(m²K). In order to evaluate worst case conditions the heat dissipated was calculated using a convection coefficient from the low end of the spectrum. With a surrounding air temperature of 50°C and if the motors are just holding the full torque so that most of the power is dissipated, then there is a chance that the air will get warm enough to cause the motors to overheat. (For detailed calculations see Appendix B). However, our calculations also show that the holding torque of the motors will not be needed due to the sufficient amount of friction on the lead screw. Therefore, the motors should not reach a warm enough state to overheat. More testing on this will be done with the prototype.

4.6 Actuator Array

Requirements set forth for the actuator array include the ability for the surface to meet the topographical requirements for the putting surface and for the support of the surface and other loads. The spacing of the actuators and the pattern for the layout needed to be established. For most 3D parametric modeling a triangular mesh is the preferred method of design. This approach was researched and while it has a good number of actuators per area the modular design of this project created a clearance problem. Where individual modules mate together there is a required minimum clearance between the center of an actuator and the mating line between two modules. With a triangular array the spacing left a clearance smaller than the allowable clearance, as shown in figure 4. This combined with a more complex layout led to this option not being used.

![Triangular patterned array.](image)

The next layout analyzed was a simple square. This design leads to a clearance that is greater than the required minimum and a regular pattern that makes the layout of the underlying frame easy to fabricate. Higher orders of geometric shapes were also analyzed but they all led to an increase in
complexity and further issues in clearance. The optimal layout determined was the square pattern as shown in figure 5.

![Figure 7: Square patterned array.](image)

The spacing of the actuators was determined by many things including: an analysis of the minimum distance needed to provide room for clearance and installation of the actuators, the distance needed between actuators to accurately replicate the desired putting green surface topography, the number of actuators to create an equal spacing in the module, and the overall cost of the actuators.

The minimum physical spacing needed was determined by the dimensions of the linear actuator assembly along with a clearance value for attachment, frame support and electrical cabling. The dimension of the motor being used is 1.7 inches square. Using this dimension plus a clearance of 2 inches between motors gives a physical minimum distance between motor centers to be 3.7 inches for a square array. The spacing available to create useable equal spacing in a 4 foot square module is: 4”, 6”, 8”, 12”, and 16”. From a cost and complexity view the number of motors should be minimized which will lead to a larger spacing. For the surface topography the smaller the distance between the actuator will allow a more accurate representation of the desired putting surface. Using these parameters with cost being a major factor, the determined spacing is 8” from center to center of each actuator, giving a total of 36 actuator assemblies per 4’x4’ module. This will give the clearance needed between motors and allow the power and control devices to be installed underneath the surface within the module cavity.

### 4.7 Aluminum T-Slot Frame

The original design of the frame used angle iron and a 4’x4’x0.25” steel plate mounted on top. This, however, was going to weight a lot and would not facilitate easy transportation of the putting green. Because of this the design was changed to use T-slot Aluminum, manufactured by Future. The t-slot gives the required strength but weights less than half of what the steel and angle frame would have. It
also provides for a much easier assembly of the frame and attachment of the actuator modules. (See drawing package for details on t-slot configuration.)

### 4.8 Power Requirement

Due to the design requirement to be able to power both modules from the wall, the entire system has been designed to meet that requirement. From a standard 110 volt 15 amp wall outlet, there are 1650 watts available. A design goal was set for each of the 4x4 modules to use less than 825 watts so that the entire system will be able to be powered from a single wall socket. A solution has been designed to accommodate all of the different power requirements that are required for the system as will be explained below. The final power drawn for each of the modules is less than 350 watts which will allow the use of smaller power supplies and allows the ability for the installation in either a commercial or residential application.

Each of the stepper motors is going to need a 12 VDC source in order to function properly. The current design calls for simple 110 VAC to 12 VDC power converters that are to be used to power all of the motor controllers which will power the motors themselves. From the 12 V source a 5 V source will be needed to power all of the miscellaneous circuitry in the system including the memory and the demultiplexors.

In order to generate both the 12 and the 5 VDC solutions simple computer converters will be used. These converters are commonly available as well as inexpensive and will provide all the needed power for the electrical components. There are two converters on each 4’x4’ module.

For a large scale installation of a modular putting green surface this power design allows a simple switch to a 220 volt circuit where each leg of the 220 volt supply would be able to provide power to half of the modules creating a balanced system.

### 4.9 Electrical Layout

The physical layout of the internal hardware of our system can be seen in a very high level view in figure 10. The diagram shows a very simple outline of how the entire system is going to work together to accomplish the requirements that have been set forth in this project. The hardware system is designed in such a way as to accommodate the critical timing constraints for the moving surface, as well as the power requirements to run the system.
The controlling computer is going to be the mastermind behind all of the movement of the reconfigurable putting green. But although it does most of the thinking, it needs to transmit its thoughts out to all of the actuators in some method such that the surface of the putting green is going to be able to change. Thus the entire physical layout of the hardware described in this section is to enable a fast and reliable methodology to accomplish this data transfer.

The first step in transmitting the data is getting it from the computer. It has been decided that the USB protocol will be used for this design. The amazing thing about our current choice is that in future models each component has been designed with a black box methodology in mind such that any communications protocol can be interchanged. That being said, USB has been selected for this implementation of the project due to budget constraints, but in future implementation, different protocols, such as 802.11 (Wi-Fi) can be implemented.

The data transmitted from the computer is going to be received by a microcontroller. Each module in the system is going to have its own microcontroller to receive the data that is being transmitted from the computer to that module. Each microcontroller is going to be used to enable a faster transformation time of the entire system. The reason a microcontroller is used in each module is for the purpose of scalability. For this initial design it is possible to remove the controllers from the array and control the entire surface from the computer. The problem with that solution is that in future designs when the array of modules increases, the overall transformation time is going to decrease dramatically. This design was chosen for future scalability.

The interface from the microcontroller to the stepper motors is a very simple design built from memory devices (flip-flops), de-multiplexors to select the desired memory device, and some simple buffers to drive the step signal to all of the stepper motors. The beauty of this solution is not only in the simplicity but in the ease of moving the entire surface at once. Because of the resolution requirement of the system is much greater than the resolution of a single step of the stepper motor, a single stepper motor
is going to be traveling in the same direction for multiple steps. The physical design that has been developed takes advantage of that fact as described below.

Each stepper controller needs three signals from the microcontroller in order to take a step. The signals are enable, the direction, and the step signal. Because the stepper motor is going to be going in the same direction and be enabled for multiple steps, the physical design that has been developed will set the direction and the enable signals for every single stepper motor in the array and hold them in the memory devices. After these signals have been set, the step signal will be sent through a buffer and sent to every motor controller in the module. This way the direction and enable signals will only have to be set periodically. In this design it has been determined to do this every 25 steps. That allows us to move the green surface in 1/80 of an inch increments, much finer than the required resolution. Because the step signal is driven by a timer interrupt, the enable and direction signals for the next 25 steps are being calculated simultaneous to sending the step pulses. If the controlling function needs to send intermediate states to the microcontroller this would happen during the sending of the step pulses as well. If it is found that the microcontroller is unable to process everything during this time, the number of step pulses can be increased up to 500, which translates into ½ inch of actuator travel, the minimum resolution.

### 4.9.1 Microcontroller

The first design question that was faced when determining what microcontroller to use was the communications interface that was going to be used to communicate the data from the computer to the microcontroller. There are many different protocols that could be implemented for this project. The major contenders that were considered for this project were USB, Ethernet, and 802.11. Other protocols that were investigated did not meet the requirements for speed.

Of the protocols that were able to be implemented for this project the major factor was cost, with the availability of the supplies and parts as a secondary concern. Because of cost constraints the current design of this project implements the USB interface between the computer and the microcontroller. The USB interface can address 127 different nodes, and with repeaters can be transferred at a distance of 30 meters.

Because of the design of the system, any of the different protocols can be substituted into the black box design. The overall system does not depend on a certain type of communications interface, the important thing is that the data is transferred quickly to all of the microcontrollers in the system. Future designs can simply switch to different communications protocols such as 802.11 or Ethernet with larger ranges and more addressable nodes by simply changing the methodology of transmit and receive on the computer and microcontroller respectively.

The microcontroller chosen for this design is the C8051F320 from Silicon Laboratories (Silabs). The major constraints in selecting a microcontroller were the design requirements of timing, cost, and ability to interface with the design that has been outlined. The Silabs C8051F320 has a 48 MHz clock, which will enable data transfer at full USB 2.0 speeds. This will enable all of the timing requirements to be
met. The next important aspect of this microcontroller is the number of digital I/O pins that are used to control all of the circuitry at a module-by-module basis. With 25 pins it has enough for the 13 pins required by the design plus room for expansion with future features.

Another important aspect of the Silabs C8051F320 is that is has a built in USB controller which allows the communication protocols to be customized in the firmware. This interface will also power the microcontroller, implying that the power solution for the hardware is simplified in that regard. This microcontroller has been chosen because it meets all of the design requirements and is familiar to the designers.

4.9.2 Motor Controller

The first criterion that the motor controller needs to meet is to interface with the selected motor. For that to be the case the motor controller must be able to pass 1.2A to the motor itself. That was a limiting factor in one of the controllers looked at. The next criterion that the motor controller needs is simplicity in control signals. Having a limited number of signals takes a lot of the work off of the microcontroller. The microcontroller only needs to generate three signals: step, enable, direction. All three of these signals are standard and are contained on all of the controllers considered.

Because these criteria were met the deciding factor in selecting a motor controller was the interconnection simplicity as well as the cost. The selected motor controller is the A4988 Pololu. This controller was selected because it meets the specifications for the motor. This controller is also cheap as well as simple to interface with. This controller meets all of the requirements that it needs to in order to meet the design requirements.

5. Software

5.1 Computer Program

The current computer program software design is partitioned into two parts that are explained independently below. The first part is the users interface. This is the part of the program with which the common user is going to interact, called the GUI (graphical user interface). After a user has selected the information from the GUI, the data is going to be sent to the other part of the program entitled the controlling function. This function is going to be in charge of controlling all of the microcontrollers in the system, which will in turn control all of the surfaces. This allows the user interface to change or be entirely replaced without the need to change the controlling function at all.

5.1.1 GUI

For the final product that is going to go to market, the GUI is probably one of the most important aspects of this project. But for the project that is being designed as a prototype, the most important aspect is the controlling function as well as the entire control system is to show a proof of concept. That
being said, the majority of design work has gone into the control system and less time has been spent developing a workable GUI. The GUI has been broken down into three tiers, the third tier is going to be implemented upon production, and the first tier has been used as a goal for this prototype.

Tier 1 is a very simple interface that will only allow a user to select a course. Tier one doesn’t even necessarily show the course that is being selected. This tier has been inserted to ensure that an interface between the system and the user is usable. This type of GUI will only do the basics but it will do the basics and accomplish the task that is has been sent to do.

Tier 2 is a little more complex than tier 1, but is not yet a production model. Tier 2 involves picking a course from some preselected courses. Once the course has been selected some type of green image will appear on the screen and the user is able to select from a few pre-defined putts which one they want to use. Tier 1 will only allow a user to select a course, and then a single putt will be used for that course. Tier 2 is going to allow the user to select from multiple putts from a given course.

Tier 3 is going to be the goal for production. Tier 3 will be a fully functional GUI with a very simple user interface. Figure 11 shows a mockup of what the tier 3 GUI might look like.

![Mockup of what the tier 3 GUI may look like.](image)

This interface is going to allow the user to select from any course that they desire, or even load a green from a specified green format into the system. After this choice has been selected the program will allow the user to select a pin location on the green, and then from the pin location the user is going to be able to pick a location for the ball to be placed. From these two points the GUI will extrapolate the data from the green and pass the information to the controlling functions. The earlier two tiers did not need to do any data extrapolation because the putting alleys were pre-determined.
For the purpose of this prototype design the goal is going to be to generate something along the lines of the Tier 1 design outlined above. The user experience will not be as exciting, but it will enable the controlling function and the control system to correctly do their jobs, which will enable to product to successfully show a proof of concept.

5.1.2 Controlling Function

The controlling function is the main brain behind the entire system. The most important thing that the controlling function is going to do is to take a matrix of integers representing the actuator positions and handle all communications with the microcontrollers. Once the system is set up, the green will be represented as a single entity outside of the controlling function meaning the details of the communication are seen as a black box to the GUI.

The next important design choice in the controlling function was to develop it so that it will be expandable for future implementation. The current implementation of the reconfigurable putting green will simply have a 6 inch elevation range to vary over. In future implementations of the putting green, the range will want to be increased so as to allow for more greens that are representable.

For the design requirements that have been given, a simple greedy algorithm can be implemented by the controlling function to ensure that all of the actuators are going to be able to arrive at their final state solutions without destroying the surface by entering into an illegal state.

The final use that the controlling function is going to handle is the harmonization of all of the different modules in the system. Each module has its own microcontroller that is going to be telling the actuators to move up and down. Because all of the actuator modules are connected via the surface, they all need to move at the relatively same time so as not to enter into an illegal state and ruin the surface. The controlling function is going to be able to harmonize the steps of the stepper motors so as to ensure that no module is transforming too fast or too slow.

5.1.3 Expandability

The entire software package has been developed in such a way as to encourage future innovation into the market of electronic devices. As has been shown, the controlling function simply needs an array of data from the GUI in order to work. If so desired in future implementations of the design, the GUI and the controlling function do not need to both be contained within the same machine.

The realization that these two systems do not have to be on the same system opens up a whole lot of possible future improvements. One of the most obvious is to put the controlling function into a computer that is connected to the putting green and then have the GUI interface that will communicate with the computer on a smart phone or some tablet PC. The black box design methodology that was used to develop this control system will not depend on the location of the GUI and the control function.
5.2 Microcontroller Interface

Our interface is actually a combination of two separate ideas. Both of these ideas are integrated in order to optimize both speed and expandability. The first of the two ideas is a methodology developed by the design team entitled a rolling buffers algorithm. The second idea is called a final state transmission.

5.2.1 Rolling Buffers

The rolling buffers technique involves three different sections of memory that are constantly interpreted differently as the time goes on. One of the buffers is considered the current state, one is considered the next state, and the final is considered the next-next state. Figure 12 puts a face to this idea.

The current state is the current location of all of the different actuators on a given module. The next state is the state that the microcontroller is going to be moving the actuators to. Thus the microcontroller can determine the enable and direction pins from the difference between the next state and the current state buffers. After the microcontroller has stepped to the next state, we can reinterpret the next state buffer as the new current state buffer, because that has become the current configuration of the actuators on the module.

The next-next state buffer is then assigned to be the next state buffer and the transformation process of the surface begins. While the transformation is happening the controlling function is going to be sending data to the buffer that was the previous current state which is now the next-next state buffer. Once the microcontroller has reached its next goal it can use the buffer that has just recently received new data as the next state buffer to go for its next goal.

The benefit of this solution is that it is very expandable for the future additions to the project that will be added. It allows for the microcontroller to be receiving its next set of instructions while still executing the previous set. This will enable many different types of movements and can actually help with future wow factors that will probably be added to the system.
5.2.2 Final State Transmission

Another design solution that is a potential use to rectify the problem with having to send a different direction and enable signal for every step is to transmit the final state of the actuator array to the microcontroller and then set the direction once and then go on with the transformation. This is portrayed by figure 13.

![Diagram of the concept of final state transmission.](image)

This transformation is very fast, because the intermediate overhead will simply be to disable certain actuators from moving as they reach their final state. This solution is possible due to the greedy algorithm that is going to be implemented as the transformation algorithm.

The negative of the final state solution is that it is not expandable. In future designs for the reconfigurable putting green, the final state transmission is not going to be flexible enough to design for all of the potential needs that are going to be required.

If we combine the two aforementioned algorithms we can achieve all of our goals. The combination of the two algorithms is possible because of the vertical resolution requirement for the putting green. Because we don’t need to be precise down to a single step, we can get the benefits of both solutions to the vertical resolution of the putting green by combining the two solutions into one.

6. Cost Analysis

The original requirement for the cost was to develop two modules within a budget of 5000 dollars. Using this as a guideline the individual components and assemblies were analyzed to meet the requirements and to stay within budget. However, several unexpected expenses developed during the fabrication process and the complete cost came to ______. A full table of costs and components is found in appendix A.

For a larger scale design where a greater change in surface elevation is needed, a means of a ‘rough’ adjustment is needed with added cost to each module. Also lighter weight frame and a more powerful motor could also be designed with an additional increase in overall cost.
7. Progress to date

7.1 Completed

One 4’x4’ module is complete, except for the microcontroller housing, and can be used as an example to complete the other. The second 4’x4’ module has four rows of actuators that have been tested and are installed into the frame. The polypropylene mat has the cup holder installed, along with all of the snap lock rivets.

7.1.1 Frame

The frame is complete with castor wheels on all four corners of the full 8’x4’ prototype and two leveling feet in the middle. A bracing bar was also installed at the intersection of the two modules on the underside of the t-slot to add extra support to the prototype. In the full scale design each corner of each module would have a leveling foot to enable custom installations on any solid surface.
7.1.2 Subsurface

The trampoline subsurface is complete with all 72 snaps installed and ready for attachment to the actuator tops. A pocket has been sewn into the trampoline material to house the cup. The height of the cup in relation to the turf can be adjusted by inserting a spacer in the bottom of the sewn cup holder.

7.1.3 Actuators

The mechanical components of all 72 actuators have been assembled. 60 of the actuators have been tested and installed in the frame.

7.1.4 Microcontrollers, Wiring, and Power Supplies

The power wiring, including the power supplies, has been completely installed into the first module. The control wiring has been routed and attached, with the microcontroller still needing to be mounted. (See wiring details and schematics to wire the second module in drawing package)

7.2 To Be Completed

7.2.1 Actuators

The tasks for the remaining actuators are as follows:

- Attach motor controllers to sheet metal actuator frame and solder motor wires to controller
- Verify smooth operation through full range of motion in both directions, up and down
- Any adjustments to actuators needed to provide smooth operation if necessary
- Installation of the remaining actuators into aluminum T-slot frame rails
- Build sheet metal housings for microcontrollers and attach them to the T-slot frame
- Complete wiring harnesses (power and logic) for second module and route along frame
- Attach power supplies to second module
- Make all electrical connections in motor controllers and the microcontroller on second module
- Ensure all actuators can run the zeroing function correctly
- Attach polypropylene sub layer to actuators and laterally adjust actuators as needed for attachment and uniform surface

7.3 Variations from Initial Design

- Cup is placed in pocket sewn into polypropylene
- Motor controller is attached to actuator frame via double sided foam tape
- Vinyl bump stop placed under motor to prevent binding at startup
- Actuator plate is attached to frame from underneath rather than on top
- T-slot aluminum frame used instead of steel frame
7.4 Further Testing

- Stiffer subsurface options to create smoother surface interpolation when loaded
- Software

7.5 Possible Upgrades

- Upgrade subsurface after 7.4 testing is complete
- Better GUI with more topographical data
- Upgrade wiring harness from solid core wire with crimped butt connectors to multi-stranded wire with soldered and heat shrink tubing connections
- Use separate electrical connectors for power and communication wire
- Fasten motor controller board to the housing, high flex wire
- Custom die for sheet metal housing
- Larger diameter rubber foot assembly

8. Summary

A re-configurable putting green needed to be designed in order to make year round putting available to more people in more places of the world. This was to be done through making a putting green that would be used indoors and be on a smaller scale than an outdoor, full size putting green. But this putting green would still need to be able to replicate many different putting green topographies.

The solution to this problem was conceived using the ideas of linear actuators under a putting green surface in order to raise and lower parts of the green to create the desired topographies. A full-scale putting green of 32’x32’ would need a maximum difference in elevation of up to 30”, however since this design is much smaller scale, only 4’x8’, the range of this prototype is only 6” for each 4’ module length. In the future, in order to achieve a greater range of elevation difference another set of course scissor jack actuators may be added to the design to get the full range needed for a larger and more challenging putting greens. As it is, 6” over the total length of the prototype (8’) is over the maximum elevation difference recommended for a typical putting green and therefore can provide a valid reconfiguration of a section of almost any known putting green in the world.

This design is of a modular construction to enable easy scalability for larger putting greens. Slight adjustments would have to be made on the power requirements of the system if more than a handful of modules are to be combined on a single wall circuit of 110 V. The adjustments to be made would entail either upgrading to a higher voltage wall circuit (220 V) or simply using more than one circuit to power the complete putting green.

The electronic configuration of the putting green is set up for easy scalability. Once the module configuration is set, only a few inputs are needed to set up the controlling function and the putting green is ready for use.
Most of the improvements for future prototypes are in the area of finding cheaper components and cheaper manufacturing techniques. Many of the components were chosen because of their availability in Logan, Utah. Many of these components would be cheaper to buy in bulk and possibly by custom manufacturing a simpler design.

Further study will go on into optimizing the putting surface and the subsurface beneath it. The customer has presented many more options for putting green material as well as subsurface material in the last few weeks. These materials will be tested against the present design and optimizations will be made.

This design meets all of the customers’ requirements and has been designed based on good engineering techniques and procedures. Refer to table 1 on page 6 for all of the requirements and how this design fulfills them.
9. References

[1] World Bank, World Development Indicators


## 10. Appendices

### Appendix A: Component Specifications

### Table of Components and Costs

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**Birdie Ball**

Birdie ball is a Bi-directional dual stimp 5/8” thick synthetic putting green. No technical data about this product was released by the manufacturer, however a sample was obtained and qualitative tests were run on it. For its intended purpose in the project birdieball putting green fulfills its design need.

**Actuator Tops**

The actuator tops chosen are Harbor Freight Tools Central Pneumatic Professional. Item# 99561:
- Shank dimensions: 1-1/4" L x 1/4" diameter
- Overall dimensions: 2-3/8" L x 3-11/16" diameter,
- Shipping weight: 0.25 lbs.

**ACME Threaded Collar**

Part #8931K89 on McMaster.com
Appendix B

Motor

PROFESSIONAL MOTOR ANALYSIS

This file will show some preliminary calculations in derived requirements for the Motor and the Lead Screw. All we have as some basic requirements we are that the surface must be able to support a load of 300lbs per 4 square feet. And that there can be no continuous duty for the motors.

As a starting/preliminary design for the lead screws we have.

Requirements:

1. The combination of the angular speed of the motor and the pitch of the screws must result in being able to move through 6 inches of distance.

Derived Requirements:

1. No-one can stand on the green as it is moving.

With the above stipulations we start with a changeable/configurable starting design.

LEAD SCREW SPECS.
We will start in english units and convert to metric

Major Diameter:
\[ D_{maj} = \text{.75in} = 0.01905 \text{ m} \]

Pitch:
\[ P = \text{.1in} = 2.54 \times 10^{-3} \text{ m} \quad \text{Pitch has units of (inches/revolution)} \]

Mean Diameter:
\[ D_{mean} = D_{maj} - \frac{P}{2} = 0.01778 \text{ m} \]

Minor Diameter:
\[ D_{min} = D_{maj} - P = 0.01651 \text{ m} \]

Number of leads:
\[ n = 1 \]

Friction coefficient of Screw on Nut:
\[ f = .08 \]
Screw Lead:

\[ L_{\text{lead}} = n \cdot P = 2.54 \times 10^{-3} \text{ m} \]

This measurement tells us what distance we will move when a single turn is completed.

Collar Specs:

Friction Coefficient:

\[ f_c = 0.0 \]

Collar Diameter:

\[ D_{\text{coll}} = 3 \text{ in} = 0.0762 \text{ m} \]

Now we Derive our Torque Requirements.

The Maximum Force that can be placed on the surface above the actuator during movement.

Now we need to find the spring-constant for the surface. We will have a square array of actuators with the minimal spacing between each actuator equal to 6 inches. Such that one actuator will have a north, south, east, west companion, along with for diagonal companions.

So we need to find the combined strength of 8 implied springs attached to one actuator. We do this with the following:

\[ M_{\text{ind}} = 6 \text{ in} = 0.1524 \text{ m} \]

\[ M_{\text{max}} = \sqrt{36 + 36} \text{ in} = 0.2155261 \text{ m} \]

The Max slope throughout the "green" is:

\[ \frac{\frac{5}{8} \text{ in}}{6 \text{ in}} = 0.1041667 \]

This gives a max angle of:

\[ \text{atan}(M_{\text{slope}}) = 0.1037923 \]

Which is:

\[ \theta = \frac{\text{atan}(M_{\text{slope}}) \cdot 180}{\pi} = 5.9468631 \text{ Degrees} \]
Here we must assume that the surface has some sort of spring constant associated with stretching it. We assume:

\[ k_{\text{surf}} := 210000 \frac{N}{m} \]

Now we solve for the force of the 8 connected springs. With the derived design requirement that each actuator has to move 6 inches.

\[ \text{delnormhyp} = \sqrt{6^2 + \left(\frac{5}{8}\right)^2} \text{ in} = 0.1532246 \text{ m} \quad \text{This is the length from one actuator head to another for the North south east and west "springs"} \]

\[ \text{delnorm} := \text{delnormhyp} - 6\text{in} = 8.245921 \times 10^{-4} \text{ m} \quad \text{This is the distance that the "spring" is stretched.} \]

We assume the slope is constant throughout the green.

\[ \text{deldiaghyp} := \sqrt{\text{Maxd}^2 + \left(\tan(\text{atan(Mxslope)}) \cdot \text{Maxd}\right)^2} = 0.2166923 \text{ m} \quad \text{Length from actuator head to actuator head for diagonal components.} \]

\[ \text{deldiag} := \text{deldiaghyp} - \text{Maxd} = 1.1661493 \times 10^{-3} \text{ m} \quad \text{Diagonal component of stretch length} \]

\[ \text{Forcenorm} := \left[4 \cdot (k_{\text{surf}} \cdot \text{deldiag}) + 4 \cdot (k_{\text{surf}} \cdot \text{delnorm})\right] \cdot \sin(\text{atan(Mxslope)}) = 173.2524571 \text{ N} \]

Thus we find the force that the Torque motor must "push up".

\[ F_{\text{conv}} := \text{Forcenorm} \]

Torque needed to raise the load:

\[ T_{\text{raise}} := \frac{F_{\text{conv}} \cdot \text{Dmean}}{2} \cdot \left( \frac{\text{Lead} + \pi \cdot f \cdot \text{Dmean}}{\pi \text{Dmean} \cdot f \cdot \text{Lead}} \right) + \frac{F_{\text{conv}} \cdot \text{Dcoll}}{2} = 0.1939607 \text{ N.m} \]

Torque needed to lower the load:

\[ T_{\text{lower}} := \frac{F_{\text{conv}} \cdot \text{Dmean}}{2} \cdot \left( \frac{\pi \cdot f \cdot \text{Dmean} - \text{Lead}}{\pi \text{Dmean} + f \cdot \text{Lead}} \right) + \frac{F_{\text{conv}} \cdot \text{Dcoll}}{2} = 0.0529865 \text{ N.m} \]
MOTOR, TORQUE AND SURFACE CONCLUSIONS.

With the above program we can input any surface spring constant and thereby find the required torque to raise and lower the loads respectively.

Torque ratings of motors TBD.

The stepper motor’s holding torque is:

\[ T_{hm} = 3.17 \text{kg cm g} = 0.3108708 \text{ N m} \]

The associated Torque curve for the motor is:

![Torque Curve Graph](image)

Where pps is pulses per second which translates into 1.8 degree steps per second. From which it can be shown that when we have an RPM range between (160 RPM to 750 RPM) we will have a minimum pull-out torque of

\[ T_{po} = 2 \text{ kg cm g} = 0.196133 \text{ N m} \]
Heat Calculations

The motor has a temperature operating range of -20 degrees C to 50 degrees C. And the Motor has a max operating temperature of 80 degrees C.

We start with the givens for the heat calculation.

\[ \text{Amps} = 1.2A \quad \text{These are the power specs for the motor} \]
\[ \text{Volts} = 4V \]
\[ \text{Watts} = \text{Amps} \times \text{Volts} = 4.8 \text{W} \]

\[ \text{Lm1} = 42.3\text{mm} = 0.0423 \text{m} \quad \text{These are the dimensions of the motor given by length,} \]
\[ \text{Wm1} = 42.3\text{mm} = 0.0423 \text{m} \quad \text{height, and width.} \]
\[ \text{Hm1} = 48\text{mm} = 0.048 \text{m} \]

\[ \text{Area} = 2 \left( \text{Lm1}^2 \right) + 4 \times (\text{Wm1} \times \text{Hm1}) = 0.0117002 \text{m}^2 \quad \text{This is the total surface area of the} \]
\[ \text{motor that will be exposed to the flow.} \]

Here we make a worst case scenario assumption that 99% of the power going to the motor is producing heat.

\[ \text{Meff} = .01 \]

\[ \text{qmotor} = \text{Watts} \times (1 - \text{Meff}) = 4.752 \text{ W} \]

Again we assume a worst case scenario and say that the ambient air temperature is 50 degrees C.

\[ \text{Tinfin} = 50 \text{°C} = 122.2 \text{°F} \]

\[ \text{hfin} = 38.45 \frac{\text{W}}{\text{m}^2 \cdot \text{K}} \quad \text{Finally we provide a value for the convection coefficient} \]
\[ \text{to see what the surface temperature will be at steady state} \]
\[ \text{conditions.} \]

\[ \text{Ts} = \text{Tinfin} + \frac{\text{qmotor}}{\text{hfin} \times \text{Area}} = 60.5630064 \text{°C} \quad \text{As this is a program it is not shown, but} \]
\[ \text{the surface temperature is found to exceed} \]
\[ \text{80 degrees C if the convection coefficient is} \]
\[ \text{below 18 W/(m²°K)} \text{so we now need to find} \]
\[ \text{the convection coefficient.} \]
The assumption here is that since free convection is not enough to keep the motor within its operating range we need to put a fan in to create forced convection.

Here is an input program to compute the convection coefficient

Air properties for 50 degrees C

\[ v_1 = 17 \cdot 10^{-6} \text{ m}^2 / \text{s} \quad \text{Kinematic viscosity} \]

\[ Pr = .711 \quad \text{Prandtl Number} \]

\[ k_{air} = .0272 \frac{W}{(\text{m K})} \quad \text{Heat Conductivity} \]

We found a simple 6 inch diameter fan that can pump 240 cfm.

\[
240 \text{cfm} = 0.1132674 \frac{\text{m}^3}{\text{s}} \quad \frac{240 \text{cfm}}{\pi (6 \text{in})^2 / 4} = 6.2093346 \frac{\text{m}}{\text{s}}
\]

\[ V_{air} = 6 \frac{\text{m}}{\text{s}} \quad \text{This is the velocity of the air produced by the fan} \]

From Incropera and Dewitt "Fundamentals of heat and mass transfer" we use the Hilpert correlation to find the average Nusselt Number with shaper factors for flow parallel with 2 sides of the motor.

We first find the Reynolds number.

\[ D_{motor} = L_{motor} = 0.0423 \text{ m} \]

\[ Re_{motor} = \frac{V_{air} D_{motor}}{v_1} = 1.4929412 \times 10^4 \]

The respective constants are

\[ C_1 = 102 \quad m_1 = .675 \]

The average Nusselt Number is

\[ Nu_{ave} = C_1 Re_{motor}^{m_1} Pr^{1/3} = 59.8001388 \]

From which we find our \( h \) value to use which leaves us in the clear to keep the motors on all of the time.

\[ h_{air} = \frac{Nu_{ave} k_{air}}{L_{motor}} = 38.4530443 \frac{1}{\text{m}^2 \text{K}} \]
Steel Plate

Analysis of the Steel Plate

Question: We are wanting the steel plate to hold 300 lbf for a 2ft x 1ft square. Assume that the plate is fixed at all sides. Determine the thickness the steel plate needs to be in order to not deflect.

Properties of Steel:

<table>
<thead>
<tr>
<th>Carbon Steel</th>
<th>Alloy Steel</th>
<th>Max Properties</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\rho_1 := 7.851,000,\frac{kg}{m^3}$</td>
<td>$\rho_2 := 7.851,000,\frac{kg}{m^3}$</td>
<td>$\rho_{max} := 7.851,000,\frac{kg}{m^3}$</td>
</tr>
<tr>
<td>$E_1 := 190,000,Pa$</td>
<td>$E_2 := 190,000,Pa$</td>
<td>$E_{max} := 210,000,Pa$</td>
</tr>
<tr>
<td>$\nu_1 := 0.27$</td>
<td>$\nu_2 := 0.27$</td>
<td>$\nu_{max} := 0.30$</td>
</tr>
</tbody>
</table>

Dimensions: dimensions of the steel plate component with structural supports

$L_x := 14\,\text{in}$  \hspace{1cm} $L_y := 4\,\text{ft}$  \hspace{1cm} Area := $L_x L_y = 0.43355\,\text{m}^2$

Varying thickness

$t := \frac{1}{4}$

Factor to multiply 300 lbf by to account for different area.

$f := \frac{Area}{2t^2} = 2.3333$

Force applied to each module: Person standing plus a safety factor of 2

Weight := 300 lbf  \hspace{1cm} SF := 2  \hspace{1cm} Force := SF\cdot Weight = 1400 lbf

Load applied to each steel plate:

Load := $\frac{Force}{Area} = 14.364\,08\,kPa$

Bending Stiffness:

$D_1 := \frac{2t^3\cdot E_1}{3\left(1 - \nu_1^2\right)} = 34982.99\,087\,kN\cdot m^2$  \hspace{1cm} $D_2 := \frac{2t^3\cdot E_2}{3\left(1 - \nu_2^2\right)} = 34982.99\,087\,kN\cdot m^2$  \hspace{1cm} $D_{max} := \frac{2t^3\cdot E_{max}}{3\left(1 - \nu_{max}^2\right)} = 39391.98\,07\,kN\cdot m^2$

Max displacement will occur at the center of the plate

$x := \frac{L_x}{2} = 0.1778\,\text{m}$  \hspace{1cm} $y := \frac{L_y}{2} = 0.6096\,\text{m}$

Calculate the displacements

$n := 1, 3, 9$  \hspace{1cm} $\Delta := 1, 3, 9$
\[
\begin{align*}
\text{w1}(x,y) &= \sum_{m} \sum_{n} \frac{16 \cdot \text{Load}}{(2m-1)(2n-1) \pi^6 \cdot D1} \left[ \frac{(2m-1)^2 + (2n-1)^2}{L_y^2} \right]^{-2} \cdot \sin \left[ \frac{(2m-1) \pi \cdot x}{L_x} \right] \cdot \sin \left[ \frac{(2n-1) \pi \cdot y}{L_y} \right] \\
\text{w2}(x,y) &= \sum_{m} \sum_{n} \frac{16 \cdot \text{Load}}{(2m-1)(2n-1) \pi^6 \cdot D2} \left[ \frac{(2m-1)^2 + (2n-1)^2}{L_y^2} \right]^{-2} \cdot \sin \left[ \frac{(2m-1) \pi \cdot x}{L_x} \right] \cdot \sin \left[ \frac{(2n-1) \pi \cdot y}{L_y} \right] \\
\text{wmax}(x,y) &= \sum_{m} \sum_{n} \frac{16 \cdot \text{Load}}{(2m-1)(2n-1) \pi^6 \cdot D\text{max}} \left[ \frac{(2m-1)^2 + (2n-1)^2}{L_y^2} \right]^{-2} \cdot \sin \left[ \frac{(2m-1) \pi \cdot x}{L_x} \right] \cdot \sin \left[ \frac{(2n-1) \pi \cdot y}{L_y} \right] \\
\text{w1}(x,y) &= 0.00375\text{-in} \quad \text{w2}(x,y) = 0.00375\text{-in} \quad \text{wmax}(x,y) = 0.00333\text{-in}
\end{align*}
\]

Resolution of the green
\[ \text{res} := \frac{1}{4} \text{in} \]

Safety Factor of resolution and deflection
\[ \text{Safe1} := \frac{\text{res}}{\text{w1}(x,y)} = 66.61153 \]
\[ \text{Safe2} := \frac{\text{res}}{\text{w2}(x,y)} = 66.61153 \]
\[ \text{Safe}\text{max} := \frac{\text{res}}{\text{wmax}(x,y)} = 75.00674 \]
Power Analysis

Amperage draw per motor:

\( a_{\text{motor}} = 1.2 \text{amp} \)

Voltage for Motor:

\( V_{\text{motor}} = 4 \text{V} \)

Watts for Motor:

\( W_{\text{motor}} = a_{\text{motor}} V_{\text{motor}} = 4.8 \text{W} \)

Number of Motors per Module:

8” Spacing: \( n = 6 \times 6 = 36 \)

Module power draw due to Motors:

\( W_{\text{motors}} = W_{\text{motor}} n = 172.8 \text{W} \)

Brand: Cooler master
Model: RS-460-PSAR-J3
Series: Elite 460
ATX12V 2.31 460W

\( V_{\text{input}} = 120 \text{V} \quad A_{\text{input}} = 8.5 \text{amp} \)

\( W_{\text{input}} = V_{\text{input}} A_{\text{input}} = 1020 \text{W} \)

Power Availability for 12V devices:

\( V_{12\text{Vout}} = 12 \text{V} \quad A_{12\text{Vout}} = 20 \text{A} \)

\( W_{12\text{Vout}} = V_{12\text{Vout}} A_{12\text{Vout}} = 432 \text{W} \)

Power Availability for 5V controllers:

\( V_{5\text{Vout}} = 5 \text{V} \quad A_{5\text{Vout}} = 20 \text{A} \)

\( W_{5\text{Vout}} = V_{5\text{Vout}} A_{5\text{Vout}} = 100 \text{W} \)

Power Availability for 3.3V controllers:

\( V_{3.3\text{Vout}} = 3.3 \text{V} \quad A_{3.3\text{Vout}} = 20 \text{A} \)

\( W_{3.3\text{Vout}} = V_{3.3\text{Vout}} A_{3.3\text{Vout}} = 65 \text{W} \)

Inrush Power:

\( \text{Inrush} := W_{\text{motors}}^2 = 245.6 \text{W} \)

\( n := \frac{W_{12\text{Vout}}}{\text{Inrush}} = 1.25 \)
Appendix C: Tables, Graphs, Etc.

Maximum Slope Chart

![Maximum Slope Chart](image)

Figure 1. It is important to understand the direct relationship between green speed and putting green slope. As green speeds increase, the potential for uncontrollable slopes also increases.

Figure 12: Graph taken from “Putting Green Speeds, Slopes, and “Non-Conforming” Hole Locations” by Jerry Lemons.

Table of Steel Plate Deflection

<table>
<thead>
<tr>
<th>Thickness (in)</th>
<th>Carbon Steel</th>
<th>Alloy Steel</th>
<th>Steel</th>
</tr>
</thead>
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<td>1/16</td>
<td>0.2402</td>
<td>0.2402</td>
<td>0.21331</td>
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<tr>
<td>1/8</td>
<td>0.03002</td>
<td>0.03002</td>
<td>0.02666</td>
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<td>3/16</td>
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NOTES:
1. UNLESS OTHERWISE SPECIFIED, ASSEMBLE USING STANDARD HARDWARE AS PER COMMON SHOP PRACTICES.

DIMENSIONS ARE IN INCHES
DIMENSIONING AND TOLERANCING
PER ASME Y14.5M-1994 TOLERANCE UNLESS SPECIFIED.
.X = .05
.XX = .01
.XXX = .005
.XXXXX = .0005

ANGLES = .05

SURFACE ROUGHNESS
BREAK SHARP EDGES .010-.020

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REVISIONS
REV. ZONE DESCRIPTION DATE APPROVED
A INITIAL RELEASE 4/18/2012 N SHAW
B REMOVED ITEMS 4/18/2012 N SHAW

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CHECKED PARTS LIST

PUTTING SURFACE 1
D-002

D-001

ASSY, RECONFIGURABLE
PUTTING GREEN

ASSY, MODULE
D-001

ASSY, PUTTING SURFACE
D-002

ELECTRICAL, MAIN
D-022

PLATE, SUPPORT
D-028

CARRIAGE BOLT, 1/2-13
P3604A725

D-001

D-002

D-028

P3604A725

3D MODEL RECREATION

ROUTE FOR Wiring HARNESS
NOTES:
1. UNLESS OTHERWISE SPECIFIED, ASSEMBLE USING STANDARD HARDWARE AS PER COMMON SHOP PRACTICES.
NOTES:
1. UNLESS OTHERWISE SPECIFIED, ASSEMBLE USING STANDARD HARDWARE AS PER COMMON SHOP PRACTICES.
NOTES:
1. MATL: 1018/1020 STEEL
2. FINISH: BLACK ZINC
3. BREAK CORNERS AND DEBURR

DIMENSIONS ARE IN INCHES
DIMENSIONING AND TOLERANCING PER ASME Y14.5M-1994
TOLERANCE UNLESS SPECIFIED
X = .05
XX = .01
XXX = .005
XXXX = .0005
ANGLES = .5
SURFACE ROUGHNESS: (SEMISMOOTH) 125
BREGA SHARP EDGES (.010-.020)
ALL DROOP FILLETS (.05)

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A INITIAL RELEASE N SHAW
B CHANGED OVERALL DIMS 4/14/2012 N SHAW

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DESCRIPTION
CHECKED
PARTS LIST
ALL SMALL FILLETS .020-.040
DISCLOSED HERIN OR HEREWITH

THIRD ANGLE PROJECTION
SHT 1 OF 1
SCALE
ENGINEER
DRAWN
DATESIGNATURES

PLATE, MOUNT

NOTES:
2. FINISH: BLACK ZINC
3. BREAK CORNERS AND DEBURR

DIMENSIONS ARE IN INCHES
DIMENSIONING AND TOLERANCING PER ASME Y14.5M-1994
TOLERANCE UNLESS SPECIFIED
X = .05
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XXX = .005
XXXX = .0005
ANGLES = .5
SURFACE ROUGHNESS: (SEMISMOOTH) 125
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SHT 1 OF 1
SCALE
ENGINEER
DRAWN
DATESIGNATURES

PLATE, MOUNT

NOTES:
2. FINISH: BLACK ZINC
3. BREAK CORNERS AND DEBURR

DIMENSIONS ARE IN INCHES
DIMENSIONING AND TOLERANCING PER ASME Y14.5M-1994
TOLERANCE UNLESS SPECIFIED
X = .05
XX = .01
XXX = .005
XXXX = .0005
ANGLES = .5
SURFACE ROUGHNESS: (SEMISMOOTH) 125
BREGA SHARP EDGES (.010-.020)
ALL DROOP FILLETS (.05)

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THIRD ANGLE PROJECTION
SHT 1 OF 1
SCALE
ENGINEER
DRAWN
DATESIGNATURES

PLATE, MOUNT

NOTES:
2. FINISH: BLACK ZINC
3. BREAK CORNERS AND DEBURR

DIMENSIONS ARE IN INCHES
DIMENSIONING AND TOLERANCING PER ASME Y14.5M-1994
TOLERANCE UNLESS SPECIFIED
X = .05
XX = .01
XXX = .005
XXXX = .0005
ANGLES = .5
SURFACE ROUGHNESS: (SEMISMOOTH) 125
BREGA SHARP EDGES (.010-.020)
ALL DROOP FILLETS (.05)

REV. ZONE DESCRIPTION DATE APPROVED
A INITIAL RELEASE N SHAW
B CHANGED OVERALL DIMS 4/14/2012 N SHAW

PARTS LIST

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DESCRIPTION
CHECKED
PARTS LIST
ALL SMALL FILLETS .020-.040
DISCLOSED HERIN OR HEREWITH

THIRD ANGLE PROJECTION
SHT 1 OF 1
SCALE
ENGINEER
DRAWN
DATESIGNATURES

PLATE, MOUNT

NOTES:
2. FINISH: BLACK ZINC
3. BREAK CORNERS AND DEBURR

DIMENSIONS ARE IN INCHES
DIMENSIONING AND TOLERANCING PER ASME Y14.5M-1994
TOLERANCE UNLESS SPECIFIED
X = .05
XX = .01
XXX = .005
XXXX = .0005
ANGLES = .5
SURFACE ROUGHNESS: (SEMISMOOTH) 125
BREGA SHARP EDGES (.010-.020)
ALL DROOP FILLETS (.05)
NOTES:
1. MATE: 6000 SERIES ALUMINUM
2. FINISH: NATURAL
3. BREAK CORNERS AND DEBURR
4. DIMENSIONS SHOWN IN [ ] ARE METRIC.

DIMENSIONS ARE IN INCHES
DIMENSIONING AND TOLERANCING PER ASME Y14.5M-1994
TOLERANCE UNLESS SPECIFIED:
X = .05
XX = .01
XXX = .005
ANGLES = .5

SURFACE ROUGHNESS
BREAK SHARP EDGES

A 87 6 5
B 43 2
C
D

875
4X .134
4X R .13

0.250 THRU ALL
P.F. FOR 1/4" DOWEL PIN

12/10/2011
N SHAW

A INITIAL RELEASE N SHAW
B REMOVED NEEDED HOLES 4/14/2012 N SHAW

REVISIONS
REV. ZONE DESCRIPTION DATE APPROVED
A N SHAW
B N SHAW

PARTS LIST

PLAN, SCALE 4:1

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C D-006 B

3D THIRD ANGLE PROJECTION

SHFT 1 OF 1

12/10/2011
N SHAW

PARTS LIST

PLATE, MOTOR

N SHAW

DERON LLC.

CHECKED

SIGNATURES

PARTS LIST

ENGINEER

DRAWN

DATE

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NOTES:
1. MATE: 6000 SERIES ALUMINUM
2. FINISH: NATURAL
3. BREAK CORNERS AND DEBURR
4. DIMENSIONS SHOWN IN [ ] ARE METRIC.

DIMENSIONS ARE IN INCHES
DIMENSIONING AND TOLERANCING PER ASME Y14.5M-1994
TOLERANCE UNLESS SPECIFIED:
X = .05
XX = .01
XXX = .005
ANGLES = .5

SURFACE ROUGHNESS
BREAK SHARP EDGES

A 87 6 5
B 43 2
C
D

875
4X .134
4X R .13

0.250 THRU ALL
P.F. FOR 1/4" DOWEL PIN

12/10/2011
N SHAW

A INITIAL RELEASE N SHAW
B REMOVED NEEDED HOLES 4/14/2012 N SHAW

REVISIONS
REV. ZONE DESCRIPTION DATE APPROVED
A N SHAW
B N SHAW

PARTS LIST

PLAN, SCALE 4:1

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C D-006 B

3D THIRD ANGLE PROJECTION

SHFT 1 OF 1

12/10/2011
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NOTES:
1. MATL: STEEL
2. FINISH: BLACK ZINC (AFTER BENDS)
3. BREAK CORNERS AND DEBURR

REV. ZONE DESCRIPTION DATE APPROVED
A INITIAL RELEASE N SHAW
B ADDED FINISH 4/14/2012 N SHAW

DIMENSIONS ARE IN INCHES
DIMENSIONING AND TOLERANCING PER ASME Y14.5M-1994
TOLERANCE UNLESS SPECIFIED.
X = .05
XX = .01
XXX = .005
ANGLES = .5
SURFACE ROUGHNESS
BREAK SHARP EDGES .010-.020
PLATE, GUIDE

REVISIONS
 REV. ZONE DESCRIPTION DATE APPROVED
  A INITIAL RELEASE N SHAW
  B ADDED FINISH 4/14/2012 N SHAW

NOTES:
REVISIONS
REV. ZONE DESCRIPTION DATE APPROVED
A INITIAL RELEASE N SHAW
B ADDED FINISH 4/14/2012 N SHAW

1. MATL: STEEL
2. FINISH: BLACK ZINC (AFTER BENDS)
3. BREAK CORNERS AND DEBURR

REV. ZONE DESCRIPTION DATE APPROVED
A INITIAL RELEASE N SHAW
B ADDED FINISH 4/14/2012 N SHAW

DIMENSIONS ARE IN INCHES
DIMENSIONING AND TOLERANCING PER ASME Y14.5M-1994
TOLERANCE UNLESS SPECIFIED.
X = .05
XX = .01
XXX = .005
ANGLES = .5
SURFACE ROUGHNESS
BREAK SHARP EDGES .010-.020
PLATE, GUIDE
NOTES:
1. MTL: POLYESTER ROD [MCMASTER CARR #8598K15]
2. FINISH: NATURAL
3. BREAK CORNERS AND DEBURR

DIMENSIONS ARE IN INCHES
DIMENSIONING AND TOLERANCING PER ASME Y14.5M-1994
TOLERANCES UNLESS SPECIFIED:
X = .05
XX = .01
XXX = .005
ANGLES = 0.5
SURFACE ROUGHNESS
BREAK SHARP EDGES .010-.020

NOTES:
2. FINISH: NATURAL
1. MTL: POLYESTER ROD [MCMASTER CARR #8598K15]
NOTES:
1. MATL: 3/4-10 ACME THREADED ROD
2. FINISH: NATURAL
3. BREAK CORNERS AND DEBURR
4. DIMENSIONS SHOWN IN [ ] ARE METRIC.

DIMENSIONS ARE IN INCHES
DIMENSIONING AND TOLERANCING PER ASME Y14.5M-1994 TOLERANCE UNLESS SPECIFIED.

- X = .05
- XX = .01
- XXX = .005
- XXXX = .0005
- ANGLES = 0.5
- SURFACE ROUGHNESS
- BREAK SHARP EDGES .010-.020

ACME, ADJUST

PARTS LIST

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(260) 489-8100
www.deronllc.com

ACME, ADJUST

SHT 1 OF 1
SCALE 4:1
SHIFT 0-0
1. Dimensions and tolerances apply after welding.

### NOTES

- Dimensions and tolerances apply after welding.
- "DIMENSIONS ARE IN INCHES. DIMENSIONING AND TOLERANCING PER ASME Y14.5M-1994. TOLERANCE UNLESS SPECIFIED." 
  - X = .05
  - XX = .01
  - XXX = .005
  - XXXX = .0005
  - ANGLES = 0.5°
  - SURFACE ROUGHNESS = 3.2

### PARTS LIST

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<td>6061-T6</td>
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<td>4</td>
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<td>21.25</td>
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### SIGNATURES

- Initial release: N Shaw
- Date: 3/17/2012

### DRAWING NUMBERS

- 125

### SCALE

- 1:6

### APPROVED

- N Shaw (3/17/2012)
NOTES:

1. MATERIALS: PLASTIC CARDBOARD, TRANSLUCENT
2. FINISH: NATURAL
3. BAG AND/OR TAG. PART APPLY PART NUMBER WITH DASH NUMBER AND REVISION LETTER NEATLY AND LEGIBLY USING .12 HIGH CHARACTERS BY PRINTING IN PERMANENT INK ON TAG. (EXAMPLE: 04XXXXX-01 REV A)

DIMENSIONS ARE IN INCHES
DIMENSIONING AND TOLERANCING PER ASME Y14.5M-1994
TOLERANCE UNLESS SPECIFIED
X = .05
XX = .01
XXX = .005
XXXX = .0005
ANGLES = .5
SURFACE FINISH: 320
ROUND SHARP EDGES .010-.020
ALL SURFACES POLISHED .0005

REVISIONS

REV. ZONE DESCRIPTION DATE APPROVED
A INITIAL RELEASE 12/10/2011 N SHAW

PARTS LIST

SIGNATURES DATE
N SHAW 12/10/2011
N SHAW 12/10/2011
N SHAW 12/10/2011

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1. UNLESS OTHERWISE SPECIFIED, ASSEMBLE USING STANDARD HARDWARE AS PER COMMON SHOP PRACTICES.

NOTES:

SUPPLIED CUP

DIMENSIONS ARE IN INCHES

DIAMETER

DIMENSIONING AND TOLERANCING

PER ASME Y14.5M-1994

TOLERANCE UNLESS SPECIFIED

.X = 0.05

.XX = 0.01

.XXX = 0.005

.XXXXX = 0.0005

ANGLES = 0.5

SURFACE ROUGHNESS = .015

BREAK SHARP EDGES (0.010-.020)

ALL EXTERNAL THREADS (0.010-.020)

CHECKED

DRAWN

ENGINEER

DATE

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REV. ZONE DESCRIPTION DATE APPROVED

A INITIAL RELEASE 12/10/2011 N SHAW

B REMOVED ITEMS 4/17/2012 N SHAW

PART NUMBER DESCRIPTION MANUFACTURER QTY.

D-017 SURFACE, PUTTING 1

D-018 SURFACE, SUPPORT 2

93-KN-10224-1U SNAP, UPPER DOT FASTENERS 72

93-NS-10412-1U SNAP, BACKING DOT FASTENERS 72
NOTES:
1. MATL: TRAMPOLINE FABRIC
2. FINISH: NATURAL

REVISIONS
REV. ZONE DESCRIPTION DATE APPROVED
A INITIAL RELEASE 12/10/2011 N SHAW
B NEW DIMENSIONS 4/14/2012 N SHAW

DIMENSIONS ARE IN INCHES
DIMENSIONING AND TOLERANCING PER ASME Y14.5M-1994 TOLERANCE UNLESS SPECIFIED
X = .05
XX = .01
XXX = .005
XXXX = .0005
ANGLES = .5

FIT TO CUP HOLDER
1. All wires are AWG 30 unless otherwise stated.

Notes:

Revisions

<table>
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<td>4/18/2012</td>
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All small fillets .020-.040

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Dimensions are in inches

Dimensioning and tolerancing per ASME Y14.5M-1994

Tolerance unless specified:

X = .05
XXX = .005
XXX = .0005

Angles = 0.5

Surface roughness 

Break sharp edges .010-.020

Electrical, main
NOTES:
1. ALL WIRES ARE AWG 30 UNLESS OTHERWISE STATED

REVISIONS

REV. ZONE DESCRIPTION DATE APPROVED
A INITIAL RELEASE N SHAW

PARTS LIST

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DIMENSIONS ARE IN INCHES
DIMENSIONING AND TOLERANCING PER ASME Y14.5M-1994
TOLERANCE UNLESS SPECIFIED.

REFERENCES:
X = .05
XX = .01
XXX = .005
XXXX = .0005

ANGLES = .5

SURFACE ROUGHNESS
BREAK SHARP EDGES .010-.020

MEMANDADDR

3D MEMANDADDR D-023 A

SCALE 1/2 SHI 1 OF 1
NOTES:
1. ALL WIRES ARE AWG 30 UNLESS OTHERWISE STATED.
NOTES:
1. MATL: 1018/1020
2. FINISH: PAINT BLACK.
3. BAG AND/OR TAG PART, APPLY PART NUMBER WITH DASH NUMBER AND REVISION LETTER NEARLY AND LEGIBLY USING .12 HIGH CHARACTERS BY PRINTING IN PERMANENT INK ON TAG. (EXAMPLE: 04XXXXX-01 REV A)

DIMENSIONS ARE IN INCHES
DIMENSIONING AND TOLERANCING PER ASME Y14.5M-1994
TOLERANCE UNLESS SPECIFIED
X = .05
XX = .01
XXX = .005
XXXX = .0005
ANGLES = 0.5
SURFACE ROUGHNESS = 6.3
BREAK SHARP EDGES .010-.020

REVISIONS
REV. ZONE DESCRIPTION DATE APPROVED
A INITIAL RELEASE N SHAW

PARTS LIST

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PLATE, SUPPORT

N SHAW
12/10/2011
N SHAW
12/10/2011
N SHAW
12/10/2011

4X THRU 1/2-13 UNC THRU .332
4X .25 45° X .25 STK

25.0 X 45°
1/2-13 UNC THR
.252 THR
.750
1.000
2.000
3.000
5.000
6.000

D-028
3
2
1

D-028
A
1
2
3
4
5
6
7
8

1:1

SHT 1 OF 1
SCALE 2:1
SHIFT 1 OF 1
NOTES:

1. Bend inward along all dotted lines to make the "case", the two holes at the bottom are used to mount the micro-controller assembly to the case. The four holes above those are used to mount the case to the T-frame.
Reconfigurable Putting Green

Purpose of Design
Golfing has been a great attraction all over the world for several decades. But in places where space is limited or harsh weather limits the time frame where getting out on the green is feasible, year round golfing becomes very difficult. And as every golfer knows, it is much easier to stay in practice than to rediscover lost technique. For this reason the idea arose to design a re-configurable putting green: a putting green that can take on the topography of any desired green. This would do away with the need for several different putting greens in order to practice on different levels of difficulty and new terrain. It would also make it possible to putt indoors in much smaller spaces making the opportunity to hone in that world class putt available to more people in more places.

Design Requirements
The requirements for this design are based around the customers need for a demo prototype of a reconfigurable putting green that he can take around and show potential investors and customers to gain support for further product development. There are 5 basic requirements given by the customer:

- Realistic putting surface: The green must be an accurate and realistic representation of a putting green and must be able to support a person standing on top in order to facilitate a realistic putting scenario.
- Transformation time: Transformation time must be reasonable. Requirement was set to a transformation time of less than 30 seconds. This requirement does not apply to a power reset.
- Power source: Each module must be able to plug into a normal wall outlet.
- Laptop controlled: The putting green must be controlled by a common device. Laptop controlled was deemed adequate by the customer and was set to be the formal requirement.
- Maintenance: A 6 month maintenance cycle was requested by the customer.

Design Specifications
- This design presents a 4’x8’ section made of two 4’x4’ modules. Because of the size reduction of the putting green, the topographical range will only need to be 6” across the module width of 4’.
- The design uses an array of linear actuators to create the topography. The actuators are mounted in the vertical direction and are used to control the surface in a square matrix pattern. Each module contains a 6x6 array of actuators with 8 inch spacing between the centers of each actuator. Each of the linear actuators has a vertical range of 6”. The actuators are attached to a subsurface to carry the loads between the actuators and to create a uniform surface. The primary purpose of the subsurface is to create a smoothly contoured putting surface that simulates the smooth curves of a putting green. Attached to the subsurface is an artificial turf that creates a seamlessly realistic representation of a putting green and must be able to support a person standing on top.
- Each module is controlled by a microcontroller. The microcontroller dictates the steps for all the stepper motors on the module. Power to the stepper motors is supplied by a computer power supply that runs on a standard 110 volt AC circuit. However, a 220 volt AC circuit can be used for larger module arrays.
- Each actuator contains a 6x6 array of actuators with 8 inch spacing between the centers of each actuator. Each of the linear actuators give precise control over the resolution of the putting surface. The microcontrollers are governed by a computers controlling function which dictate the steps of the motors. Power to the stepper motors is supplied by a computer power supply that runs on a standard 110 volt AC circuit. However, a 220 volt AC circuit can be used for larger module arrays.
- Each 4’x4’ module is self-contained and can be easily moved via castor wheels mounted on the base of each module. Each module has a connection to the computer through USB.

Performance Data and Test Results
Surface granularity
- The actuator spacing of 8” was determined for the following reasons: cost, spatial clearance and size of motors. Future testing will include testing actuator spacing effects on putting realism by having Dan and Jeff putt on the surface and determine how realistic it is and if the actuator spacing is acceptable. When locked will support 300 lbs per 4 square feet
- Initial hand calculations from MAE 4800 stated actuators would hold weight. We have had multiple team members (150 lbs.-200 lbs.) individually stand and walk upon the prototype with no failure in the actuators.
- Total transformation time of 30 seconds between topographies
  - Each individual actuator has been tested and is capable of going through its full range of travel in 25-26 seconds. The controlling function in theory should not increase this transformation time by more than a few milliseconds.
  - The sub-surface has passed some initial testing; however, some adjustments will need to be made to actuator spacing in order to tighten up gaps. The trampoline material marginally meets the requirements. A better sub-surface or composite assembly should be researched in order to better hold the weight of a putter. More testing to be done with actual green topographies.
  - Subsurface is connected by snaps which are epoxied into the rubber sanding foot. Testing was done in order to deem the epoxy worthy. Epoxy withstood a medium torque and a significant tensile load indicating a more than adequate bond strength for the small loads expected. The snap will unnap before the epoxy fails. Durability should be good, but only time will tell.

Results
Performance data indicates putting surface is ready for testing with actuating functions; however, further testing will include testing actuator spacing effects on putting realism by having Dan and Jeff putt on the surface and determine how realistic it is and if the actuator spacing is acceptable.

Team Fore