Dual Axis Solar Tracker

Senior Project

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Acknowledgements

I would like to thank my partner Weston Sapia for allowing me to help him with this project and our advisor Vladimir Prodanov for helping us along the way. I would also like to thank my dad, Rich Walton, Jerry Woods, Ron Gruener, and Scott Levine for helping my with the construction of the solar panel base.

- Jason Birnie

I would like to express my thanks to all of the people that have made this project possible for me to complete. First of all, I would like to thank my father, Gary Sapia, for all of the guidance that he gave me throughout this project. Without his help in designing, realizing, and troubleshooting the circuitry, this project would never have become reality.

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- Weston Sapia

I. INTRODUCTION

Global climate change has become a recurring theme in today's society. This force has caused our generation to push for a more environmentally friendly standard. This has helped to kick start a number of inventive alternative energy solutions including solar panels, wind turbines, and electric cars, to name a few.

Solar panels are currently being made with a single axis tracking system to help provide a more efficient use of the sunlight that strikes the earth every day. Dual axis solar trackers, which provide some efficiency gains over single-axis systems, are starting to become more prevalent; however, there are more single axis systems on the market today.

This could be due to the fact that the dual-axis system tends to be far more expensive than the single-axis system. The purpose of this project is to show that this need not be the case. It is possible to incorporate extremely effective tracking systems without breaking the bank. Dual systems can and should be incorporated everywhere. They help to increase the power output of a network without actually improving or expanding the capabilities of the panels themselves. All that needs to be changed is the base which they sit on.

The group has chosen to construct a dual-axis solar tracker that will not only tilt the panels horizontally, but will also rotate a full 360 degrees. No CPUs (central processing units) of any kind will be necessary for this design; instead, a combination of BJTs (Bipolar Junction Transistors), operational amplifiers, MOSFETs (metal-oxide semiconductor field-effect transistor), and logic gates will be used in the circuitry. Using only analog components helps to keep the price down, as there won't need to be any expensive chips for the design. Also, the CPUs tend to be very power-hungry. The design used for the project is also meant to use as little power as possible when idling. This will help to counter any arguments that the extra hardware will simply use all of the extra power that it helps to generate.

This report exclusively covers the progress of the project from the specifications through testing.

II. BACKGROUND

Solar Panel

Solar panels, or photovoltaic (PV) systems, are used both residentially and commercially to collect energy from the sun and offer an alternative energy solution. These panels typically use a semiconductor material to capture the photons from the sun and convert them into energy which can be used to power devices that would otherwise require power from either batteries or the power grid.

Once the semiconductor has 'received' these photos, electrons are released and flow freely around the device. Due to the electric field generated by the panel, these electrons travel in a direction which allows them to be used in DC (direct current) power applications. The power can also be converted to AC (alternating current) power via an inverter. Ideally, the surface of the panel must be positioned orthogonally with respect to the sun for the cells to produce maximum energy that they can.

Solar Tracker

A solar tracker consists of a solar panel which can orient itself to allow for the panel to face the sun as directly as possible. The most common trackers are single axis tracker which allows the panel to rotate horizontally. This is common because they tend to be cheaper than their dual-axis counterparts, and by simply adding one axis of tracking, the efficiencies produced by the panel can be amplified significantly. With the technology of today, many of these trackers have a computer system that rotates the panel according to set parameters such as the time of day and year. As the efficiency of photovoltaic systems increases and the size of these panels decrease, trackers are becoming more and more popular. Having a tracker allows the consumer to buy fewer panels than they otherwise would need to. The added efficiency takes the place of the panels that the user would otherwise need to purchase. Because of the relatively high cost of the panels, adding the ability to track the sun's movement across the sky can be a much more cost-effective method than buying more panels. Also, since the panels are both large and inflexible, the area taken up by these extra panels can be used for other purposes.

III. REQUIRMENTS

Before the design of the tracker can be made, certain specifications must be defined. These specifications include:

- The solar panel must tilt horizontally as well as rotate a full 360 degrees
- The motors and the circuit components must run off of the 12 volts provided by the solar panel
- The design should allow for any resizing without significant changes being made to the structure or circuitry
- The circuit must lock the motor in place while not in use to ensure that the panel maintains its current position
- Voltage and/or current limitations of circuit components must be taken into consideration
- The structure must be able to move freely without any limitations on the motor's movement which might cause something to break

IV. DESIGN

Sensor Circuit

When the idea was originally presented, the first iteration of the design was completed using almost nothing but a string of operational amplifiers with an H-Bridge at the end. After some simulation and discussion, it was eventually decided that there were far too many problems with this design to allow for realization. The design had too many operational amplifiers in a row, which made it far too likely that it would begin to oscillate, and oscillations would ruin the purpose of the design. Also, Op Amps are devices which require a lot of current to support, so putting them in a minimalist design is typically a bad idea, as they will draw too much power. Operational Amplifiers, despite being relatively inexpensive, still remain far more expensive than discrete components, such as BJTs. This causes the price to jump, making the tracking system less than ideal. Therefore, it was decided that the design should incorporate as few amplifiers as possible for all of the reasons listed above.

The next iteration of the design process was a much more feasible idea. The theory showed the circuit to be almost ideal. There was very little current drawn during the off portion of the cycle, making the circuit more efficient. Also, only one operational amplifier and one comparator was used, keeping both the cost and power consumption down. This circuit, shown in Figure 1 on the next page, wound up being the base upon which the final iterations were drawn. It was really the biggest step toward finding a circuit that worked for the project. There were a few issues with this particular design, but the basis was there. Essentially, this circuit worked a whole lot better in CAD programs than it did in the real world. It also require a matched pair of NPN resistors to be used in a current mirror. Having a current mirror in the design makes the individual cost of chips go up because the chips bought then have to have dual NPN BJTs in order for the transistors to be well matched. While this isn't a design-killer, it is a slight drawback.

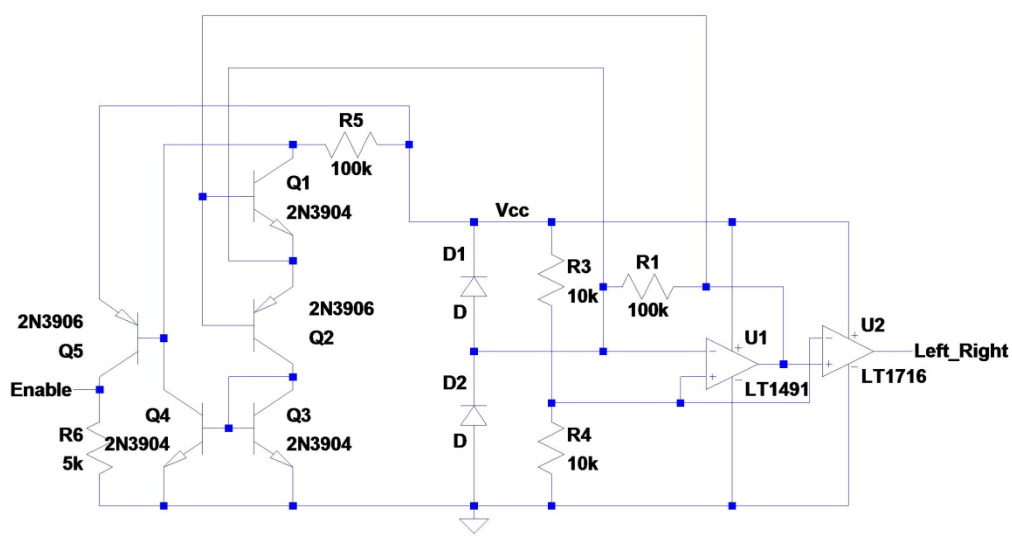

Figure 1: First Possible Circuit Schematic

After building the above circuit a few times, it was determined that the reproducibility was somewhat difficult to achieve, as every time the circuit was built, it seemed to behave a little bit differently, and it was a finicky, periodic circuit at best. There were times that it worked very well, and there were times that it didn't behave as expected at all. This led to the next change, which was a minor revision of the previous design.

The new design showed some promise, as the basics were easier to understand, and the reproducibility was there. The circuit, shown in Figure 2 below, was simpler because the circuit was enabled by simply having enough current flowing through the feedback resistor to create a large enough voltage drop to turn on one of the PNP transistors, thereby enabling the output.

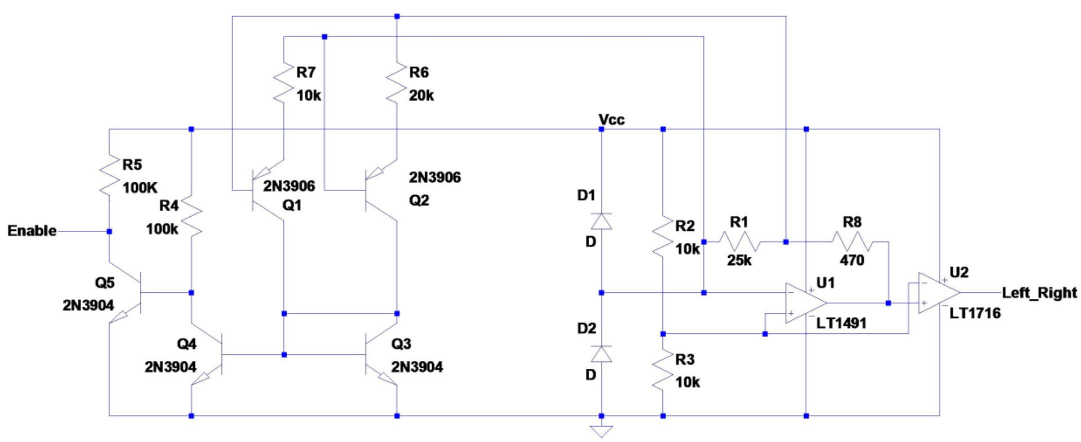

Figure 2: Second Iteration of the Sensor Circuitry

This circuit still required a matched pair of NPNs for a current mirror, so that was still a drawback, but at least the operation was easier to understand, allowing for easier building and troubleshooting. This circuit almost made the cut for the final design. Despite the fact that it was working as expected, and proved to be a fairly reliable design, the fact that there was still a current mirror involved was still a slight issue.

Despite wishing for another idea to make the circuit slightly better, a full control system was built, and that meant that it was time for testing. In order to accomplish this, two power supply boards were obtained. One was a buck converter that was designed to convert the 12 volts from the solar panel down to the 5 volt rails that the entire sensor circuit ran on. The other supply, a boost converter, was obtained to take the 5 V output from the buck converter, and convert it to 18 V to allow for the MOSFETs in the H-Bridge (shown later) to be turned on completely. Once all of this was soldered together, a test jig was created with the two sensor photodiodes split apart from each other to see if simply tilting them away from each other was enough to get the circuit to turn on.

This was accomplished, but when hooking the design up to the 12 V battery that was meant to represent the solar panel, two wires were accidentally crossed, causing the battery to be wired in the wrong direction. This caused the entire sensor circuit to blow, undoing all of the previous work. Essentially, this was a “back to the drawing board” moment.

After realizing what had happened, it was determined that the entire circuit needed to be rebuilt. This is when the final design was confirmed, and the final construction could begin. The eventual design was basically the same as the previous iteration, but the reference side of the current mirror was replaced with a resistor, making the circuit even more efficient and reliable. This brought the total tally of components in the sensor circuitry to 4 BJTs an operational amplifier, and a comparator, along with a few resistors. At this point, it was determined that the design was as “bare bones” as could be achieved, and the rebuild could begin.

The final design is shown in Figure 3 below.

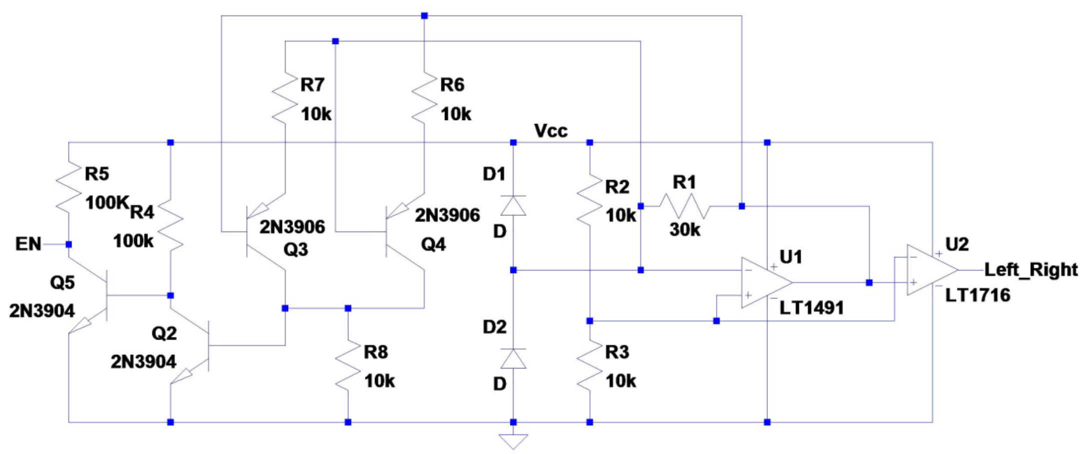

Figure 3: Final Design of Sensor Circuitry

This design was chosen as the final for a number of reasons: it allowed for easy changing of the sensitivity by simply changing the value of the feedback resistor. The larger the resistor is, the more sensitive the circuit is to slight changes in the amount of light that is incident upon the two different photodiodes. You can make the circuit as sensitive or insensitive as necessary by altering that value. If this project were to become a product, then that resistor would most likely be changed to a potentiometer with a knob available to the user to allow the customer to change the sensitivity as they desire.

This design also had the best power dissipation of all of the designs tested. The amount of energy used was completely insignificant when compared to the extra energy captured by simply assuring that the solar panel is pointing in the correct direction. When idling, the vast majority of the circuit's components are off, meaning that they are drawing little to no current. The only real current drawn is from leakage, which can't really be fixed by any method other than buying more expensive, power-efficient parts.

Logic

Despite attempting to design a completely analog solar tracker, there was still a slightly digital component that needed to be fulfilled. There are two signals coming from the sensor circuit, one to decide which direction to turn the motor, and another choosing whether or not to turn the motor. These two signals needed to be adapted to run the four MOSFETs that make up the h-bridge which runs the motor. The easiest way to take two signals and run four different components independently is with digital logic.

That is where the 7400 integrated circuits came in handy. After figuring out the truth table required to run the h-bridge, shown below in Table 1, the next step was determining how to realize the truth table using nothing but NAND gates from the 7400 chip. The original logic circuit is shown below in Figure 4.

Left_Right	Enable	M1	M2	M3	M4
0	0	0	1	0	1
0	1	1	1	0	0
1	0	0	1	0	1
1	1	0	0	1	1

Table 1: Original Truth Table for Operation of H-Bridge

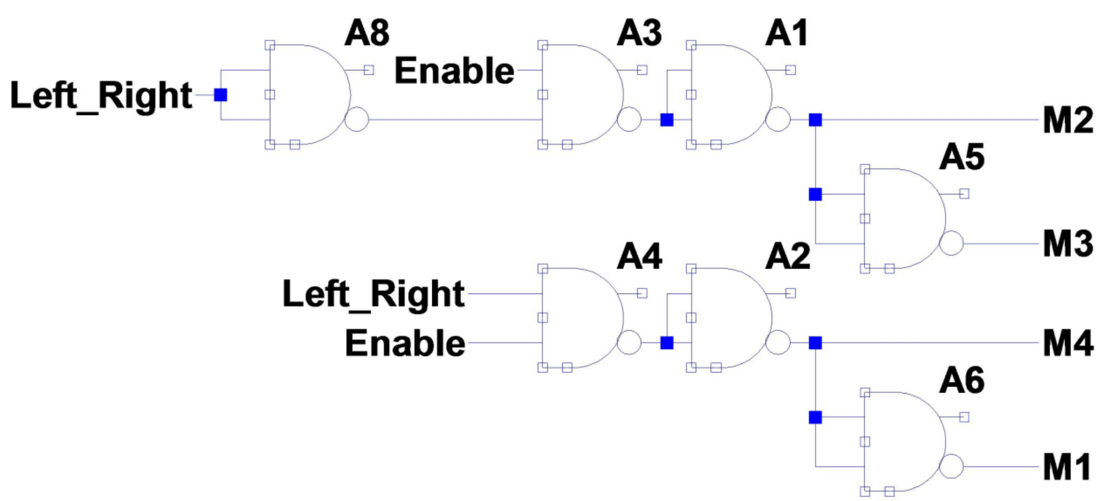

Figure 4: Original Logic Circuit

This truth table is designed to allow the motor to turn one direction when the Left_Right signal is low, and the opposite direction when the Left_Right signal is high, but both of these movements are allowed only when the Enable signal is high. When the Enable signal is low, the bottom two MOSFETs are turned on, causing the motor to have no voltage drop across it, essentially locking the motor into place.

Once the truth table was figured out, the implementation was relatively easy. There wasn't a long drawn-out design process of any kind. The biggest change to the logic came near the end of the project. After many problems with the designing of the driver circuit, it was finally determined that the driver would work better if it were run on two signals, instead of four. All this did was eliminate the M3 and M4 columns of the truth table. It turned out that using the signals for M1 and M2 was enough to allow the circuit to function without any compromises whatsoever. In fact, it is actually a better design because this way gets rid of an extra 7400 chip, saving even more power. The final logic truth table is shown below in Table 2, and the associated schematic is shown in Figure 5.

Left_Right	Enable	M1	M2
0	0	0	1
0	1	1	1
1	0	0	1
1	1	0	0

Table 2: Final truth table

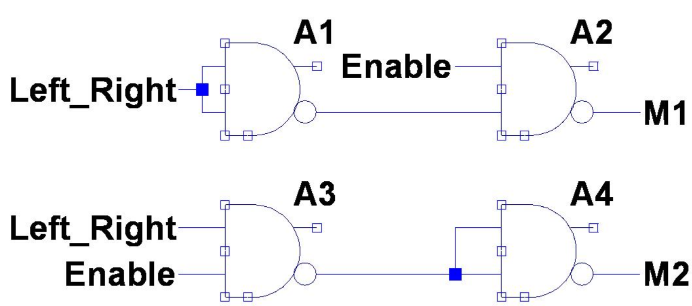

Figure 5: Final digital logic to convert sensor signals into driver signals

H-Bridge and Driver

The driver circuit for the h-bridge required much iteration to achieve an acceptable design. Originally, the plan was to simply drive the MOSFETs using a single NPN, but it was determined that the NPN didn't have the drive to do so. When this was scrapped, the next setup involved one NPN and one PNP to drive the gate of the MOSFETs. This circuit had its own issues with leakage current and the fact that the BJTs didn't allow for a rail-to-rail output, making it difficult to fully turn the MOSFETs on and off. These issues led to a lot of extra, unneeded power dissipation as well as a high possibility of "shoot-through" current which would burn up the h-bridge itself. "Shoot-through" current occurs when two stacked MOSFETs are both either fully or partially on, allowing the full 12 Volts to reach ground. Since the MOSFETs are designed to have a very low on resistance, the 12 Volt supply is then dropped across what is essentially two 0.020 Ω. Ohm's law still applies, showing that this situation would lead to a current of 600 Amps flowing through each MOSFET. The MOSFETs are only rated for about 10 Amps, making this an extraordinarily bad situation. This current is a main concern in the design of the h-bridge.

The next design for the driver circuit involved using a set of comparators to drive the gates. There would be one comparator per gate of the h-bridge. The comparators would have a common reference voltage as one of the inputs to determine when to turn on and off. This design worked well in theory, but there were a couple of issues with it in reality. The fact that the comparators had the same voltage reference level meant that they would all be switching at exactly the same time. While this makes sense in theory, in reality, this can lead to issues with "shoot-through" current. This is because the MOSFETs cannot turn on and off instantaneously as they do in the world of electronic theory. There is a finite amount of time that it takes to turn the gates on and off. Essentially, this means that there are points during which two stacked MOSFETs can be partially on at the same time.

Luckily, there is a very simple, very quick solution to the problem with "shoot-through" current. Instead of using only one reference level for the comparators, use two slightly different, yet close values for the comparator references. This works because, like the MOSFETs, the logic that drives the comparators takes a finite amount of time to switch between output levels. This means that the stacked comparators, with their different references, will turn on at almost the same time, yet close enough together that the circuit will still work as expected. Adding this buffer allows the MOSFETs to turn on and off without overlapping the on time. This eliminates the "shoot-through" current entirely. The final design for the drivers, as well as the h-bridge itself is shown below in Figure 6. The inductor that the h-bridge is driving was used to simulate the impedance of the motors that would go in that spot.

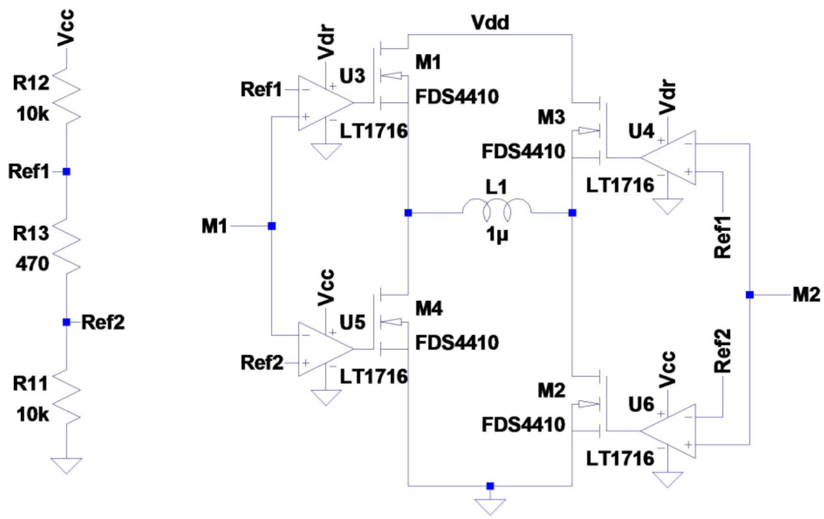

Figure 6: Final Driver with H-Bridge

Structure

When presented with the structural design of a dual axis tracker, there were many requirements that had to be met. The first step in the design process was to determine the range that the panel would tilt. After consulting with fellow colleagues in the Power Department who have studied solar panels and tracking systems, it was determined that the range would span approximately 45 degrees, either up or down, from horizontal. There is no need for the panel to travel more than the 45 degrees because the rotation about the vertical axis will account for the need to move in any direction. Once that was resolved, the next step was to determine how the motor would move the panel and the corresponding base which would support it.

The initial design called for a lever to be connected from the solar panel to a fixed point on a circle which was connected to the motor shaft. As the shaft turns, the placement of the lever on the circle would cause the panel to tilt up and down, much like the wheel of a train engine. Two vertical supports would extend up from the base, where the motor is housed, to hold the panel up and allow for the horizontal movement. Inside the base would house a planetary gear which would allow for the 360 degree rotation of the whole structure. Upon further investigation, this design was ruled inadequate due to future resizing constraints. If one were to try and use this design on a larger scale, the parts needed would be far too large and costs would therefore increase drastically.

The next design incorporated a base with four legs and a single shaft extending upward from the legs. This shaft would support the panel and allow for tilting via an oval-shaped cam attached to the panel which would rest on the shaft, thereby allowing the panel to tilt. As the cam would rotate, the panel would move accordingly which would allow for a total tilting of 45 degrees, spanning from horizontal (perpendicular to the shaft) to about 45 degrees from horizontal. The pivot point would be at the top of the shaft where a rod would go through two fabricated brackets and the shaft. A simple sketch of the idea can be seen in the picture of Figure 7 on the next page.

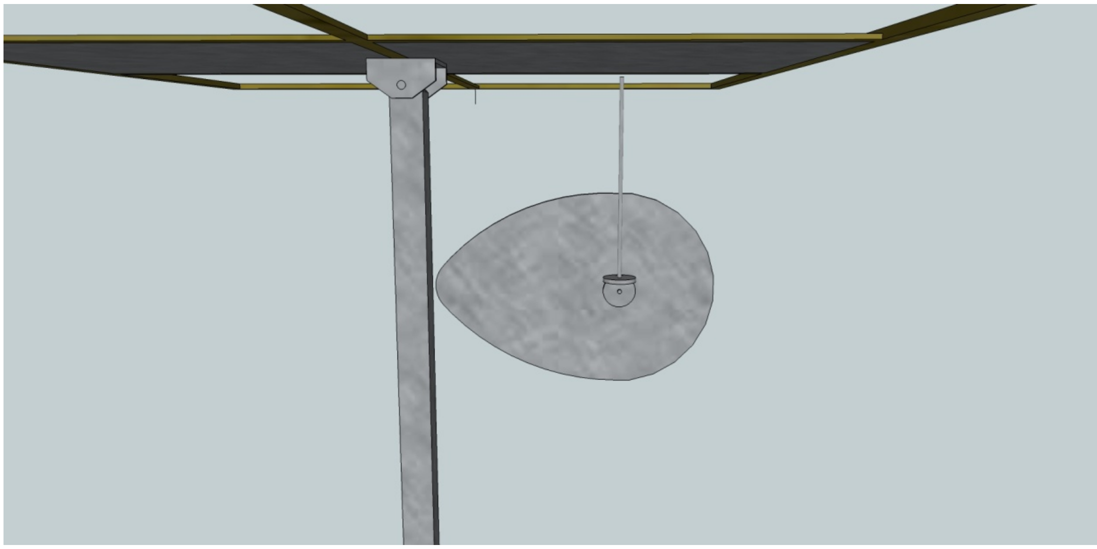

Figure 7: CAD drawing of cam method for tilting the panel

In order to rotate the panel in a clockwise direction, a rod must be placed inside the shaft which can move freely with respect to the shaft. In order to achieve this, bearings must be placed inside the shaft and the rod must travel through these bearings to avoid any unnecessary friction. A gear will be connected to the shaft to form a planetary gear while another gear will be attached to the motor which is attached to the free moving shaft. The movement of the motor will allow for the panel to rotate in either the clockwise or counterclockwise direction.

Unfortunately, problems arose during the design of the cam and this design had to be reevaluated. While keeping the same design for the rotation upon the vertical axis of the system, a linkage system was developed to allow for the tilting movement of the panel. This new design calls for the motor to have a lever connected to its shaft which is then connected to a fixed point on the panel support via a ball and socket joint. Ball and socket joints were used at both ends of the rod to allow for the movement of the lever and the panel. The bracket connecting the panel to the motor can be adjusted to meet rotational specifications depending upon the location of the rod. This new design was tested using AutoCAD and can be seen in Figure 8 below. The design allows for a larger range of motion of the panel and can easily be adjusted to different ranges by simply drilling additional holes both in the lever and the support brace on the panel.

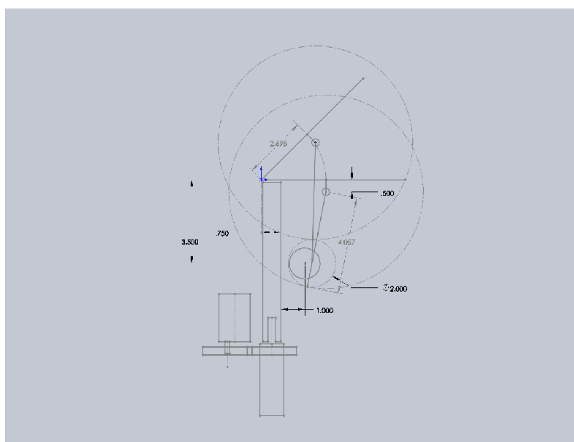

Figure 8: Linkage Rod Design in AutoCAD

V. CONSTRUCTION

Structure

Once the design was complete, the first step in constructing the structure was to build a mock structure using cardboard. This would allow us to see any problems or corrections that needed to be addressed before potentially wasting time and materials. The main goal for this step was to construct the linkage system and make sure that there were no errors from the CAD simulation. Once this was built and tested, the next step was to determine the materials needed for the design. Square tubing, sheet metal, gears, ball and socket joints, hinges, skateboard bearings, and threaded rods were all used in the construction of the base and rotating mechanisms.

Figure 9: Rotational Mechanisms of Solar Tracker

Figure 10: Support for Tracking Mechanisms

In order to have a strong, yet relatively light base, 1 inch square steel tubing was used to support the entire structure. Two legs were cut at lengths of 24" each and then welded to together with the shaft cut at 36" and welded to the top of the feet. A picture of this can be seen in Figure 10 above. Holes were drilled at the end of each leg to allow for bolts to be used as a way to level the tracker on almost any surface. If the ground on which the panel was sitting was not perfectly flat, then the bolts could be adjusted to level the base structure.

Building the piece where the panel would tilt would be the next step. A sheet of aluminum was cut to represent as well as support the solar panel and then bolted to the support brackets. The brackets were then clamped to a mock shaft which would allow for any adjustments without having to waste material. The next step was to construct an angled bracket which would attach the bottom of the panel to the ball and socket joint which in turn is connected to the motor through the offset disc. Multiple holes were drilled in this bracket to allow for any adjustments that might need to be made.

Once this was complete, the bracket that would attach the motor to the shaft was fabricated. The bracket was cut out of aluminum and connected to the motor via the screws which came with it. The bracket was then hose-clamped onto the mock shaft to again allow for any adjustments. The lever which would attach to the drive shaft was machined to allow for it to be inserted on the drive shaft and the ball socket. This lever included another hole to allow for a set screw to be screwed onto the motor shaft to account for the d-bore shape of the motor's shaft. Once this was completed, a threaded rod was cut to length and the socket joints were inserted onto both ends.

The final step incorporates the 360 degree rotation of the panel. The first step in this was to find ball-bearings which would house the threaded rod and allow for minimal friction while turning. Roller blade wheels were cut to fit within the square tubing and hold the ball-bearings in place. Two of these were inserted inside the tubing to allow for rigidity of the rod. Multiple other bearings were placed on top of bolts on the threaded rod to minimize any swaying movement which might occur.

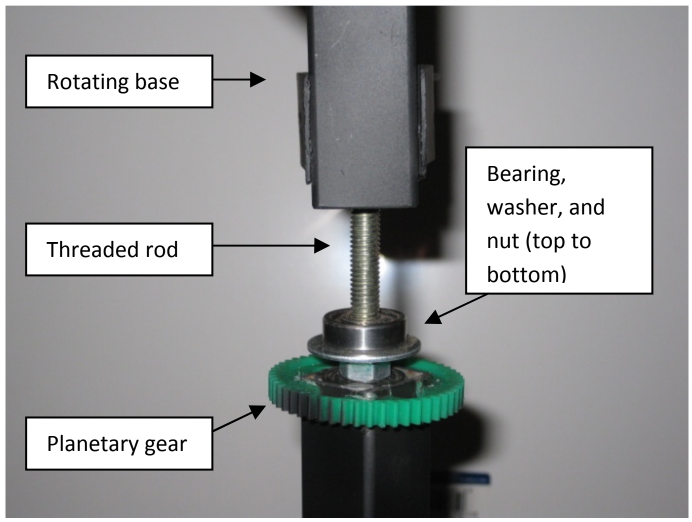

Figure 11: Rotational Configuration of Base

A plastic gear was machined to allow for it to fit over the 1 inch tube and act as the planetary gear. To ensure that it would not move, the bottom of the gear was hot glued to the tubing. A bolt was inserted onto the threaded rod which housed a washer to provide a platform for the rotating portion of the base to sit. This bolt rested on the bearings placed inside the lower portion of the base. Figure 11 shows this configuration. A connection piece was fabricated to connect the motor to the gear which would turn the upper portion of the base. Once this was done, a large piece of aluminum which measured 1 inch by 12 inch was cut to support the motor onto the base. The motor with the attached gear was held up to the planetary gear to measure how far the motor would sit from the base. After determining this distance, one side of the aluminum strip was riveted to the base and wrapped around the motor where it was then riveted to the other side of the base. Two holes were drilled to allow for a zip-tie to run through and clamp the motor to the aluminum strip.

After constructing all these pieces individually, they were connected together and tested using a motor and a 12V battery. Upon completing this test, everything was disassembled and prepped for paint. When the paint was dry, the whole structure was reassembled and retested.

VI. TESTING

Structure

The testing of the structure was broken up into the horizontal movement, the clockwise rotation, and then both combined together. Once the fabrication of the pieces regarding the horizontal movement was complete, it was clamped to a mock tube and the motor was connected. A 12V battery was then connected to the motor and the shaft traveled 360 degrees before the motor was shut down. While the motor was running, the torque of the motor was checked to make sure that it would be able to hold the additional weight of the circuitry. Also, the angularity of the panel was checked to allow for the desired range of motion. Once this was complete, the clockwise rotation was tested next.

To test the clockwise rotation, the same procedure was used. Once all the pieces were made and placed onto the base, a battery was connected to the motor and the motor was allowed to rotate more than 360 degrees before it was shut down. During this test, I looked to make sure the driving gear would not slip off the planetary gear due to any uneven surfaces on the gears.

After this was performed, both the upper and lower portions of the base were connected together and tested to make sure that there were no clearance issues, swaying or torque issues from the motor.

VII. CONCLUSIONS AND RECOMMENDATIONS

The designing, constructing, reconstructing, and finalizing of this solar tracker was an exceptional educational experience. This project gave the students first-hand knowledge of exactly how much work and effort it takes to fully realize a design. Just the theoretical development of the circuits as well as the mechanical side of the project was a many month process that required far more iteration than originally planned for. Simply getting things to simulate in a manner that is acceptable is a whole lot harder than it sounds. If nothing else, this project has taught the students that underestimating the time commitment required to complete a task is a huge mistake that can cost you everything.

When it comes to the actual building of the circuits, almost nothing ever works the first time. Even if the design built does work after construction, oftentimes, non-idealities cause the design to be unrealistic to use in the design. The only effective way to get the project done is to spend hour after hour troubleshooting, redesigning, and rebuilding broken circuits.

This project has taught the students that no matter how sure you are about a design's ability to work in the real world, you never know until you actually build it. Forgetting a pull-up resistor, or forgetting to ground a circuit can lead to hours of trouble, and it is always better to go out and build a design, no matter how trivial it may seem on paper.

This assignment, while it is a little cruder than what would be implemented out in the real world of solar tracking designs, was a great first attempt at constructing a system that would effectively track the sun. There are a few changes that would have to be made in order for this to be a marketable product, but the changes are relatively minor, mostly cosmetic, and at the same time, unrealistic for a prototype. One example of a change is a more sophisticated set of rotation mechanisms that would both hide the motors as well as protect the electronics from the elements. Ideally, both of the motors would be hidden inside the upper vertical shaft of the base. The electronics would eventually find their way onto the bottom of the solar panel support, and they would be in some way covered by a box of some kind.

Another change that would have to be incorporated into the design is some sort of shielding on the leads coming from the photodiodes. The photodiodes are extremely sensitive to electromagnetic interference (EMI), and this can ruin the devices. Since the diodes are the basis of the entire project, they would need to be very well protected so as to ensure the robustness of the design.

The final change is a little bit more complex, yet wouldn't be very difficult to realize. Currently, there is a way to determine which way the motor should turn, and there is a way to determine if the motor should turn, but there isn't anything in place to determine if the design is seeing any light at all. Right now, it is only sensitive to differences in light, not whether there is any incident light at all. One fix for this would be to add a single photodiode that is looking in the same general direction as the panel itself, and use it to determine if there is any sunlight incident upon the panel. If the panel is seeing light, then the circuit would act as it does now, whereas if the extra photodiode doesn't see a significant amount of light, then the panel would rotate on the vertical axis a limited number of times (such as two or three), or until the photodiode sees light. Adding this to the project would help the circuit to account for the switch from night to day. Instead of wondering whether the circuit will work after a night has passed, it would be a great way to ensure that the panel is facing the correct direction come morning.

VIII. BIBLIOGRAPHY AND REFERENCES

Sensor

Help with design of the sensor circuitry was provided by:

- Dr. Vladimir Prodanov, Professor, Cal Poly State University
- Gary Sapia, FAE, Linear Technology
- Josh Quintero, Associate Engineer, Linear Technology

Logic

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- Dr. John Oliver, Professor, Cal Poly State University

Driver and H-Bridge

Help with the driver and h-bridge was provided by:

- Gary Sapia, FAE, Linear Technology
- Josh Quintero, Associate Engineer, Linear Technology
- Paisley, R. (2001, May 1). *"H" Bridge Motor Control Circuits*. Retrieved April 25, 2010, from Model Railroad and Misc. Electronics: http://home.cogeco.ca/~rpaisley4/HBridge.html

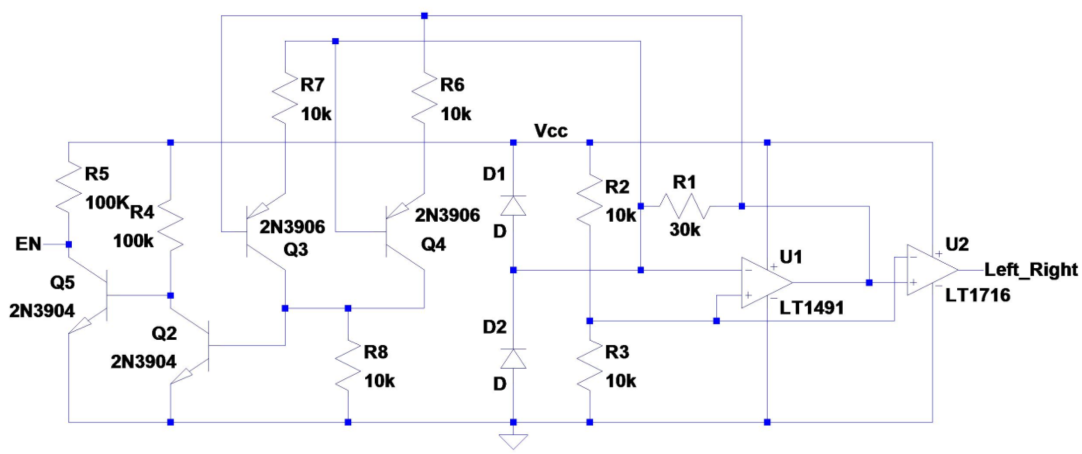
Structure

Help with the structure was provided by:

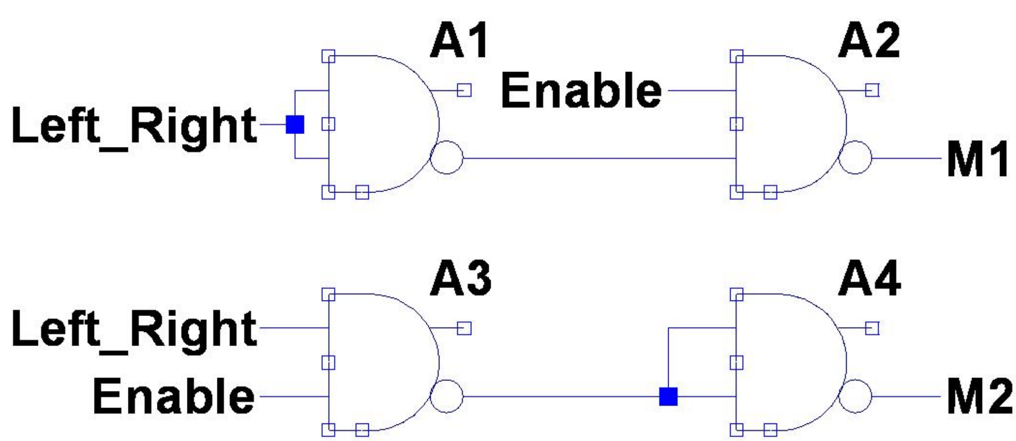
- Rich Walton, Owner, Jerry Woods Enterprises
- Jerry Woods, Owner, Jerry Woods Enterprises

Appendices

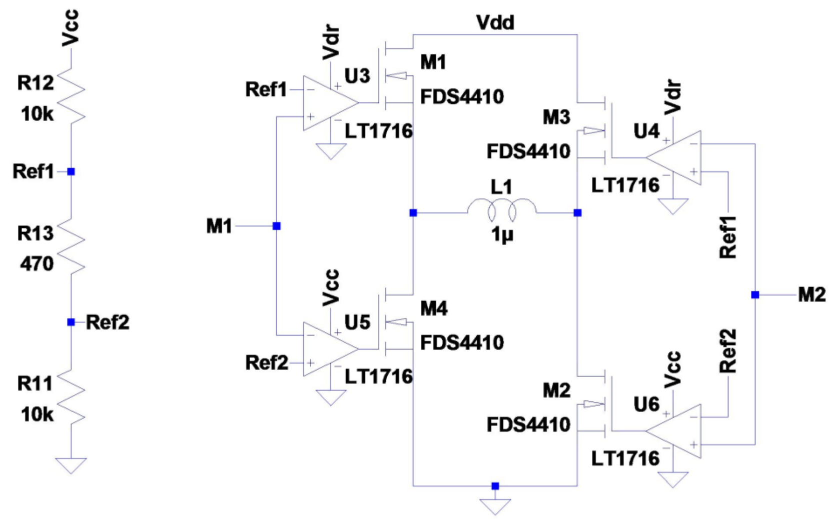
A. Schematic



Sensory Circuit



Logic Circuit



Driver Circuit

B. Parts List and Cost

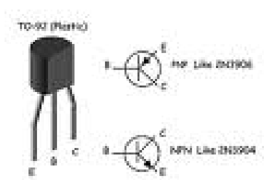
Component	Quantity	Price
SFH2505	4	$2.76
2N3904	4	$0.12
2N3906	4	$0.14
LM741	2	$1.76
LM311	10	$1.40
FDS4410	8	$2.63
7400	2	$3.00
3 foot long, 1 inch square tubing	2	$40.26
2 feet × 2 feet aluminum sheet	1	$14.36

Total Cost = $66.43

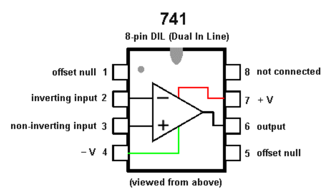
C. Time Schedule:

	Estimated Time	Actual Time
Circuit	4 Weeks	10 Weeks
Structure	2 Weeks	4 Weeks

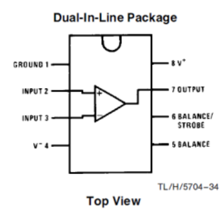
D. IC Pinouts



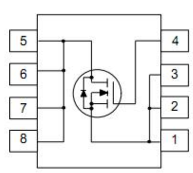
2N3904 and 2N3906 Pinout



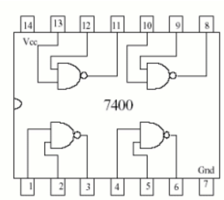
LM741 Pinout



LM311 Pinout



FDS4410 Pinout



7400 Pinout