A Two Axis Mirror Positioning System with Quadrature Encoder Output

by

Rick Bryan Woodruff

Submitted to the Department of Mechanical Engineering in Partial Fulfillment of the Requirements for the Degree of Bachelor of Science

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Abstract

This project was conducted in support of a solar concentrating technology that required the design and construction of a low cost, two axis rotational drive system with a resolution of one degree or better. The scope of this project was to design and build a two axis drive system capable of supporting a 20" square acrylic mirror. Cost, reliability, and the ability to be built by students using student resources were of primary concern.

The primary design concern was the development of a low cost feedback system. Several different feedback sensors were considered, and a quadrature encoder was chosen. To reduce cost, the encoder disk was made from an overhead transparency with a slotted image printed on it. The required encoder accuracy was 1.0 degree, and a measured accuracy of 0.85 degrees was achieved. The encoder was designed with an optimum accuracy of 0.55 degrees per transition and the observed discrepancy in resolution is primarily due to high tolerances that could not be met with hand assembly.

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1.0 Introduction

The theory that large scale emissions of greenhouse gasses could cause the earth’s climate to change on a global level has been around for some time. With publications like the latest report from the Intergovernmental Panel on Climate Change and Al Gore’s film *The Inconvenient Truth*, this theory is becoming a topic of mainstream debate. The leading source of greenhouse gasses is the burning of fossil fuels, which release large quantities of CO2 during combustion\(^1\). Recently, public awareness about the consequences of the large scale release of CO2, and concerns about energy security has revived interest in renewable fuels not seen since the 70’s. Today’s energy market is perfect for new and innovative ideas that displace the use of fossil fuels. One such idea is a solar focusing technology developed by an MIT undergraduate called Lightshed\(^2\). Lightshed consists of an array of mirrors that focus solar radiation onto a central beacon. This energy can then be used for electricity generation, industrial thermal processes, or space heating; all of which currently rely heavily on the use of fossil fuels. It is unique in that each mirror contains its own control system, allowing it to act independently of a central control station, and making the system versatile and easy to install.

Many different solar energy systems exist on the market today. From silicon wafers that convert the sun’s rays directly to electricity, to giant parabolas that focus the sun and create the high temperatures needed for stirling engines\(^3\). Another technology currently in the pilot phase is the solar power tower. A solar power tower consists of large field of mirrors controlled from a central unit that focus the sun’s rays on a stationary beacon. These designs have been proven effective in large scale systems like Solar II in California which provides 10 MWe\(^4\) of power. Unfortunately these systems are difficult to scale down because of unique engineering challenges and the need for experienced installation. Lightshed is very similar in design to the Solar II system, but aims to bring down the cost by making smaller, mass producible units that can be installed by a general contractor and on a much smaller scale. The goal of Lightshed is to make solar concentration available to small scale users like commercial buildings, rural areas, and third world countries by setting the unit size as one mirror, rather than one field.

Currently the Lightshed team is in the process of applying for several business competitions and needs a display unit to show the technology and provide data from field testing. The purpose of this thesis is to design and construct the mechanical component of the Lightshed system to be used for product showings and field trials. It will also provide a testing platform for the controls engineer to develop the solar tracking system. The mechanical component includes a two axis drive system capable of 180 degree rotation and a feedback output.

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\(^2\) Lightshed was developed by Alex Hornstein. A provisional patent has been filed.

\(^3\) http://www.stirlingenergy.com/

2.0 Description of the system

Lightshed is a solar concentration system that focuses radiant heat from the sun onto a target. As shown in Figure 2-1, an array of mirrors is installed in close proximity to an energy conversion beacon. The energy conversion beacon is a placeholder for the application specific device that utilizes the solar thermal energy collected by the array of mirrors.

![Figure 2-1: A potential configuration for the Lightshed system. Easy to install mirror modules are placed in the field and automatically find the sun and the beacon. When the sun is in the sky, the mirrors will track the midpoint between the sun and the tower, focusing the sun's rays on the beacon. Each mirror module works independently of the others, eliminating the need for any external wiring.](image)

Lightshed is based very closely on existing technologies such as the recent power tower installation in southern Spain. In this application, a concrete tower 40 stories high is bathed with sunlight from over six hundred, 120 m² mirrors. It is the first commercially operated European power station to use this technology, but the initial results look promising. Solucar, the company that owns the field claims an output of 11 Megawatts, but plans to expand it's capacity to one hundred times that much.

Much like the mirrors in the Solucar installation, the Lightshed mirror module concentrates the sun onto a tower. Focusing the sun’s rays is desirable because it increases the temperature at which solar energy can be utilized. In electricity generating applications, an increased temperature translates into a higher thermal to electric conversion efficiency, and in thermal processes, many desirable reactions only take place

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at high temperatures. Numerous methods for concentrating the sun have been developed, but most require elaborate engineering and specialized installation. Lightshed is different because it is a system of mirrors that require no infrastructure. Installing a Lightshed mirror is as easy as digging a hole in the ground.

2.1 Design specifications

The primary goal of this project is to develop a testing rig and prototype for a single Lightshed mirror module. This testing rig will aid the controls engineer in developing the feedback system necessary to track the sun and reflect it onto the beacon. The requirements decided upon as a result of combined efforts with the controls engineer were:

- Provide an output signal that allows for the calculation of position to within one degree or less.
- Design a frame that will not plastically yield in a 20 mph wind with the mirror oriented perpendicular to the ground.
- Rotational speed of 2-6 rpm.
- Support a mirror size of 0.25 m².
- Be able to be manufactured and assembled by students using on campus facilities.
- Minimize cost and maximize reliability and scalability.

The accuracy of one degree or less is a ball park estimation of the trade off between the beacon size, mirror to beacon separation, and the mirror’s position accuracy. A position accuracy of one degree and a mirror to beacon distance of 15 meters translates into a beacon width of twice the mirror width to collect all of the energy. The beacon does not need to be this wide, and indeed the optimum beacon width will be somewhere between the mirror width and twice the mirror width.

Because the system will be tested outside, it is important that it withstand a moderate breeze when the mirror is positioned perpendicular to the ground. It is believed that this orientation will provide the highest wind drag, and the force applied will be in the direction that causes the greatest moment on the lower part of the shaft. The highest average monthly wind speed in Boston, MA is 13.7 mph, but no estimates for daily peak wind speed were available. A value of 20 mph was chosen somewhat arbitrarily, but based on an estimation of the top wind speed that will be encountered on an average sunny day during testing. In the event of higher winds, the mirror module could orient itself perpendicular to the ground, greatly lessening the forces exerted upon it.

It is also important that the mirror module can be built by students using facilities available on campus. The first modules produced by the Lightshed group will be built

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6 Conversations with student Alex Hornstein, MIT 9/06-5/07
7 Discussed further in section 3.2.1.
using machine tools and assembled by hand, so design choices should take this into consideration. In addition to ease of manufacture; cost, reliability, and scalability must also considered in order to minimize the transition to mass production.
3.0 Design

3.1 Wind Loading and Frame Design

The shape of the mirror support frame will be the same as the former version of Lightshed shown in Appendix B Figure 6-2. This design was tested in the proof of concept model and performed well. A single mount in the center of the mirror was also considered, but the drive system and motor mounting becomes much more difficult. For this reason, the mirror will be held by a central driveshaft that is attached to a U-shaped support as shown in Figure 3-2. One side of the frame will contain the drive system that controls the position of the mirror support tube shown in Figure 3-3, and the other side will hold a bushing. An assembled model is shown in Figure 3-16.

The system is designed for outdoor use, and it must withstand wind. The dominant wind resistance will come from the mirror, and will be the largest when the mirror is facing the wind. For this reason, the system will be modeled as a flat plate oriented perpendicular to the flow. From the Fluid Mechanics textbook by Frank White, the drag on a body immersed in a fluid is given by the following equation,

\[ F_{\text{drag}} = \frac{1}{2} \rho V^2 A C_d, \]

Where \( F_{\text{drag}} \) is the force applied to the surface, \( \rho \) is the density of the fluid, \( V \) is the velocity of the fluid, \( A \) is the area, and \( C_d \) is the coefficient of drag. The coefficient of drag can be determined theoretically, empirically, or from a table. In most cases \( C_d \) is dependant on the fluid velocity because the drag force changes significantly when the flow separates from the surface. The coefficient of drag for a flat plate is independent of velocity for reasonable values because separation occurs at such a low fluid velocity. For fluid velocities corresponding to a Reynolds number \( \geq 10^4 \), the coefficient of drag \( C_d \) is 2.0. For a 0.25 m² mirror, this condition is met at a wind speed of less than one mile per hour. Substituting the values for the surface area of 0.25 m², the density of air, and the coefficient of drag into Equation 1 and plotting against wind speed gives the graph shown in Figure 3-1.

Figure 3-1: Force vs. wind speed for a 0.25 m² mirror in the worst case scenario oriented perpendicular to the flow. The circled areas show the yield points for two different frame materials, both are for half inch outside diameter. During storms, the field of mirrors could orient themselves parallel to the ground, greatly reducing the drag force.

Also shown on this plot are the yield points of two different materials and wall thickness for the weakest part of the mirror support system. As shown in Figure 3-2, the weakest point is where the tube frame meets the top bearing. For the prototype, 0.035” wall thickness plain carbon steel will be sufficient, as testing will be not be preformed during storms. For winds up to 60 miles an hour, thicker wall tubing and a solid drive shaft should be used. It should also be noted that these wind speeds are for conditions during operation. During a storm, all of the mirrors could orient themselves parallel to the ground, reducing the drag force by orders of magnitude.

Further optimization of the frame could be achieved by resizing/redesigning the portion of the driveshaft that experiences peak loading. As shown in Figure 3-2, peak loading occurs right above the upper bearing.
Figure 3-2: A plot of stress distributions within the support frame for 0.065" wall tubing and a solid drive shaft in an 60 miles an hour wind. The deflection in this figure shows only the relative direction, the magnitude is not to scale. The stress distributions for 0.035" wall tubing look exactly the same, differing only in magnitude. Note that the peak stress occurs right above the location of the upper bearing. This figure was created using Solidworks.

Half inch steel tubing was selected for the design because it provides adequate mirror support while remaining sleek and unobtrusive. It was used in all parts of the frame for ease of manufacture. All steel parts that will be exposed to the weather must be painted to prevent corrosion. When scaling up the mirror size, an optimization should be done to find if enlarging the tube diameter in only the high stress areas, thereby increasing the manufacturing challenges of mating different sized tubing, would be more economical than enlarging all of the tubing.

PVC was suggested as a possible alternative frame material because it will not corrode like unpainted steel, it does not require welding, and it is relatively cheap. It was not selected as the final material because it’s not as rigid as steel, it degrades under sunlight, and it doesn’t look professional. Stainless steel was also considered for the frame design because it will not corrode, but the price is much greater than steel.

Another issue not addressed here is the phenomenon of vortex shedding. When a fluid stream travels past a body, vortices often form on the low pressure side. These vortices produce varying forces on the body, and can excite resonant modes in the system. At some point, an analysis of the resonant modes of the mirror system’s two axes and the
vortex shedding frequencies for different mirror orientations should be performed. This could be done by modeling the frame as a second order system and comparing the vortex shedding frequency of the mirror for the highest wind speed to the resonant frequency of the system. If the maximum vortex shedding frequency of the mirror is near or below the resonant frequency in either axis, something should be done to change the way air flows past the module, or the system should be stiffened by increasing the tube diameter, wall thickness, or changing the material of construction.

The tube that physically supports the mirror will also be 1/2” tubing, with two pieces of flat 1/16” steel welded in place. A solid model of the tube is shown in Figure 3-3.

![Figure 3-3: The mirror attachment system. M5 bolts hold the acrylic mirror in place against the steel supports. It is supported by the drive assembly on one end, and a bushing on the other.](image)

This tube is supported at the top of the frame structure shown in Figure 3-16. On one side the drive assembly will secure it, and on the other side a bearing will hold it in place. The mirror will then be mounted onto the tube by bolting it through the metal plates. The mirror material currently being used is acrylic, and in the future it may be changed to polished metal.

The former version of Lightshe (Version 4) was supported by a tripod design as shown in Appendix B Figure 6-2. This design was chosen because it allows it to be placed almost anywhere with little to no setup. At that stage in development, the ability to support itself in a breeze was not taken into account. It would be advantageous if the system was mounted on a tripod for table top display purposes, but a quick look at the force vs. wind speed chart in Figure 3-1 shows that it would be completely unreasonable in the field. For this reason, a pole mounted design was chosen. Pole mounting the mirror module will make its use as a table top display more difficult, but will prevent the system from tipping over in the field. In soil, the pole mounted design can be installed in
a hole filled with rocks or concrete, or on a rooftop, a piping network could be used. The pole size was set at a diameter of 2" as required by the chosen drive system. This diameter allows for the entire drive and feedback systems to be enclosed in the support pole.

3.2 Drive system

Once a day, a Lightshed mirror makes its track across the sky. As defined earlier, each axis should be capable of 180 degrees of rotation. Interestingly, this system is different from many electromechanical systems because it makes less than one rotation per day. Over the course of the day, the mirror tracks the midpoint between the sun and the beacon, and at night it returns to the starting point, ready for the sun to peek back over the horizon. Because of the extremely slow nature of the system, a geartrain is absolutely necessary. While in theory the mirror could move at around 15 degrees per hour, it is advantageous for the speed to be fast enough to be visible as the Lightshed team is in the process of competing in several business competitions, and a working, moving model is desired. For this reason, the design range for the motor speed was set somewhere between 2-6 rpm.

3.2.1 Motor selection

The motors for the Lightshed system are one of the most expensive parts; therefore great care should be taken to reduce cost when selecting them. Several different motor types were evaluated for their cost, performance, and availability of built-in position sensing.

The earlier Lightshed mirror modules used model airplane servos for their drive system. Lightshed Version 3 is shown with its creator Alex Hornstein in Figure 6-1. Servos are convenient because they include a geartrain and feedback in the same module. Their position is controlled by a variable voltage input, which can be easily achieved with an A/D converter connected to the control system. Unfortunately, their feedback performance was deemed unsatisfactory by the controls engineer. The reason for this inaccuracy is most likely the use of a potentiometer for feedback. More on the reasons potentiometers cannot be used as feedback for this system is described in section 3.1.1.

Another drive system with an inherent method of determining position is the stepper motor. Stepper motors operate by sequentially energizing coils that cause a rotor to rotate, much like a DC motor. Unlike the DC motor, these coils can be energized very slowly in a controlled manner such that the position of the rotor is known. Unfortunately the stepper motor is considered a feed forward system, in that the control system can tell the motor to go to a certain position, but no verification that the motor has moved is given. Another disadvantage is that the stepper controls the position of its output shaft, and not the mirror frame itself, any slop in the geartrain or motor mounts will translate directly into an error in position.

The final motor type that was considered is the DC motor. DC motors operate at a much higher speed than 2-6 rpm, but because low speed applications are common, many DC motors with an integrated gear system can be found. Unfortunately low cost DC motors
do not come with feedback, so external feedback will be needed. A search of the small motor distributors was conducted, and one motor stood out as the clear winner. It is available from Marlin P. Jones & Associates as part number 2732-0300 at mpja.com. For small quantities the price is $12.95, or in quantities of 10 or more the price is $9.95. It is rated at 6 rpm @ 12 V. A picture of the motor is shown in Figure 3-4.

Another desirable feature of this motor is the all metal gearbox which is more robust than a plastic gearbox. Unfortunately, no data was found on the operating characteristics.
3.2.2 Motor Mounts and Bushings.

The first design of the motor mounts and bushings included two bushings and a motor mount for both axes. This was condensed into one bushing plus a motor mount/bushing combination as shown in Figure 3-5.

Figure 3-5: Exploded view of the drive system. A steel motor coupling is held in place with a set screw and transfers torque to the delrin motor coupling. The lower motor mount also acts as the lower bushing.

The only thing that differs between the upper and lower drive systems is the distance between the upper drive shaft bearing and the lower drive shaft bearing. The upper drive system is more condensed because it must fit into a smaller package, and additional constraint is gained from the bearing on the opposing side of the mirror frame.

The material chosen for the bushings and motor mounts is delrin. Delrin is very slippery, making it a good choice for bushings, it is also relatively stiff, and easy to machine. Most of the other non-steel parts for the system are also made from delrin to keep the materials count to a minimum. In a mass production process, many of the pieces such was the motor mount and upper drive shaft bearing would most likely be made from a cheaper, injection molded plastic, with a bushing insert of a slippery material.
3.3 Choice of Feedback Sensor
Because the Lightshed mirror module is an independent system, it is important that it be able to sense the sun, sense the beacon, and then move to the appropriate location. The sun and beacon sensors, along with the control system will be added later as an attachment, but it is advantageous to integrate the mirror position sensors into the mechanical design. The two types of sensors that were considered are potentiometers and optical encoders.

3.3.1 Potentiometers
The previous versions of Lightshed shown in Appendix B used potentiometers hot glued to the ends of the drive shafts to calculate the mirror position. During bench testing, it seemed to behave surprisingly well, but no quantitative measurements of accuracy were taken, and no long term tests were performed. Potentiometers have the advantage of being cheap, easy to install, and take up relatively little space. Additionally, many types like those containing cermet or conducting plastic elements have essentially infinite resolution, meaning the accuracy of the system would only be limited by the analogue to digital converter. Unfortunately the resistance will shift with temperature, vibration, and cycles. Because the resistance can vary over time, accurate determination of the position is difficult, and potentiometers were ruled out as a reliable feedback source in an outdoor application.

3.3.2 Optical Encoders
Another type of feedback considered was the shaft encoder. Optical shaft encoders measure movement by counting the number of times a signal is interrupted by a patterned disk fixed to a shaft. This movement can then be translated into a position by defining a point on the disk as zero, and counting the number of interruptions that occur after locating that point. Unlike potentiometers, shaft encoders don’t drift over time due to physical changes of the system because patterns on the encoder disk don’t change with time. Two types of optical encoders exist, transmissive and reflective. As shown in Figure 3-6, reflective sensors work by shining a light onto a patterned disk and measuring the intensity of the light reflected back. This is usually done with a photodiode or phototransistor. Transmissive sensors work in much the same way, except they measure the amount of light that passes through the patterned disk.
Figure 3-6: A diagram of reflective and transmissive encoders. Reflective encoders work by emitting light onto a patterned disk and measuring the intensity of light that is reflected back, while transmissive encoders measure the amount of light passing through a slotted disk.

Reflective encoders are advantageous because the patterned disk is extremely easy to make. All that is needed is a disk with regions of higher and lower emissivity, i.e. a piece of paper printed on a printer. This is particularly attractive considering that the first production of Lightshed will be done by students. Unfortunately, a full transition from light current to dark current for a reflective sensor happens on the order of several millimeters, while many transmissive encoders operate in the sub-millimeter range. For this reason, transmissive sensors were used in the final design.

Another consideration when designing the encoder is the need for directional information. An encoder gives an output signal with a frequency proportional to the speed of rotation, but it gives no information regarding the direction of rotation. Two encoders that are out of phase are required to determine the direction of rotation, and thus a dual sensor package is desirable. This is called a quadrature encoder. In addition to providing directional information, a quadrature encoder increases the resolution of a given disk by two if the sensors are located 90 degrees out of phase by providing two transitions for each feature on the disk. The resolution in degrees per step for a single encoder is given by the equation,

\[
res_{\text{Single}} = \frac{360}{N_{\text{slots}} \times 2},
\]

where \(N_{\text{slots}}\) is the number of slots for one full rotation of the disk. This is found by dividing the circumference of the encoder by two times the minimum detectable feature width. The doubling of the feature width is required because each feature must be accompanied by an equally wide section of low opacity material. The number of slots for 360 degrees of disk is given by

\[
N_{\text{slots}} = \frac{\pi D_{\text{encoder}}}{2d_{\min}}.
\]
where $D_{encoder}$ is the diameter of the encoder disk and $d_{min}$ is the minimum feature width\textsuperscript{10} as shown in Figure 3-7 below.

\begin{figure}[h]
\centering
\includegraphics[width=0.5\textwidth]{encoder_diagram.png}
\caption{Diagram of the variables used in Equation (3). Note that the thin line showing the optical diameter is not actually printed on the disk.}
\end{figure}

The resolution of a quadrature encoder is very similar to a single encoder, but the second sensor doubles the resolution by creating two signal transitions per feature. The resolution in degrees per step for a quadrature encoder is given by

\begin{equation}
res_{Quadrature} = \frac{360}{N_{slots} \times 4}.
\end{equation}

Quadrature encoders were chosen because they provide directional data and double the effective resolution of a given encoder disk.

### 3.4 Optical Encoder Design

Initially, the plan was to build the entire encoder system from scratch using a phototransistor, LED, and a slotted disk. Figure 3-8 below shows a diagram of the proposed system.

\textsuperscript{10} This value is set by the manufacturer and can be found using the data sheet for the chosen sensor.
Figure 3-8: Initial design for the encoder system. This design was scrapped after preliminary testing showed a high dependence on tolerances that could not be easily controlled. The lower support is the lower motor mount, and the upper support is the lower bearing, these parts too were modified and in the final design is only one piece.

To test the feasibility of this design, a test rig was constructed. Instead of a slotted disk, an overhead transparency was printed with the image of a slotted disk. An LED was positioned on the bottom side of the disk, and a phototransistor was positioned on top. One side of the phototransistor was connected to +5 v, and the other side was attached through a resistor to ground.
Figure 3-9: A crude test rig designed to assess the feasibility of the proposed encoder layout. The distance between the photodiode (top) and the encoder wheel was varied, along with the distance between the wheel and the LED (bottom). A small piece of tape with a slit in it was used to reduce the aperture of the phototransistor.

Optimal performance was found when the phototransistor was very close to the encoder wheel. Replacing the phototransistor with a white sheet of paper showed that as the distance between the wheel and the encoder increased, the projected image became more blurry. Figure 3-10 shows scope traces measured during a best-case performance.

Figure 3-10: Scope trace for the best performance obtained from the system described above. The variation in frequency is primarily due to the jitter of my hand. This output would be suitable as a feedback signal if filtered through a chip like the 74HC14 hex inverter.
As shown in Figure 3-10, a distinct change was observed in the sensor output as regions of high and low opacity passed through the LED/sensor pair. This signal could be improved by optimizing the LED current, sensor spacing, transistor resistance and adding filtering. One drawback to this system was that the signal was highly sensitive to variations in the disk to phototransistor distance. Another drawback not initially realized was that it will be very difficult to accurately space two phototransistors 90 degrees out of phase.

### 3.4.1 Encoder Package

For the reasons listed above, it is desirable to find a package that includes two phototransistors located a certain distance apart. Because the distance between the sensors is fixed, it does not vary with the manufacturing of the mounting system. Many different sensors were considered, two of the most economical dual package encoders are shown in Figure 3-11.

![Figure 3-11: The EESX-1131 (left) and the EESX-1031 (right). These are two of the encoders that were considered. The larger package is desirable for hand manufacturing, but does not provide sufficient accuracy.](image)

The first Lightshed systems will be built by students, making the EESX-1031 desirable due to its through hole mounting system. The EESX-1131 has a higher accuracy, but will be much harder to solder because of the surface mount package. To decide between these two sensors, an estimation of their resolution in the Lightshed application was considered.

The two variables needed to calculate resolution as shown in Equations (3) and (4) are the minimum slot width, and the diameter of the disk, where the diameter of the disk will be dependant on the physical dimension of the sensor because the entire encoder setup
must fit within the 2" mounting tube. Using the data sheets for the two sensors, and conservative estimates for the mounting location inside the tube, Table 3.1 compares the accuracy of the two sensors.

<table>
<thead>
<tr>
<th></th>
<th>EESX-1131</th>
<th>EESX-1031</th>
</tr>
</thead>
<tbody>
<tr>
<td>Minimum sensing width</td>
<td>0.012&quot;</td>
<td>0.020&quot;</td>
</tr>
<tr>
<td>Estimated disk diameter</td>
<td>1.25&quot;</td>
<td>0.9&quot;</td>
</tr>
<tr>
<td>Number of slots</td>
<td>163</td>
<td>71</td>
</tr>
<tr>
<td>Accuracy</td>
<td>0.55 degrees</td>
<td>1.26 degrees</td>
</tr>
</tbody>
</table>

Table 3.1: Comparison of accuracy for the EESX-1131 and the EESX-1031. The accuracy is dependant on both the minimum sensing width and the disk diameter. The disk diameter is limited by the 2" housing and the physical size of the sensor.

To meet the accuracy requirement of 1 degree without enlarging the housing tube diameter, the EESX-1131 should be used.

3.4.2 Encoder Disk Design

The encoder disk for a transmissive detector consists of a thin piece of material with regions of high and low opacity. This is generally done by cutting slots around the perimeter of a disk. For a student built prototype, an alternative method of fabrication is desirable. Encouraged by the results seen in the experiment shown in Figure 3-9, an overhead transparency printed on with a laser printer was used for the final design.

The pattern that is printed on the transparency is very specific to the tolerances of the sensor, the desired resolution, and the need for the two phototransistors to be 90 degrees out of phase. As shown in Table 3.1, the minimum sensing width for the EESX-1131 is 0.012". Ideally this slot width should be used to achieve maximum resolution, but the data sheet doesn't specify if this minimum width provides 90 degree out of phase operation. Figure 3-12 below outlines the variables considered when assuring the proper phase shift.
If 90 degrees out of phase is desired, and A is located at the first edge, then B can only be located in certain places, this affects the width of the slots because the distance $AB$ is fixed by the sensor.

Because the distance $AB$ is fixed at 0.031", the feature width $D$ as shown in Figure 3-12 is given by the following equation:

$$AB = n \times D + 0.25D$$

where $n$ is the position of B. Solving Equation (5) for $n=1$ gives a feature width of 0.125", much too large to achieve the desired resolution. When $n=2$, the feature width is equal to 0.0248", making the width of the dark region 0.0124". This is the ideal slot width considering that it is almost exactly the minimum slot width.

Now that the feature size is known, a more accurate estimation of the sensor location is needed to design the feature to be printed on the disk. A solid model of the disk mounting system described in the next section is shown in Figure 3-13 below.
Using the distance from the axis of rotation to the optical axis of the encoder as the radius of the encoder disk, and substituting into Equation (3) gives 165 slots for 360 degrees of disk. This corresponds to an accuracy of 0.55 degrees. The actual disk will only have 83 slots to limit the system to 180 degrees of rotation, but the accuracy will remain the same. This is not necessary, but limiting the range of the unit may be desirable in situations where accidentally shining the sun in the opposite direction of the beacon is not desired. Also, some portion of the disk should be blacked out to provide a homing position, i.e. a startup position with a known mirror orientation such that the control system can periodically reset the position count. This is necessary to ensure that if encoder skips or double counts a slot, these errors don’t accumulate over time causing large position drift.

3.4.3 Encoder Disk Mounting

The disk mounting system must provide support for the encoder disk, rigidly attach it to the driveshaft, and not interfere with the encoder. Because material to be used is flexible, it is important to provide a rigid support such that it doesn’t move around inside the encoder. If the transparency contacts the inside wall of the encoder, it may become scratched during operation. Two designs were considered for supporting the disk. The first design is thin sheet of acrylic that has the same diameter as the printed transparency. Because the acrylic is clear, it should not affect the performance of the sensor. This design is nice because it provides full support to the entire disk. The drawback is that it also would increase the thickness of the disk. Because the slot in the encoder is only 0.080” wide, any extra material will increase the likelihood that it will rub on the encoder wall.
The other option is to design a support that will hold the disk up to a certain point, with the edge of the transparency free-floating in the encoder. Inserting only the edge of the disk into the encoder is advantageous because it minimizes the thickness of the disk and in turn the possibility of rubbing.

Delrin is used extensively in the rest of the system so to minimize the materials of construction it was also used for the encoder disk mount. Initially, the encoder wheel was to be glued onto the delrin bushing, but no readily available glues would stick to delrin. Glue would also prevent the changing of the encoder disk if it is damaged. The design was modified such that a press fit insert holds the encoder in place. An interference fit of 2-3 thousandths was determined empirically. Figure 3-14 below shows an exploded view.

![Figure 3-14: Exploded view of the encoder disk retaining bearing. The retaining ring (left most) press fits into the bearing, holding the encoder disk in place. The bearing is then secured to the drive shaft using a set screw. The inner black ring is a reference to show the edge of the encoder disk.](image)

After the encoder disk assembly has been snapped together, it is slid onto the drive shaft, and held in place by as set screw.

The encoder itself is a surface mount component and is soldered to a 1/16” circuit board. This board is then inserted into a slit in the upper bushing as shown in Figure 3-13. The upper surface of the encoder sits flush with the face of the busing.
3.4.4 Encoder Circuitry

The encoder sensor does not directly output a usable signal based on the presence of an opaque object. Therefore it is necessary to include a small amount of control circuitry to obtain the desired signal. This circuit will eventually be integrated into the controls circuit, but the controls engineer must know what to include.

The phototransistors inside the sensor act like a valve, allowing the flow of current when exposed to the emitter, and blocking the flow of current when an opaque object is inserted into the sensor slot. To change this current into a logic voltage, it is necessary to add a resistor between the phototransistor and ground. When current is flowing, more voltage drop will be over the resistor, when no current is flowing, more voltage drop will be over the phototransistor. The value of the resistor needed depends on many things, including the power emitted by the LED, the transmissivity of the clear regions of the encoder disk, and the slot width when the slot width is very small.

In addition to these resistors, another resistor is needed to limit the current through the LED emitter. From the datasheet\(^\text{11}\), a typical operating voltage is 1.1 V, and a reasonable current is 10 ma. This sensor will be supplied with 5 V, so the voltage drop over the resistor should be around 3.9 volts. Dividing the voltage drop by the current gives 390 ohms. Figure 3-15 shows the circuit used to read the output of the encoder.

![Diagram of the encoder circuit. The values for the pull down resistors on the output of the sensor were determined empirically using a potentiometer.](image)

A 74HC14 was added to filter the signal. The two 12.8 kΩ resistors were measured empirically by adjusting a potentiometer while turning the encoder at a constant speed until the output of the 74HC14 inverter had a duty cycle of 0.5. This was necessary because the output of the encoders is a sine wave rather than a square wave. More on the reasons for this is discussed in the Results section.

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\(^{11}\) The data sheet for the EE-SX1131 is available online at: [http://www.pohl-electronic.de/alt/EESX1131.pdf](http://www.pohl-electronic.de/alt/EESX1131.pdf)
3.5 Complete Solid Model

Figure 3-16: Solid model of the completed system. Bolts are not shown in this model.
Figure 3-17: Exploded view of the upper drive housing. The internals of the lower drive housing are identical other than the spacing between the motor assembly and the upper bushing.

Figure 3-18: Exploded view of the mirror support frame and mirror. Welds are located at all places the pipe is bent.
4.0 Results

A Lightshed mirror module was built, and a great deal was learned about the assembly and operation of the system. Only the lower drive system received an encoder, as the soldering of the surface mount encoder was very difficult, and only one is needed to evaluate its effectiveness. The lower drive assembly was also equipped with a cutaway to allow for the viewing of the encoder and drive system. Below is a picture of the finished Lightshed module.

Figure 4-1: A photo of the prototype Lightshed mirror module. The mirror appears hazy because the protective coating is still on it. A great deal was learned during manufacturing, assembly, and testing, and is discussed below.
4.1 Manufacture and Assembly

Several issues were encountered during manufacture and assembly that could be modified to allow for easier construction. While certain parts of the construction are difficult, the system meets the requirement of being able to be machined, and built by students. All parts were machined in student machine shops, and all assembly was done by hand.

The tube steel frame was the most difficult to manufacture not because of its complexity, but because of the requirement for welding. Access to welding facilities on campus is difficult, and outsourcing the construction of the frame may be necessary. The welds on the frame shown in Figure 3-17 and Figure 3-18 may be unavoidable, but if it were possible to eliminate them through some other construction, it could greatly reduce the amount of time spent on the frame. Another issue with the use of hand cutting and welding of steel tubing is accuracy. It was difficult to achieve the accurate 90 degree angles needed for the upper shaft alignment, and some bending was needed after welding.

Another intricacy not initially considered is the routing of wires through the tube steel frame to attach the upper drive system to the rest of the system. Passing wires through the frame is completely reasonable, and was achieved, but great care must be taken to remove all burrs from the insides of the tubes. Sending the motor wires through a frame with burrs was one of the most time consuming parts of assembly. The burrs also represent an electrical shorting hazard as they may cut through the wire insulation with time.

The most costly part of the system as mentioned early is the gearmotor. Unfortunately, this cost is relatively fixed, and can only be reduced by buying in quantity. Another large cost of building the prototype system was ordering the parts from McMaster Carr. McMaster specializes in small quantity fast turn around orders, and a cheaper source for stock materials should be found.

The most likely part to fail is the delrin motor coupling shown in Figure 3-5. During testing visible weakening of this part occurred, and in the future it should be changed to brass or some other metal that will not fuse with the steel (i.e. not steel).

4.2 The Encoder System

The performance of the encoder system was very good considering the materials of construction and operating at the limits of resolution of the sensor. As much as the design of the system tries to eliminate the need for high tolerances in assembly, the encoder module is very sensitive to changes in position along the shaft. It was found that moving the encoder disk from one side of the encoder to the other could vary the phase shift by more than 180 degrees. The encoder disk was adjusted by hand until the phase shift was approximately the desired 90 degrees, getting it exact would be very difficult. Scope traces were taken at both the sensor output, and the output of the hex inverter.
Figure 4-2: Scope traces for both channels of the encoder. These were taken before the inverter chip. They are sinusoidal because the slot width is very close to the minimum width.

The scope traces shown in Figure 4-2 are sinusoidal because the slot width is so close to the minimum slot width. When the black region is placed in the sensor, the voltage goes very close to zero, and when a clear piece of overhead transparency is used, it goes close to five volts. If the slot width were increased, the output of the sensor would approach a square wave, but this would also dramatically reduce resolution. To deal with this problem, the output of the sensor is filtered through a 74HC14 inverter chip as shown in Figure 3-15.
Figure 4-3: Scope traces for both channels of the encoder after passing through hex inverter. This data was taken over a longer period of time and expanded using the seconds/div knob causing the transitions to look slightly tapered. This method was used so that a long stretch of encoder transitions could be recorded, and then froze while the time between transitions could be recorded.

The data in Figure 4-3 shows the output of the 74HC14. To analyze the accuracy of the encoder, a long stretch of data is desired. This was achieved by freezing a full screen of data at 250ms/division and expanding it to 50 ms/division. In this manner, the time lag between the two signals on high to low, and low to high transitions was measured for 17 full transitions. In addition, the period was also measured for these 17 transitions such that an average phase shift could be calculated. A plot of the data can be found in Figure 4-4.
The average period length is 155 ms and the average transition time is 47.5 ms. The phase shift can then be found by dividing the period length by the transition time and multiplying by 360 degrees. The phase shift calculated for this encoder setup is 113 degrees, slightly higher than the 90 degrees that was designed for. The most obvious reason for this discrepancy is the disk alignment inside the encoder. Because the disk is illuminated from a point source and measure by two separate photodetectors on the opposing side, the distance between the emitter and the disk is very important. The closer the disk is to the emitter, the larger the projection of the disk image is on the photodetector side of the encoder, effectively changing the slot width. As shown in section 3.4.2, the slot width directly affects the phase shift. This explains the large variability seen when adjusting the encoder disk, and suggests that careful placement of the disk is needed for successful operation.

The variation in transition time and the non-ideal phase shift mentioned above will both decrease the previously calculated accuracy. The phase shift of 113 degrees decreases accuracy because the period has more resolution in one part than the other, lowering the resolution below ideal. Figure 4-5 below shows again the scope traces from the 74HC14 with particular times labeled.

Figure 4-4: Data collected for period and phase lag for both low to high and high to low transitions. If the encoder were indeed 90 degrees out of phase, the transition time would be one quarter the period.
Figure 4-5: Scope traces of the output from the 74HC14. Labeled on the chart are (A) one full period length, (B) the time lag between rising edges, and (C) an example of the time lag with added uncertainty. The resolution of the encoder can be determined by dividing C by A, and multiplying by the number of degrees of rotation for one period.

Labeled on the chart is (A) the length of time for one full period, (B) the time between rising edges, and (C) the time between rising edges with the added uncertainty of the transition time. The overall resolution of the encoder is then,

\[ R_{\text{actual}} = \frac{C}{A} \theta_{\text{period}}. \]  

Where \( \theta_{\text{period}} \) is the degrees of rotation for one period and \( R_{\text{actual}} \) is the actual resolution of the encoder. Using the data shown in Figure 4-5, the average period time (A) is 155 ms, average transition lag (B) is 47.5 ms, and the standard deviation is 5.9 ms. Table 3.1 lists the number of degrees rotated for one quarter of a period (the ideal accuracy), multiplying by 4 gives a rotation of 2.2 degrees for one period. Using an uncertainty of two standard deviations to approximate the value of C, and calculating the resolution as shown in Equation (5), the result is 0.84 degrees. Even with the non-idealities of the system, the resolution of the system still meets the specification of sub-degree accuracy. The system could be further improved by better positioning of the encoder disk to make the phase shift closer to 90 degrees, but this is difficult to do with hand assembly.
4.3 Microcontroller Feedback

A short demo of the prototype system was prepared using the Intel 8051 to control the position of the mirror. The final control system will use a different architecture, but a stand in control system is desirable for display purposes. Both axes of the prototype received a drive system, but an encoder was only installed on the lower axis. For this reason, the feedback system will only control the lower axis. A short program was written to interface with HyperTerminal, a PC program that allows communication through the serial port. Upon startup, the position of the mirror is set to 80h (hexadecimal) or 128 in decimal. Every few hundred milliseconds the position of the encoder is sent to HyperTerminal. At any time, the user can type a two digit hexadecimal value into HyperTerminal and the mirror will move to the new location. Each increase of 1 in the position represents one encoder transition, or approximately 0.55 degrees. The assembly code for this program can be found in Appendix C.

In addition to the program above, a small amount of circuitry is needed to provide power to the motors and interface with the 8051. The circuit used in this application is shown in Figure 4-6. The system is able to control the mirror to within one encoder transition, although it becomes unstable if the voltage is very high. With the voltage low, the movement of the mirror is very slow, so the feedback was modified to allow an error of one encoder position to either side of the desired position. This provides a resolution of approximately 2 degrees which is more than adequate for display purposes.
Figure 4-6: Circuit Diagram used to implement feedback with the 8051. Only relevant connections are shown.
5.0 Conclusion

With increasing oil prices, growing awareness about global climate change and increasing concerns about national security, now is the perfect time for new and innovative energy technologies. The Lightshed system aims to address these concerns through solar energy, specifically solar thermal concentration. While solar thermal concentration with a field of mirrors has been done before, Lightshed is unique in that each mirror module will be a separate entity, with no need for central control.

The drive system, support structure, and feedback system were designed paying close attentions to the requirements of low cost, reliability, and the ability to be manufactured by students. The control system will be added in the future, and the mechanical prototype developed in this thesis will aid in its design. In the construction of the first module, several issues with the current design were found. One of them is the welding requirement on the mirror support frame. Welding facilities on campus are hard to find, and the tolerances associated with hand welding are borderline for the alignment of the upper driveshaft. Another issue is the routing of wires through the tube steel frame, great care should be taken to remove all burrs before welding.

The encoder system was the most intensive part of the design process, as it was designed from scratch for this particular application. To meet the accuracy requirement of 1.0 degree, the encoder was designed with an optimum accuracy of 0.55 degrees, and a measured accuracy of 0.84 degrees was achieved. The lower than optimum resolution is due to the variability of disk placement within the encoder, which caused the phase shift to be 113 degrees rather than the desired 90 degrees. It is also due to the variability in phase transition time, which may be a result of variations in the printed slot width.
6.0 References

Cited


5. Conversations with student Alex Hornstein, MIT 9/06-5/07

6. Discussed further in section 3.2.1.


9. The data sheet for the EE-SX1131 is available online at: http://www.pohl-electronic.de/alt/EESX1131.pdf

Additional References

2. Conversations with Prof. Steven Leeb, MIT 2/07-5/07
Appendix

6.1 Appendix A: Part Drawings
Base Tube
Material: Steel

6 Holes
0.22" Dia.

Cut to length for application
Lower motor mount and bushing
Material: Delrin
Motor coupling
Material: Steel

1/8" steel pin
0.5" length
Drive shaft coupling
Material: Delrin
Upper bushing and encoder mount
Material: Delrin

Slot for encoder PCB
Threaded M5 0.5" depth
Upper motor housing
Material: Steel
Upper housing end cap
Material: Delrin
Mirror support frame and end plug
Materials: Frame-steel, Plug-Delrin
Top frame bearing
Material: Delrin
Encoder Disk
Material: Overhead transparency
6.2 Appendix B: Previous Versions

Figure 6-1: Lightshed version 3 with creator Alex Hornstein in the reflection. Version 3 was created by gluing together parts cut by a laser cutter. Mirror control was achieved using aircraft servos. (Courtesy of Alex Hornstein)
Figure 6-2: Lightshed Version 4 (foreground) and Version 3 (background). Lightshed version 4 used the same motors as selected for this project, but torque was transferred to the mirror through an angled gearbox. (Courtesy of Alex Hornstein)
6.3 Appendix C: Assembly Code

; This program was developed for the control of Bryan Woodruff's senior thesis.
; On bootup, the position (count) is set to 80h. Each consecutive set of the
; encoder results in an increment or decrement of the position.
; Every few hundred milliseconds the current position is transmitted using serial
; communications. Upon receiving a two byte serial packet, the system will update
; the desired position (cmd) and move there.

org 00h
ljmp start

org 00h
lcall PWM ; Checks the desired state of motor control
           ; Changes the outputs accordingly with a PWM signal
reti

org 100h

COUNT EQU, 26h ; Current Position
CMD EQU, 21h ; Desired Position
STATE EQU, 22h ; Encoder state
W0 EQU, 23h ; Wait loop variables
W1 EQU, 24h
DIFF EQU, 27h ; Difference between desired and actual
eerrorf equ 0 ; bit 0 is error status

start:
clr p1.6 ; Motor output status bit (clr = off)
clr p1.7 ; Motor output status bit (clr = off)
mov count, #80h ; Set count to 80h
mov state, #00h
mov w0, #00h
mov w1, #00h
lcall init ; Setup timers and interrupts
ljmp main

loop00:
jnb p1.4, E00 ; Check status, if same skip to next
inc count ; If different increment count
mov state, #10h ; Change state
ljmp main

E00:
jnb p1.5, main ; Check status, if same skip to main
dec count ; If different decrement count
mov state, #01h ; change state
ljmp main

;-----------------------------
loop10:
jb p1.4, E10
dec count
mov state, #00h
ljmp main

E10:
jnb p1.5, main
inc count
mov state, #11h
ljmp main

;-----------------------------
loop01:
jnb p1.4, E01
dec count
mov state, #11h
ljmp main

E01:
jb p1.5, main
inc count
mov state, #00h
ljmp main

;-----------------------------
loop11:
jb p1.4, E11
inc count
mov state, #01h
ljmp main

E11:
jb p1.5, main
dec count
mov state, #10h
ljmp main

;-----------------------------
main:
; Prints to screen in hex ever few hundred ms
inc w0 ; Increment print counter
mov a, w0
cjne, a, #255, read ; First print wait loop
mov w0, #00h
inc w1 ; Increment MSB print counter
mov a, w1
cjne, a, #22, read ; Second print wait loop
mov w1, #00h
mov a, count
lcall prthex ; Send current position out serially

; Updates command
jnb ri, continue ; Check to see if byte received
lcall getbyte
mov cmd, a ; Update command
continue:

;check to see if move is needed
-------------------------------
mov a, count
clr C
subb a, cmd
cjne a, #1, next3 ; Allow error of 1 high
sjmp off
next3:
cjne a, #255, Equal ; Allow error of 1 low
sjmp off

mov a, count

Equal:
cjne a, cmd, move ; If the count = command turn motors off
off:
clr p1.6
clr p1.7
ljmp read

; Move motor command
-------------------------------
mov: clr C
mov a, count
subb a, cmd ; Find out direction
mov diff, a

cpl p1.3

jc forward

reverse: ; Move reverse

setb p1.7
clr p1.6
ljmp read

forward: ; Move forward

setb p1.6
clr p1.7
ljmp read

; See if encoder has changed

;---------------------------------------

read:

mov a, state
cjne a, #00h, next
ljmp loop00

next:

cjne a, #01h, next1
ljmp loop01

next1:

cjne a, #10h, next2
ljmp loop10

next2:

cjne a, #11h, read
ljmp loop11

; PWM routine

;---------------------------------------

PWM:

cpl p1.2 ; Change high/low pwm state

jb p1.7, forward1

jb p1.6, reverse1

setb p1.0 ; If both motor state variables are

setb p1.1 ; low, turn motor off

ret

forward1:

setb p1.1

low0:

jb p1.2, high0

mov th0, #50

setb p1.0
ret

high0:
  mov th0, #100
  clr p1.0
  ret

reverse1:
  setb p1.0

low1:
  jb p1.2, high1
  mov th0, #50
  setb p1.1
  ret

high1:
  mov th0, #100
  clr p1.1
  ret

;-----------------------------------------------

; Subroutines
;-----------------------------------------------

wait:
  mov rl, #255

wait1:
  djnz r0, wait1
  djnz rl, wait1
  ret

init:
  mov tmod, #22h
  mov tcon, #50h
  mov th1, #0fdh
  mov scon, #50h
  mov rl, #65
  setb ie.7 ; enable interrupts
  setb ie.1 ; enable timer 0 overflow interrupt
  mov th0, #80h
  ret

; The following subroutines were taken from
;
getchr:
    jnb ri, getchr
    mov a, sbuf
    anl a, #7fh
    mov cmd, a
    clr ri
    ret

sndchr:
    clr scon.1
    mov sbuf, a

txloop:
    jnb scon.1, txloop
    ret

; subroutine prthex
; this routine takes the contents of the acc and prints it out
; as a 2 digit ascii hex number.

prthex:
    push acc
    lcall binasc ; convert acc to ascii
    lcall sndchr ; print first ascii hex digit
digit
    mov a, r2 ; get second ascii hex digit
    lcall sndchr ; print it
    mov a, #32
    lcall sndchr
    pop acc
    ret
; subroutine binasc
; binasc takes the contents of the accumulator and converts it
; into two ascii hex numbers. the result is returned in the
; accumulator and r2.

binasc:
  mov r2, a ; save in r2
  anl a, #0fh ; convert least sig digit.
  add a, #0f6h ; adjust it
  jnc noadj1 ; if a-f then readjust
  add a, #07h
noadj1:
  add a, #3ah ; make ascii
  xch a, r2 ; put result in reg 2
  swap a ; convert most sig digit
  anl a, #0fh ; look at least sig half of acc
  add a, #0f6h ; adjust it
  jnc noadj2 ; if a-f then re-adjust
  add a, #07h
noadj2:
  add a, #3ah ; make ascii
ret

; Get byte
;--------------------------------------------------------
getbyt:
  lcall getchr ; get msb ascii chr
  lcall ascbin ; conv it to binary
  swap a ; move to most sig half of acc
  mov b, a ; save in b
  lcall getchr ; get lsb ascii chr
  lcall ascbin ; conv it to binary
  orl a, b ; combine two halves
ret

; subroutine ascbin
; this routine takes the ascii character passed to it in the
; acc and converts it to a 4 bit binary number which is returned
; in the acc.

ascbin:
  clr errorf
  add a, #0d0h ; if chr < 30 then error
jnc notnum
clr c ; check if chr is 0-9
add a, #0f6h ; adjust it
jc hextry ; jmp if chr not 0-9
add a, #0ah ; if it is then adjust it
ret

hextry:
clr acc.5 ; convert to upper
clr c ; check if chr is a-f
add a, #0f9h ; adjust it
jnc notnum ; if not a-f then error
clr c ; see if char is 46 or less.
add a, #0fah ; adjust acc
jc notnum ; if carry then not hex
anl a, #0fh ; clear unused bits
ret

notnum:
setb errorf ; if not a valid digit
ret