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Design of a Flexible Solar Cell Testing Mechanism

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Design of a Flexible Solar Cell Testing Mechanism

A Major Qualifying Project Submitted to the faculty of the WORCESTER POLYTECHNIC INSTITUTE in partial fulfillment of the requirements for the Degree of Bachelor of Science in Mechanical Engineering

Submitted: April 25, 2019
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Abstract

Flexible solar cells offer more versatile and diverse applications than traditional photovoltaics. In development, the structural and electrical integrity of the cells must be tested in response to mechanical stresses. This project aims to develop a fixture to test the effects of fatigue, bending at various radii, and stretching on flexible solar cell prototypes. The test fixture offers repeatable, consistent, and precise experiments to assess efficiencies and material responses in controlled environments. The design consists of a dry box for testing in different atmospheric conditions, a linear actuator to control and iterate bending radii, and an automation system for fatigue testing. A prototype was fabricated and tested with flexible solar cells to observe the effect of bending and fatigue.
Acknowledgements

The team would like to thank Professor Pratap Rao for his guidance, recommendations, and constructive feedback which were instrumental in the successful completion of this project. Additionally, the team extends its thanks to graduate student Nicholas Pratt for his assistance with solar cell fabrication and suggestions.

The team would also like to thank the Robotics and Electrical Engineering students who have lent assistance during this project, including Eric Carkin, Dillon Arnold, and Parker Grant. Likewise, the team expresses its gratitude to the Washburn Labs faculty especially the senior instructional lab technician, Ian Anderson.
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1.0 Introduction

In a world with growing dependence on energy and electric energy consumption, as well as concerns over the environmental impact of carbon emissions, the generation of reliable and consistent energy sources is key to the future of power. Research and development in renewable energy sources has progressed and is seen as a promising technology to further clean energy generation. Of specific interest is energy generated from harvesting sunlight.

Solar cells have had growing prominence in electric energy generation. To continue the growth and use of solar cells, new innovations are required to increase their applicability and efficiency. One such innovation is flexible solar cells. Flexible solar cells can have a variety of applications ranging from use on curved surfaces to complete bending on fabrics. When this application is supported with efficient, functioning solar cells, the wide scale dissemination of such technology has the potential to change the way energy is generated.

In order to test the flexibility and electrical performance of flexible solar cells in research environments, researchers commonly bend samples to specific radii while measuring their efficiencies. Common techniques for such testing include bending samples around curved surfaces with determined radii, compressing the sides of cells to induce bending, or applying cells to stretchable materials. Each method has a variety of advantages and disadvantages, such as ease of operation or the ability to completely control the desired radii. However, none of these systems provide the ability to measure other factors such as strain, test flexibility in different orientations such as twisting, or automate iterative testing for fatigue analysis.

To obtain consistent and reliable flexibility, efficiency, and electrical output data, a device is needed to standardize testing. By developing a specific device to measure these factors in an automated system controlling the bending and force applied to cells, measurements on different
individual cells or types of cells can be reliably compared. Such comparisons can conclude which solar cell configurations and materials produce the greatest electrical output while providing the desired flexibility. This device can also be used to repeat bending iterations in order to study how fatigue may affect or degrade cells. Other measurements such as strain, and other movements such as twisting can also be accomplished with this device. These factors will assist in the development and research into improving flexible solar cells.

Throughout this project, different designs from other solar cell testing platforms, as well as other applications will be studied to find feasible mechanisms to achieve the desired goal of the final design. Several designs will be developed and prototyped to assess the best system and mechanism. Through a process of testing and improving the mechanical design, the device will be fabricated for practical use. The final design will then be used to test solar cell flexibility and establish the procedure to use the device.
2.0 Background

The use and reliance on constant energy sources has become commonplace in modern society to power ever more technologically dependent lives. As the world's population grows, energy demand increases, and environment declines, scientists and engineers are met with the challenge to provide plentiful, reliable, and clean energy. Solar cells are on the forefront of the growth of renewable energy and promise a future less reliant on fossil fuels for energy generation. Of particular interest to researchers is developments made toward creating flexible solar cells using perovskite material. This chapter will review the current and future energy use in the United States, the outlook of solar cell technology, gains in perovskite solar cell research, and the technology required to advance flexible solar cells.

2.1 Energy Consumption

The United States is the second largest energy consumer in the world, using 97.7 quadrillion BTUs in 2017 (U.S. Energy Information Administration, 2018c). Under nearly every economic scenario, the U.S. Energy Information Administration projects that the United States’ energy demand will increase by 2050, surpassing the 2007 peak by 2033 as seen in Figure 1 (U.S. Energy Information Administration, 2018a).
Of the 97.7 quadrillion BTUs consumed in 2017, approximately 90% of this energy was produced domestically, with 78% being produced from fossil fuels including natural gas, petroleum, and coal (U.S. Energy Information Administration, 2018). The prevalence of each energy source is shown in Figure 2 in addition to the distribution of consumption by each sector. Electric power consumes the most energy, followed by transportation, industrial, and residential sectors.

**Figure 1: Projected energy consumption growth 1990-2050 (U.S. Energy Information Administration, 2018).**
In response to growing concerns over fossil fuel and carbon emission driven climate change, contributions of renewable energy sources have increased, nearly doubling between 2000 and 2017 (U.S. Energy Information Administration, 2018b). As seen in Figure 2, renewable energy now accounts for 11% of all energy consumption in the United States. Renewable energy sources are expected to grow in the next 3 decades, accounting for 64% of electric generation growth through 2050 (U.S. Energy Information Administration, 2018).

2.1.1 Solar Cell Energy Generation

Solar cells are a promising component of the future of renewable energy. Projections show that solar PV will lead the growth of renewable energies, accounting for the largest amount of energy generated by 2050 as seen in Figure 3 (U.S. Energy Information Administration, 2018).
2.1.3 Current Solar Cells

The most prominent commercially available solar PVs have trade-offs between price and efficiency. Efficiency, the measure of energy generated compared to the maximum possible energy generation from the sun, often drives the cost of solar cells or panels. The most efficient PVs produce the greatest amount of energy, increasing their manufacturing costs and ultimate price tag. A variety of solar PVs are available in the market, each satisfying a different efficiency and price range.

Crystalline silicon PVs currently dominate the market, accounting for approximately two-thirds of all PV installations in 2009 (Tester, 2012). Silicon solar cells are composed of crystal silicon which absorbs light and releases electrons for energy use. Electrons move through the silicon to the front contact where they are collected and enter the electrical circuit before returning to the back contact of the cell to recombine as seen in Figure 4 (Knier, 2018). Both single crystalline cells composed of a single silicon crystal and polycrystalline cells composed of many silicon crystals are available (Tester, 2012). Single crystal structures are more efficient and costly.
than polycrystalline structures, due to the improved electron transport properties and increased manufacturing costs.

![Silicon P-N junction solar photovoltaics](image)

**Figure 4: Silicon P-N junction solar photovoltaics.**

Thin-film PVs have significantly reduced costs over other designs in tradeoff for lower efficiencies (Tester, 2012). These cells are made of amorphous silicon, which does not have a crystal structure yet has high absorption qualities. Thin-film PVs have thicknesses of 1μm or less with the same configuration as a crystalline PV as shown in Figure 4, making them inexpensive to manufacture.

The differing characteristics for these various PV types are outlined in Table 1.

**Table 1: Comparison of commercially available solar PVs (Tester, 2012).**

<table>
<thead>
<tr>
<th></th>
<th>Single Crystalline Silicon</th>
<th>Polycrystalline Silicon</th>
<th>Thin-Film</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Cost</strong></td>
<td>Expensive</td>
<td>Inexpensive</td>
<td>Inexpensive</td>
</tr>
<tr>
<td><strong>Efficiency</strong></td>
<td>Highest efficiency</td>
<td>Inefficient</td>
<td>Inefficient</td>
</tr>
</tbody>
</table>
2.2 Perovskite solar cells

Of key importance to the growth of widespread use of solar cells is improving cell efficiency and reducing manufacturing costs. Perovskite based solar cells have been suggested as the future of photovoltaic energy generation based on its unique properties and inexpensive manufacturing.

Perovskites take the chemical formula $ABX_3$, where $A$ and $B$ are cations, with $A$ being larger than $B$, and $X$ is an anion (Green, Ho-Baillie, & Snaith, 2014). These materials have several promising properties that suggest proliferation of their use in solar cells is possible. First, perovskites are easy to fabricate, reducing production costs. Second, they have strong solar absorption, allowing for more sunlight to be absorbed to generate power. Third, they have low non-radiative recombination rates, making more electrons reach the electric circuit thereby improving efficiency.

Perovskites are limited, however, by their stability (Shirayama et al., 2016). Upon exposure to moisture, including the humidity present in ambient air, and ultraviolet radiation, the material degrades and loses its properties and efficiency. It is widely acknowledged that the perovskite reacts with $H_2O$ in the air, though the exact degradation mechanism and reaction is still debated.

2.2.1 Perovskite Cell Structure

A variety of structures have been tested and researched for perovskite cells, most containing common features including an anode and cathode for integration to the electric circuit, a hole transport layer, an electron transport layer, and the absorption layer. Figure 5 displays the common features.
2.2.2 Substrate

Solar cell substrates act as the base for the cell, upon which the operating layers are deposited (Werthen, 2011). Glass is the most common substrate used in traditional and experimental cells, due to its rigid and translucent properties. However, research is being conducted to determine if less rigid substrates can be applied efficiently to solar cells, as will be elaborated in section 2.3.

2.2.3 Anode & Cathode

The anode is responsible for transferring electrons from the solar cell to an external electric circuit which will transmit the generated power for use. This layer is commonly clear and fixed to the clear substrate, allowing sunlight to penetrate into the cell layers where energy is generated. Similarly, the cathode accepts the spent electrons and transfers them back into the solar cell. This layer is commonly not exposed to sunlight, and therefore does not need to be clear to transmit light. Ideal anodes and cathodes have a small resistivity, allowing the maximum efficiency of electron transfer out of the cell.

A common anode material used in solar cell design is indium tin oxide (ITO) (Guo et al., 2016). ITO is a ceramic material that exhibits a high electrical conductivity, which is necessary to transport electrons between the cell and the electric circuit. It likewise has a high optical
transmittance, allowing light to pass through and reach the absorption layer beneath. Conversely, ITO is a brittle material that does not react well to stresses. Its electrical conductivity is reduced when altered under mechanical deformation.

Cathode materials are generally selected from high work function noble metals in order to maximize the open circuit voltage (Jiang, Sheng, Shi, Feng, & Xu, 2014). Gold, platinum, and silver are common selections for this application.

2.2.4 Electron and Hole Transport Layers

The electron transport layer (ETL) is responsible for transporting electrons from the absorber layer to the anode. In perovskite solar cells, the perovskite material can act as the electron transport material (Gondal, Popoola, & Qahtan, 2017). An independent electron transport layer is often added however to improve electron collection and cell efficiencies. Metal-oxides such as titanium dioxide and zinc oxide, and organic ETLs are most common for this application.

The hole transport layer (HTL) is likewise responsible for transporting holes from the absorber layer to the cathode (Gondal et al., 2017). Common materials selected for the HTL are spiro-OMeTAD ([2,2,7,7-tetrakis(N,N-di-p-methoxyphenyl-amine) 9,9-spirobifluorene]), copper thiocyanate, and poly-3-hexylthiophene, among others.

Ideal ETL and HTL materials have a conduction band similar to that of the perovskite layer, enabling a more efficient transfer of electrons and holes between the two layers (Gondal et al., 2017). Similarly, high electron mobility is favorable to extract the maximum number of electrons possible from the cell. Dependent upon the applications and design of the solar cell, characteristics such as temperature processing and mechanical properties can be selected. For example, a flexible solar cell would require low processing temperatures to be compatible with the substrate material, and a high young’s modulus to prevent plastic deformation.
2.2.5 Absorber and Insulator

The absorber layer is responsible for converting light energy into electric energy. Sunlight that penetrates the solar cell and reaches the absorber layer excites electrons according to the materials band gap and the light wavelength, creating an electron and hole pair. Each carrier then moves to its respective side of the cell.

As previously discussed, perovskite materials have several properties making them ideal for solar cell applications including their fabrication, solar absorption, and non-radiative recombination rates. Due to its ability to easily degrade, it has been found that adding insulative materials to the cell structure can reduce its degradation (Li et al., 2018). Specifically, the addition of polystyrene on top of the perovskite layer and after the conductor can provide a barrier to prevent moisture from contacting the perovskite.

2.3 Solar Cell Flexibility

As thin film and perovskite solar cells grow in efficiency and producibility, so do the prospects of the development of flexible solar cells (Pagliaro, Ciriminna, & Palmisano, 2008). The mechanical properties of these photovoltaic devices broaden the possibility of fabricating solar cells on flexible substrates. Likewise, the “simple, cheap, and low-energy deposition methods” such as spin coating used to produce thin-film and perovskite solar cells indicates the possibility of producing inexpensive devices for greater proliferation in the market (Chopra, Paulson, & Dutta, 2004).

2.3.1 Applications of flexibility

Flexible solar cells have the potential to reach more applications and uses than conventional rigid solar cells (Pagliaro et al., 2008). Prominent applications of such technology include uses on pliable surfaces such as fabrics on backpacks or tents. This would provide power to remote areas,
such as for soldiers in the field (Turnbull, 2013). Of particular interest is wearables, the integration of solar cells into clothing to bring convenience to charging electronic devices such as phones and laptops (Bertoni, He, Wang, Xiong, & Yang, 2017). Less obvious applications are derived from the thin and lightweight properties of flexible solar cells. Traditional solar cell uses on structures such as homes and businesses can be improved, by replacing bulky solar panels with integrated roofing and windows (Pagliaro et al., 2008). Flexible solar cells may also find applications on curved surfaces, such as cars. Their applications to space exploration are additionally being researched, since they add less weight to space exploration and can be rolled to be expanded in space (Gaskill, 2017).

2.3.2 Flexibility Limitations

Several factors are considered in studying the flexibility of solar cells. The mechanical properties of materials in the cell’s composition, and the electrical effects of bending both impact the performance of the cell.

The motion and mechanical flexibility of solar cells are largely dependent upon the substrate on which they are assembled. While glass is typically used for rigid solar cells, flexible solar cells have been created on a variety of substrates such as paper, polymers, metals, and plastic (Barr et al., 2011; Kang, Park, Ryu, Chang, & Kim, 2006; Weerasinghe, Huang, & Cheng, 2013; Yaowen Li et al., 2016). Since the solar cell layers deposited on the substrate are extremely thin, the cell is capable of bending within the physical constraints of the substrate.

While cell flexibility is dependent largely upon the substrate, the properties of each layer limit the effectiveness of the cell when bent (Yaowen Li et al., 2016). This is an efficiency rather than physical constraint. The materials commonly used in different cell layers have poor mechanical robustness against the flexing of the cell. Transparent conductors used as an electrode
on substrates have been found to be fragile against bending and are often the cause of device failure or degradation (Yaowen Li et al., 2016). Likewise, the poor mechanical properties of the absorption and transport layers of cells can create cracks or deformations within the layers as shown in Figure 6 (Poorkazem, Liu, & Kelly, 2015). Such defects interfere with carrier transport, allowing for increased recombination, increased resistance, and decreased short circuit current density.

![Figure 6: Solar cell cracks in response to bending (Poorkazem et al., 2015).](image)

### 2.3.3 Current State of Flexible Solar Cells

Despite the challenges associated with flexible solar cells, current research has proven that the technology has the potential to compete with traditional photovoltaics. While rigid perovskite solar cells have reached efficiencies of 22.7%, flexible perovskite solar cells have reached records of 18.4% efficiency (Feng et al., 2018). This result remains relatively constant under the influence of bending, dropping to approximately 15% with a bending radius of 4mm, as seen in Figure 7. Bending was seen to have minimal impact on the short circuit current density of the cell, at approximately 21.75 mA cm$^{-2}$. 
Figure 7: Record efficiency of perovskite solar cells under bending (Feng et al., 2018).

Single-junction solar cells have also reached high efficiencies, with a flexible, thin-film GaAs photovoltaic device developed by Alta Devices reaching an efficiency of 27.6% (Kayes et al., Jun 2011). This device reached a short circuit current density of 29.6 mA cm$^2$, an open circuit voltage of 1.107V, and a fill factor of 84.1%. Results were not reported however on the cell performance under bending.

Likewise, CIGS and CdTe solar cells have seen advancements (Petter Jelle, Breivik, & Drolsum Røkenes, 2012). As seen in Figure 8, the efficiencies of CIGS and CdTe flexible solar cells have reached 18.7% 13.8% respectively. The flexible CIGS cells have surpassed the efficiency of rigid CdTe on glass substrates and is nearing that of rigid CIGS on glass substrates.
Figure 8: CIGS and CdTe flexible solar cell efficiency development (Petter Jelle et al., 2012).

2.3.2 Measuring flexibility

In order to assess the efficiency, electrical performance, and bending of solar cells, researchers use a variety of bending methods. Samples are subjected to bending of different radii, and the efficiency and electrical performance of the device is measured at each radius to determine the cell operation when flexed.

The most rudimentary technique employed by researchers to test flexible solar cells is bending samples around objects with a fixed and known radius. This technique is widely used and can be seen in various publications (Kim, J. et al., 2016; Law et al., May 2006; Poorkazem, Liu, & Kelly, 2015; Yoon et al., 2017). Measuring flexibility on curved surfaces in simple in application and provides an easy way to subject samples to specific, known radii. As seen in Figure 9, depending on the radius and size of the sample this technique can provide a consistent and uniform bending to the entire surface of the sample. It is also advantageous since electrical connections can be easily attached to the sample. This technique, however, is dependent on the size of curved objects and therefore cannot provide measurements at any desired radius. Likewise, if the radius
is small enough that the sample occupies more surface area than possible on the curved device, the entire sample may not be subjected to the same bending radius.

Figure 9: Flexibility testing with curved surfaces (Kim et al., 2016; Law et al., May 2006).

A slightly more advanced technique used to test flexible solar cells is compressing the samples edges together to induce bending (Kim, B. J. et al., 2015; Schubert & Werner, 2006; Yaowen Li et al., 2016). This technique has many forms, as seen in Figure 10. This technique provides more control over the bending radii. Instead of finding objects with the exact desired radius, the compression technique can be used at nearly any radius. It can be deduced from the images however, that this does not provide a consistent bending radius over the entire sample. The area in the center of the sample experiences the smallest bending radius, which then increases toward the edges of the sample. Likewise, it can be deduced from the images that arranging contacts with the cell to measure efficiencies and electrical output could be hindered by the vice-like mechanism.
Employing a different and unique testing system, some researchers do not depend on measuring cells at different radii (Martin Kaltenbrunner et al., 2012). Rather, a technique is used that mimics the flexibility and movement of pliable materials as seen in Figure 11. Once fabricated, solar cells are attached to a stretched elastomer. Electrical performance measurements can then be conducted under different tensile strains on the sample. This technique is limited in application, suitable for solar cells with extreme bending capabilities. The wrinkles in Figure 11 are estimated to have a bending radius of 10 μm. While this provides a more realistic simulation of flexibility and pliability, the bending and wrinkles are largely uncontrolled.

Figure 10: Flexibility testing with compression (Schubert & Werner, 2006).
Each of these techniques lack the ability to measure more than the bending radius and electrical performance of solar cells (Kim et al., 2015; Kim et al., 2016; Martin Kaltenbrunner et al., 2012). Other factors such as strain experienced by the solar cell have not been reported in testing results using these methods. Likewise lacking in reports on these techniques is the ability to automate the system for precision and repeatability. While repeated bending iterations are reported for fatigue testing results, there is no indication that an automated system was utilized, especially in the case of testing with curved surfaces (Poorkazem et al., 2015). Finally, these systems are limited to uniaxial bending and are not used to test solar cell performance under different flexible motions, such as twisting or tension.
3.0 Scope

The goals of this Major Qualifying Project are twofold. First, a device capable of bending flexible solar cells with specific radii, while measuring the strain and electrical efficiencies, will be designed and fabricated. Second, this device will be tested and used to measure the bending, strain, and electrical efficiencies in flexible solar cells in order to compare the consistency of data to previous testing methods. These goals have a variety of purposes that will contribute to the progress and research of flexible solar cells.

The device will be made to fit in a clear box for controlled environments and be controlled externally for testing. The constraints of such a device are as follows:

- Solar cell sample must be easily loaded and removed from device
- Device must work for self-supporting and flimsy solar cells
- Device must be compatible with Solar Simulator, requiring a quartz window and UV resistant acrylic
- Device must have probes to measure the cell that can be read outside the box
- Device must work in different gaseous environments, requiring a sealed chamber that can contain different gaseous compositions
- Device must measure efficiency of the solar cell before and after the bending process
- Device must control the radius to which the cell is bent, in both convex and concave directions
- Device must be automated

By designing a device to test solar cell flexibility, such tests can be standardized, allowing for consistent data collection. Measurements of cell efficiency and power generation under constraints such as bending radii, number of bending iterations, and force, will be more consistent and reliable
when completed with an independent device free from human error. Additionally, of particular interest is the ability to repeat bending iterations to assess fatigue. With an automated device, measurements under repeated bending can be taken without researchers needing to complete this manually.

The completed device will then be used to determine how layers react to bending. Individual layers can be tested independently to determine their limits and constraints, or testing can take place on the entire cell. Since efficiency and power measurements will be taken on the cell during bending, the point at which failure or decreasing results can be determined, and the layer(s) causing the failure can be investigated. By developing the technique and procedure to investigate each layer, the bending limitations of future cell designs can be tested. The limiting or constraining layers can be determined and replaced with new materials to improve cell flexibility.
4.0 Methods

Several steps were taken to design the test fixture. First, the existing testing mechanism was studied to understand how the design must interact with the testing equipment and software. Second, ideas were brainstormed based on best practice research. Third, designs were compared with design matrix tools to select the best concept. Finally, the selected concept was developed through iterations of design.

4.1 Best Practice

The current method used in Professor Rao’s solar cell research involves bending the cells around objects with a known radius as previously described in section 2.4.2. After bending, the cell’s efficiency is then measured with the normal lab technique. In order to design a mechanism that properly interacts with the measurement apparatus, this process must be understood.

The solar cells are exposed to a light source that mimics that of the sun, providing \(1000 \frac{W}{m^2}\) of solar irradiance. Cells are mounted on a glass slide with double-sided tape and are clamped such that they are 130mm away from the light source and 5.5in high from the top of the table, effectively lining up with the center of the light source. Electrical leads are positioned to touch the electrical contacts (positive and negative terminals) of the cell. This configuration can be seen in Figure 12.
Figure 12: Solar cell measurement configuration.

Measurements are taken using ECC-Lab. The light is temporarily blocked from reaching the cell to establish a baseline, after which the light is exposed from the cell. Over a period of fifteen to twenty seconds, the cell is exposed to a concentrated ultraviolet light source. ECC-Lab then makes a current (in milliamps) vs voltage bias (in volts) graph of the output. Figure 13 shows a typical current vs. voltage bias for a solar cell.

Figure 13: Current Density vs Voltage graph.
Knowing the current vs voltage bias is important when determining the current density of the cell (measured in milliamps per square centimeter, $\frac{mA}{cm^2}$). This is calculated by dividing the current by the total area of the cell. This current density can then be multiplied by the voltage bias to get the power density of the solar cell. This can be directly compared to the power density of the light making contact with the cell to determine the efficiency of the cell, e.g. the percentage of the light energy hitting the cell that the cell is able to convert into electrical power.

In the new design, the same measurement system will be used to characterize the cells. As such, the positioning of the cell with regards to the light source and the placement of the electrical leads must remain the same. Likewise, the solar irradiance must not be weakened or degraded through the sealed chamber.

4.2 Brainstorming

Based on the most common types of bending tests described in section 2.4.2, as well as additional research conducted on different testing mechanisms, several design concepts were generated. Three primary concepts were studied, including a rotating device, 3-point bending, and circular compression.

4.2.1 Rotating Mounts

Since the device is intended to control the bending radius of the cell, as well as the convex and concave direction of the cell, a mechanism was considered that would mimic compression testing as described in section 2.4.2 with the additional element of rotating the mounts on the sides of the cell. A similar design was found to be manufactured by Yuasa System Co., LTD. Their Tension-Free™ U-shape Folding Test claims to apply only a bending load without tension or
friction to a sample. This operated by sliding one side mount close to a fixed side mount and allowing the mounts to rotate with the motion of the device, as seen in Figure 14.

![Jig Movement](image)

Set the sample flat on the tilt clamp. The equipment will repeat flat and bend motion. When bending, the tilt clamp moves downward so the sample would bend in natural U-shape. It is possible to perform vertical tests by setting the tilt clamp up right.

**Figure 14: Yusa System Co., LTD Tension-Free™ U-shape Folding Test (Yusa System, 2018).**

This specific device is limited however for this application. The system is large and bulky, preventing it from being enclosed in a sealed chamber for controlled environmental testing. Likewise, the device only operates in one direction and does not allow for both convex and concave bending. Finally, this is intending for folding and will not conform to different bending radii.

4.2.2 Three Point Bending

Three point bending is commonly used in experiments to find the elastic modulus of a material. In this testing the sample it help laterally on both ends and then a force is applied to the center of the sample to create a bending moment. To find the elastic modulus in this experiment, the force is increased until the sample breaks. Figure 15 shows an example of an Instron machine performing a three point bending experiment.
This method offers a lot of control and the ability to measure the force that is applied to the sample. While this method would control the different radii by changing the radius of the object applying the force in the center, it cannot easily be changed to bend a sample in both convex and concave shapes. In addition, applying pressure directly to the center would cause damage to the solar cell being tested and could only be applied once rather than multiple times.

4.2.3 Circular Compression

Traditionally, the folding and bending of a flexible solar cell was done by hand by wrapping the cell around objects with a known radius, such as a pen. This method of testing has multiple variables that can impact the accuracy and validity of the test. First, it is impossible to test using this method in different atmospheric conditions. The cell must be held in the same environment as the tester, and this environment can vary by location or local weather and atmospheric conditions. Second, every time the cell is manually wrapped around a cylinder the orientation and stability of the cell differ. This can throw off the accuracy of the bending test. As such, the team
wants the device to be able to provide consistent bending stresses of desired radii, that can easily be repeated in different atmospheric conditions.

Commonly, a device that acts like a hydraulic press is used to bend thin film materials to desired radii. The device consists of a static platform and a press that is parallel to and moves perpendicularly and in a linear fashion towards and away from the platform. The thin film material is secured to the bottom of the press and the top of the platform in such a way that as the press head is lowered toward the platform, the material bends in a predictable manner, with the radius of the bend being half the distance between the press head and the platform. The device is shown in Figure 16.

![Circular compression test device (Auzins, 2012).](image)

Figure 16: Circular compression test device (Auzins, 2012).

Two major issues in the circular compression design exist. First, it is only able to bend the cells, it is unable to perform a stretching test without major alterations to the design of the device. Second, it will have difficulty maintaining consistent bending radii when bending extremely flimsy materials that have little structural rigidity. Materials with structural properties similar to those of materials such as tissue paper or plastic wrap will droop and not hold the constant radius desired for testing. If attempting to test thin film solar cells with properties similar to these materials, the circular compression device may be unsuitable.
4.3 Design Matrix

In order to select the best design concept for this application, a design matrix was used to evaluate each design. Each concept was assessed by the following criteria:

- Ease of use: ease to load and unload cells, as well as operate the device
- Self-supporting cells: ability to support and measure cells
- Flimsy cells: ability to support and measure flimsy cells
- Measurement compatibility: ability to operate well with the specified measurement procedure
- Control bending radii: ability to properly control the bending radii of the cell
- Concave and Convex: ability to measure cell performance with both convex and concave bending
- Fatigue/automation: ability to be automated and complete fatigue testing
- Stretching: ability to conduct tests under tensile stress

Each category was rated on a scale of 1-5, with 5 being the highest rating and indicates the ability for the design to execute that criteria. This resulted in scores as outlined in Table 2, with the rotating mounts achieving the highest score. For this reason and considering the advantages of this concept, the rotating mounts design was selected for development and fabrication.
4.4 Iterations

To develop the rotating mount mechanism, a design was created for two plates that would come together and compress a cell to a specified radius. Each plate has a rotating hinge on which the cell will be mounted. Several iterations of this main design were completed to maximize the design.

In the first iteration, the walls are contained in a mount frame to achieve the appropriate height required for performance measurements as seen in Figure 17. The walls move together with slides on the metal bars. Additionally, a clamp was designed to hold the cells on the hinge as seen in Figure 18. This design was bulky and had significant interference between the walls, preventing cells from being folded almost completely in half for the most extreme bending testing. Likewise, this required that an entire actuator system be designed to match the dimensions of this system.

Table 2: Design Matrix.

<table>
<thead>
<tr>
<th>Concept</th>
<th>Ease of Use</th>
<th>Self Supporting</th>
<th>Flimsy</th>
<th>Measurement Compatibility</th>
<th>Control Bending Radius</th>
<th>Fatigue and Automation</th>
<th>Stretching</th>
<th>Sum</th>
</tr>
</thead>
<tbody>
<tr>
<td>Rotating Mount</td>
<td>4</td>
<td>5</td>
<td>2</td>
<td>5</td>
<td>4</td>
<td>5</td>
<td>5</td>
<td>35</td>
</tr>
<tr>
<td>3 Point Bending</td>
<td>5</td>
<td>5</td>
<td>1</td>
<td>3</td>
<td>4</td>
<td>2</td>
<td>5</td>
<td>26</td>
</tr>
<tr>
<td>Circular Compression</td>
<td>3</td>
<td>5</td>
<td>1</td>
<td>2</td>
<td>3</td>
<td>3</td>
<td>5</td>
<td>23</td>
</tr>
</tbody>
</table>
In an effort to achieve convex and concave bending, a mechanism was designed to control the rotation direction of the hinge. In this iteration, the mounting system was maintained. However, the walls dimensions were adjusted to make the hinge flush with the plate, and the hinges were lengthened to allow for control of the rotation. This design is shown in Figure 19. As with the first design, this design is bulky and requires custom actuator elements.
Figure 19: Design iteration two.

The effort to reduce the size of the system and adapt it to existing actuator controls led to the final design of the test fixture.
5.0 Results

In this section, the final design and prototype will be described. Results of testing conducted with the prototype will be reported.

5.1 Final Design

The final design of the test platform consists of adapted actuators and custom made parts to achieve a controlled bending radius. All elements were combined with electric automation capabilities to improve the functionality of the system.

5.1.1 Linear Actuator

In order to achieve the precision required, an existing linear actuator was selected to adapt for this application. The SainSmart Linear Stage Actuator with Nema17 Stepper Motor for CNC Router was selected for its stage on which the mounting system could be built, as seen in Figure 20.

![Figure 20: SainSmart Linear Stage Actuator with Nema17 Stepper Motor for CNC Router (SainSmart, 2018).](image)

The stage has an effective travel length of 100mm and is operated by a Nema 17 stepper motor. It has a vertical load capacity of 10kg and has repeat position accuracy to ± 0.03mm. Modification to the actuator included boring holes into the back plate to add a mount for the system, as seen in Figure 21.
5.1.2 Plates

To compress the cells together, two plates were designed. These were dimensioned such that, with the mounts in place, the walls could be compressed as flat as possible without interference. The walls were manufactured out of aluminum and were cut to the desired dimensions on a CNC MiniMill. The manufactured walls can be seen in Figure 22.
The walls were mounted onto the actuator with an ‘L’ bracket and screws onto the stage and fixed mount attached to the end plate of the actuator.

5.1.3 Hinges

To bend the cells and rotate the mount with the bending motion, hinges were adapted for this application. Hinges were cut to the appropriate dimension to match the walls to which they were mounted. The hinges on opposite walls have interlocking knuckles to prevent interference when the walls are flush. A slot was cut from the center of the hinges, to allow for the cells to be attached. Cotter pins fit through this hole to grip the cell, as shown in Figure 23. Additionally, a metal strip was added to the top of the hinge mounts to aid in the rotation of the hinges as the walls are moved together.

Figure 23: Hinge assembly.

5.1.4 Bending Orientation Actuator

In order to control the bending direction of the cells, convex or concave, a mechanism was added to force the hinges to rotate in a specific direction. A stepper motor and gear system was designed to control a lever that would direct the hinges rotation. This system can be seen in Figure
24. Before the stage mounted wall moves toward the fixed wall, the lever is rotated such that the hinge is slightly oriented in the desired direction. The lever is then returned to its resting position to prevent interference. The positions of operation can be seen in Figure 25.

Figure 24: Gear and stepper motor flip mechanism.

Figure 25: Hinge orientation settings.
5.1.5 Dry Box

The dry box chamber was constructed out of half inch UV-resistant acrylic. The one foot by one foot box was designed with interlocking pieces to achieve robust structural integrity, as seen in Figure 26. The top piece of the box is removable to allow equipment to be loaded inside. The sides were glued together with acrylic cement. To create a seal, a square rubber gasket was added to the top of the box, and silicone was applied to all inside edges of the box. Ports were added to the box to allow for the necessary wiring and air controls. Two ports, one toward the bottom and one toward the top of the box provide the air inlet and outlets required to control the environment. Additionally, three ports allow the wiring for the stepper motors and measurement electrical leads to enter the box while communicating with the necessary computer programs. The total assembly can be seen in Figure 26.

Figure 26: Box assembly.
5.1.6 Arduino

The code for the Arduino can be broken down into two files: a code for stretching and a code for bending. The code for bending starts with a four loop which takes in the users imputed iterations for the number of times the sample bends concave and then convex. As the code runs through the cycle the number of iterations is decreased by one until it reaches zero. Then an if statement is put into place so that the program only runs when the iterations are greater than zero. The code starts by moving the motor connected to the flipping mechanism in one direction to push against one side of the hinge to start the hinge to move concave. Then the motor causes the flipping mechanism to move back into a neutral position. The code then moves the linear actuator motor until it reaches the users imputed radii. From there the code moves the linear actuator in the opposite direction until the sample has no bend and is straight. This happens again but the motor flips the hinge in the opposite direction.

5.1.7 Wiring & Power Supply

In order to control the motor to the flipping mechanism and the motor to the linear actuator, the motors were wired to two separate control boxes which were then wired to the Arduino. A 13 volt DC connection was used to power both the control boxes and the motors. Since the stepper motors are have four wires that need to be connected this means that the motor need to be controlled by a bipolar driver. The wires in the motor are connected to four coils which, when activated in different orders, control the amount and direction of steps the motor turns. Our particular motor has four phases for the gear with 50 teeth this correlates to the 200 steps it takes for one complete rotation. Through the use of the control boards and Arduino the motors can be controlled to move in small increments or steps in either direction at various speeds. The instructions for use and wiring diagram for the automation controls can be seen in Appendix C.
5.2 Testing/Analysis

To assess the feasibility and applicability of the design, several tests can be conducted. Measurements that will be taken when the device is actually used in research settings can be replicated to simulate how the device will operate and perform.

5.2.1 Material Testing

Several materials were tested by measuring the strain experienced while the material is bent. Strain gauges were attached to samples of material with super glue and mounted in the device. The materials were subjected to continuous bending from being flat with no bend to being completely folded. LabVIEW programming and wiring was used to measure and record the results from the strain gauge. The testing setup can be seen in Figure 27.

![Figure 27: Material testing strain gauge setup.](image)

The results of this test are found in Figure 28. The latex glove and cloth materials performed similarly with minor microstrains. The PET/ITO performed consistently, however
experienced much higher microstrains. This is attributed to the effects of the strain gauge attached to the material. The strain gauge, a material similar in properties to the PET/ITO, changed the movement of the latex and cloth materials since it did not have similar characteristics. In the case of the PET/ITO, it was observed that the strain increased as the bending radius decreased and the material became close to being completely folded.

![Material Strain Bending Tests](image)

**Figure 28: Material strain bending testing.**

The strain in the materials was also measured when the materials were stretched. These results were limited by the materials ability to stretch with the strain gauge attached. The latex glove performed consistently, while the cloth experienced high strains cutting off when the material was stretched by 6mm, as seen in Figure 29. At this distance, the strain gauge was not completely secured to the cloth and separated from the material. Similarly, the PET/ITO did not perform well under this test, with the material being stretched beyond its ability and breaking off of the device.
5.2.2 Solar Cell Testing

Lead iodide solar cells were tested in the device to observe the effects of bending on the cell performance, as well as assess the device. Three cells were tested, each bending to a different radius for 70 iterations. Each cell was mounted to the device and measured for its initial performance and efficiency. Subsequently, the cell was bent to a determined radius at increments of 10, after which it was measured again. When the cells were measured, the probes were moved in place to be in contact with the cell when it was flat, in a configuration shown in Figure 30. The probes contacted the gold and ITO conductive layers.
The results of the performance of the cells can be seen in Figures 31-33. For both the 15mm and 10mm bending radii, no clear correlation was observed between the number of iterations and the performance of the cell. For the 10mm bending radius, the highest power outputs occurred after the cell was bent, with the worst performance occurring when the cell was never bent. Additionally, no clear observations could be seen with the efficiency of the cell. As seen in Figure 33, the efficiency of the 15mm and 10mm bending cells decreased and increased respectively. This yields an inconclusive result as to the influence of bending. These results are unexpected and indicate that bending cells with these curvatures does not result in a significant impact on the performance. More testing at higher iterations is required to more clearly observe any correlations.
Figure 31: Cell power performance with 15mm bending.

Figure 32: Cell power performance with 10mm bending.
One additional cell was bend to a radius of 5mm. After one bending iteration, the cell no longer produced a power output and was deemed broken. To confirm that this break was a valid result, the PET/ITO layer was tested. The resistance of the material was measured after being bent to different radii. As seen in Figure 34, the material broke between a bending radius of 11mm and 9mm. This suggests the cells should not work after being bent to this radius and confirms the results of the 5mm bending test.

**Figure 33:** Normalized cell efficiency performance after bending.

**Figure 34:** PET/ITO resistance testing.
6.0 Conclusions and Recommendations

In order for the research and development of flexible solar cells to yield functioning, well performing photovoltaics, practical testing must be done on cell prototypes. The existing methods to test flexible cells are cumbersome and impractical, and risk damaging the cells in the process. They are likewise limited in their application, requiring manual tests on a small scale absent of the ability to test how cells can perform in long term, flexible situations. Additionally, current systems are difficult to use to test cells performances in different environments in accordance with the cells chemistry. This absence necessitates the design and manufacture of a device better facilitate the testing of flexible solar cells.

By conducting best practice research and brainstorming, several design concepts were identified as a potential testing mechanism. The best concept was selected by using a design matrix to identify the criteria that were best supported in each design. Finally, several design iterations were created to lead to the final prototype design. This design was fabricated and tested in the laboratory environment to assess its feasibility. As a result of this testing, several recommendations for future improvements can be made:

1.) Create an enhanced user interface - In the future, improvements can be made to the device by creating an improved user interface over the Arduino code. Programs such as LabVIEW could provide an easier system to control the automation during solar cell tests.

2.) Improved probe connections in the dry box - While testing the device in the dry box, the probes are difficult to place in contact with the cell. This is due in part to the tight clearance of the probes in order to achieve a seal, as well as the flexibility of the cell when mounted. Future improvements could include a system to make the cell rigid after it is bent to
improve the probe connectivity, as well as a new way to create more moveable probes while maintaining the seal in the box.

Despite these challenges in the design, this system proved to be operational and a well-functioning device to test flexible solar cells. The automation in the system provides researchers the ability to assess their photovoltaic prototypes at specific radii and fatigue criteria. The dry box additionally allows researchers to control the environment in which cells are tested. These capabilities will provide the ability to better measure, characterize, and test flexible solar cells to diagnose shortcomings that need to be improved for the large scale development of such technologies.
References


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Appendix A: Device SolidWorks Design

Figure 35: Device isometric view.

Figure 36: Device side view.
Figure 37: Device top view.

Figure 38: Device assembly exploded view.
Figure 39: Wall dimensions (inches).
Appendix B: Box SolidWorks Design

Figure 40: Box assembly.

Figure 41: Box exploded view.
Appendix C: Automation Controls Instructions

**Instructions for Bending Testing**

*Note for easiest and best results make cells to test with a large area around it than can be touched without damaging the cell and to be gripped into the mechanism

**Step 1)**
Download Arduino Software onto Personal Computer
https://www.arduino.cc/en/Main/Software (link to software)

**Step 2)**
Check Wiring of the Two Stepper Motors to the 2 Div Boxes to the Arduino

![Diagram of Wiring](image)

*note if wiring diagram is hard to read go to Flexible MQP Testing file Wiring Diagram for a JPEG you can enlarge

Make sure that the wires are securely in place, if a wire is lose or comes loose the program will not run properly.

**Step 3)**
Plug the cable that connects to the arduino to your person computer. DO NOT PLUG DC POWER INTO OUTLET YET.

**Step 4)**
Go To Flexible MQP and open up file Bending Test Arduino Code

**Step 5)**
For more flimsy samples have prepared metal strips attached to at least the top, if the sample is extremely flimsy and flexible attach another prepared metal strip to bottom.

Example:
The metal piece can be attached first using double sided tape followed by sliding the pins.

**Step 6)**
Place Sample in between hinges. Note this can be done by removing the hinges with the slits from their pins. To attach sample first connect the sample to the hinges with double sided tape. You must make sure that the sample is straight with not bend. Then place a pin on both sides of the sample using the slits and place the hinges back onto the pins. Note you may have to use your finger to move the linear actuator up or down in order to place the hinge back in so it is straight.

**Step 7)**
On your personal laptop, look at the arduino file you open in step 4 and compare to pdf file Bending Arduino Code PDF found in Flexible MQP Testing. If the main code does not match fix so that it matches the code in the PDF.
Step 8)
Input the bending radii under the input \textit{int Radius}, wanted speed under into \textit{int Speed}, the starting distance between the plates into \textit{int Distance}, and number of iterations wanted under \textit{int tracknumber}. Pay close attention to the notes after these inputs they hold helpful advice. For max radii \textbf{Input}: Note that the plates can be 96.37 mm away max, the radii must be smaller than this

```
const int stepsPerRevolution = 200;  // Nema17 motor has 200 steps in 360 degrees rotation
// initialize the stepper library on pins 8 through 11:
Stepper LinearStepper(stepsPerRevolution, 8, 9, 10, 11); // pins 8,9 go to PULL+ & PULL-, pins 10,11 go to DIR+ & DIR-
Stepper RotationalStepper(stepsPerRevolution, 4, 5, 6, 7); // pins 8,9 go to PULL+ & PULL-, pins 10,11 go to DIR+ & DIR-
```

\textbf{int tracknumber = 5;} // SET HOW MANY TRACKS YOU WANT UP AND BACK
\textbf{int Speed = 1700;}
\textbf{int Distance = 88.75;} //starting distance between the plates
\textbf{int Radius = 30;} //in mm

\textbf{DO NOT EDIT ANY OTHER VARIABLES OR LINES OF CODE.}

Step 9)
Place a little bit of vacuum grease on the probe pins and test to see if the pins move easily around the stopper.

Step 10)
Secure stopper probes into box and move probes so that they do not interfere with the plates when they move

\textbf{*Note if you are testing in air skips steps 11-14}

Step 11)
This step is only if you want to test in a nitrogen environment. Attach Nitrogen valve to the bottom port and vacuum valve to the bottom port. Note the vacuum must have a open close switch hooked up for this to work

Step 12)
Turn on the vacuum for 3 minutes then turn off

Step 13)
Turn on the nitrogen valve for 3 minutes then turn off
Step 18)
Press the reset button on Arduino

Step 14)
repeat steps 12 and 13 five times

Step 15)
Press the Upload button

Step 16)
Wait 2-3 minutes AFTER the program says done uploading at the bottom of the screen. This will appear at the bottom of the screen. **DO NOT SKIP THIS STEP**

```cpp
void loop() {
    // put your main code here, to run repeatedly:
}
```

*note this is an important step. If you skip this step the code will not run properly.

Step 17)
Plug the DC Power supply into an outlet for both the flipper motor and linear motor. You need two different 13 V power supplies.
Step 19)
After the sample has been bent and finished its cycles unplug the DC power supplies.
Step 20)
Mount the probe pins so that you do not have to hold them while testing and clip the wires to the red and white wires coming out of the box. This is simply to switch the normal probes to the ones inside the box.
Step 21)  
Push probes into the box further so that they touch the connections of the cell.

Example of Probes touching Cell

Step 22)  
Sign in to the computer, turn on equipment and test cell like normal operations.

Step 23)  
**Note that this step is only for the nitrogen environment:** turn on the vacuum for 3-5 minutes before opening up the box.
Appendix D: Arduino Code for Bending

```cpp
// include stepper library
#include <Stepper.h>

const int stepsPerRevolution = 200; // Nema17 motor has 200 steps in 360 degrees rotation

// initialize the stepper library on pins 8 through 11:
Stepper LinearStepper(stepsPerRevolution, 8, 9, 10, 11); // pins 8,9 go to FULL+ & FULL-, pins 10,11 go to DIR+ & DIR-
Stepper RotationalStepper(stepsPerRevolution, 4, 5, 6, 7); // pins 8,9 go to FULL+ & FULL-, pins 10,11 go to DIR+ & DIR-

int tracknumber = 5; // SET HOW MANY TRACKS YOU WANT UP AND BACK
int Speed = 1700;
int Distance = 0.75; // starting distance between the plates
int Radius = 30; // in mm

// DO NOT TOUCH CODE BELOW
int startDistance = 96.37 - (96.37 - Distance);
int Travel = startDistance - Radius;
int Steps = Travel * 305.316;
int Reverse = -1*(Steps + 150);
void setup()
{  
  for (int i = tracknumber; i > 0; i = i - 1)
    {  
      if (tracknumber > 0)
        LinearStepper.setSpeed(Speed);
        LinearStepper.step(150);
        RotationalStepper.setSpeed(75);
        RotationalStepper.step(105);
    }
}"
```
RotationalStepper.step(-105);
LinearStepper.setSpeed(Speed);
LinearStepper.step(Steps);
LinearStepper.step(Reverse);
LinearStepper.step(150);
RotationalStepper.step(-100);
RotationalStepper.step(100);
LinearStepper.step(Steps);
LinearStepper.step(Reverse);

}

void loop() {

  // put your main code here, to run repeatedly:

}

Code used for Inputting Stepper Motors

  // include stepper library
  include <Stepper.h>
  
  const int stepsPerRevolution = 200; // Nema17 motor has 200 steps in 260 degrees rotation
  
  // initialize the stepper library on pins 8 through 11:
  Stepper LinearStepper(stepsPerRevolution, 6, 9, 10, 11); // pins 8,9 go to FULL+ & FULL-, pins 10,11 go to DIR+ & DIR-
  Stepper RotationalStepper(stepsPerRevolution, 4, 5, 6, 7); // pins 4,5 go to FULL+ & FULL-, pins 6,7 go to DIR+ & DIR-

Code used for User Inputs

  int tracknumber = 5; // SET HOW MANY TRACKS YOU WANT UP AND BACK
  int Speed = 1700;
  int Distance = 88.75; // starting distance between the plates
  int Radius = 30; // in mm

Code Used for Calculations

  int StartDistance = 96.37 - (96.37 - Distance); // calculates new start distance from max start
  int Travel = StartDistance - Radius; // calculates distance to travel
  int Steps = Travel * 305.316; // converts mm into steps
  int Reverse = -1 * (Steps + 150); // calculates steps for motion in opposite direction
Code used for Bending in Concave Direction only

```java
LinearStepper.setSpeed(Speed);
LinearStepper.step(150);
RotationalStepper.setSpeed(75);
RotationalStepper.step(105);
RotationalStepper.step(-105);
LinearStepper.setSpeed(Speed);
LinearStepper.step(Steps);
LinearStepper.step(Reverse);
```

Code used for Bending in Convex Direction only

```java
LinearStepper.setSpeed(Speed);
LinearStepper.step(150);
RotationalStepper.setSpeed(75);
RotationalStepper.step(-100);
RotationalStepper.step(100);
LinearStepper.step(Steps);
LinearStepper.step(Reverse);
```

Code used for Multiple Iterations (For Loop)

```java
for ( int i = tracknumber; i > 0; i = i - 1){
    if (tracknumber > 0){
    }
}
```