Designing a Strain Measurement System based on Circle Grid Analysis for Sheet Metal Forming Applications

Mr. Relmane Baptiste, University of Maryland, Eastern Shore

Relmane Baptiste, is a 2014 graduate from the University of Maryland Eastern Shore (UMES) with a Bachelor of Science Degree in Engineering, specializing in Electrical Engineering. Mr. Baptiste designed a Strain Measurement System for his Senior Design Project. This design was based on Circle Grid Analysis for Sheet Metal Forming Applications, where he extensively utilized Multisim and Solidworks to complete his Senior Design Project. During his undergraduate studies, Mr. Baptiste also completed a workshop at NASA in Wallops Island, VA. The week-long workshop afforded himself and fellow participants the opportunity to build small scientific instrument payloads which were flown on a NASA sounding rocket. The experiments included a battery of sensors that captured environmental readings during flight. In addition to the workshop, Mr. Baptiste completed an internship with Booz Allen Hamilton in Linthicum Heights, MD. At Booz Allen Hamilton he performed research, test and analyses of Mobile Ad Hoc Network (MANET) portable communication radios. Furthermore, he constructed, assembled and tested N-type coaxial cables for Rapydconnex communication system for administration and maintenance of critical communication systems. Mr. Baptiste is currently employed at Aberdeen Proving Ground, MD with CERDEC as a Modeling, Simulation and Test Engineer.

DeOndre L Clark Jr, University of Maryland, Eastern Shore

DeOndre Clark Jr graduated in Fall 2014 with a Bachelor of Science Degree in General Engineering Specializing in Computer Engineering from the University of Maryland Easter Shore. For his Senior Design Project, Mr. Clark Designed a Strain Measurement System based on Circle Grid Analysis for Sheet Metal Forming Applications. During the summer of 2014, Mr. Clark was a Student Research Assistant at the University of Maryland. He programmed and tested a RC car to navigate autonomously using Ardupilot. He developed and evaluated autonomous systems for a RC boat. Designed a boat to withstand 50 lbs. for a ISCO sensor. Designed a High Reduction Ratio Planetary Drive with solidworks and printed the model using a 3D printer.

Dr. Payam Matin, University of Maryland, Eastern Shore

Dr. Payam Matin is currently an Associate Professor in the Department of Engineering and Aviation Sciences at the University of Maryland Eastern Shore (UMES), Princess Anne, Maryland. Dr. Matin has received his Ph.D. in Mechanical Engineering from Oakland University, Rochester, Michigan in May 2005. He has taught a number of courses in the areas of mechanical engineering and aerospace at UMES. He has served as departmental ABET committee chair through a successful accreditation visit in Fall 2012. Dr. Matin’s research has been mostly in the areas of Computational Mechanics and Experimental Mechanics with applications in Solid Mechanics, Plasticity and Sheet Metal Forming. Dr. Matin has published more than 25 peer-reviewed journal and conference papers. Dr. Matin is the recipient of NSF MRI award as a Co-PI. Dr. Matin worked in Automotive industry for Chrysler Corporation from 2005 to 2007. He Joined UMES in August 2007. He is affiliated with ASME and ASEE professional societies.

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For characterizing formability of sheet metals, circle grid analysis is used as an experimental means of measuring forming strains in stamped sheet metal parts. This method involves etching a pattern of circle grid with known dimensions on sheet metal before forming operation, and measuring the new dimensions of the deformed circles after forming operation. The etching process is usually conducted through an electrochemical material deposition. While electrochemical marking systems are available commercially, they could be pricy depending on the specifications. For educational and research needs of the department, a team of undergraduate students is assigned to design and prototype a cost effective electrochemical marking system for strain measurement application in a senior design framework. The design project is defined with certain design requirements and design constraints, which match with the industry standards. The learning objectives of the project are articulated from the start. The design team put into practice their knowledge of circuit analysis to simulate, design and prototype the circuitry that etch circle grid on sheet metal as desired for strain measurement. The principles of electrochemical deposition are also considered for design purposes. A prototype is built and tested successfully to the specifications. A transparent ruler is designed based on definition of true strain for strain measurement. In this paper, the learning objectives and learning outcomes of the projects are discussed.

Introduction
Sheet metal forming is generally referred to manufacturing processes in which sheet metal is deformed plastically into a desired geometry of a product. Sheet metal forming has wide applications in today’s industries such automotive, aerospace, defense, and so on. There are several sheet metal forming processes including stamping, hydroforming, deep drawing, roll forming, etc. The mechanics of sheet metal forming is mainly introduced in [1-2]. Formability is defined as ability of sheet metal to be deformed plastically without any failure. In the recent years, several studies have been conducted to characterize sheet metal formability [3-7]. To characterize sheet metal formability, it is important to measure the forming strains that sheet metal experiences at the end of a forming process. Additionally, accurate measurement of forming strains has been shown instrumental for FEM-based crash simulation, where an accurate material model is needed [8-9].

Figure 1 Close of Circle Grid on Sheet Metal Specimen Before Deformation.
Circle grid analysis is one of the most effective methods used as an experimental means of measuring forming strains in stamped sheet metal parts. This method involves etching a pattern of circle grid with known dimensions on sheet metal before forming operation (as shown in figure 1), and measuring the new dimensions of the deformed circles after forming operation (depicted in figure 2).

Figure 1 Sheet Metal Specimens after Deformation.

The etching process is usually conducted through an electrochemical material deposition. A DC voltage is applied between a rocker (or roller) pad and the blank sheet metal specimen as shown in figure 3 [10]. The stencil, which is usually a pattern of circle grid is placed in position on top of the sheet metal blank specimen. The stencil is a woven fabric over which non-conducting coating has been applied. However, in producing the stencil, the non-conducting coating is removed at the locations where marking is desired allowing current to flow to sheet metal blank. Stencils are available in different patterns, styles and sizes. A felt pad saturated with proper electrolyte completes the circuit between the rocker (or roller) pad and the stencil, providing the necessary electrochemical action that etches marking on sheet metal blank specimen.

Figure 3 Schematic of Electrochemical Marking [10]
As established in industry standards, Table 1 shows the etching process characteristics for steel sheet metal in terms of voltage and time duration. The process should be conducted with chromic acid solution as electrolyte based on the following specification:

<table>
<thead>
<tr>
<th>Metal</th>
<th>Electrolyte</th>
<th>Etching Characteristics</th>
</tr>
</thead>
</table>
| Steel  | 100 grams of chromic acid and 100 ml distilled water | 3-6V-DC  
5-60 seconds |

Table 1 Steel Electrochemical Characteristic

Similarly, Table 2 shows the etching process characteristics of aluminum sheet metal in terms of voltage and time duration. The process should be conducted with sodium hydroxide solution as electrolyte based on the following specification:

<table>
<thead>
<tr>
<th>Metal</th>
<th>Electrolyte</th>
<th>Etching Characteristics</th>
</tr>
</thead>
</table>
| Aluminum | 10 grams of chromic acid and 100 ml distilled water | 15-30V-DC  
5-60 seconds |

Table 2 Aluminum Electrochemical Characteristic

Although these characteristics can be verified by Faraday’s law of Chemistry, they will be simply adopted as design specifications in this project.

While electrochemical marking systems are available commercially, they could be pricy depending on the product specifications. For educational and research needs of the department, a team of undergraduate students is assigned to design and prototype a cost effective electrochemical marking system for strain measurement application in a senior design framework.

**Educational Goals**

While the project is a senior design project, it targets the following main educational goals:

1- The project aims to improve the ability of the students to design a realistic system and its components under realistic design requirements and constraints.

2- The project aims to improve the ability of the students to understand and apply fundamental principles of mechanics of materials for strain measurement, basics circuits, circuit simulation, chemistry, electronic laboratory testing and validation.

3- The project is to improve the ability of the students to apply modern engineering tools (such as Multisim, Excel, Circuit lab equipment) to analyze and design a realistic system and its components.

4- The project is to improve the students’ hands on skills in fabricating circuitry and working prototype of circuitry system.

5- The project aims to improve the ability of the students to design and conduct experiments to validate the performance of their design.

6- The project aims to improve the students’ written and oral communication skills.
The educational goals of the project correlate closely with most of the ABET student outcomes (a-k), which are widely accepted in engineering education community. These outcomes have introduced and mandated by ABET for engineering programs to ensure the quality of engineering graduates. Projects similar to this project would help engineering educators to cover many student outcomes in senior design classes, which improve the quality of engineering education. Two senior level students worked on this project over the course of two semesters under senior design project I and II classes. The students worked in the summer time between the two semesters. It is intended that the project complements the prior works of the other educators in improving senior design classes [11-14].

**True Strain Calculations Based on Circle Grid Analysis**

For the purpose of circle grid analysis, several strain measurement techniques are available to measure true strains after sheet metal deforms. The easiest method is to use a flexible film-strip ruler (calibrated to different level of true strains) to read the strains directly. For such purpose, the guide lines of the film strip ruler can be aligned to the major and minor axes of the resulting ellipses achieved after deformation. The true strain method is used to characterize the permanent (plastic) strain of the sheet metal after it has been deformed [2]. Figure 4 depicts the deformation of a circle of the grid into elliptical forms. The major strain is defined as the greatest strain, while the minor strain is defined as the least strain. The oval on the right represents the case where both the major and minor strains are positive. The oval on the left represents the case where the major strain is positive while the minor strain is negative.

![Figure 4 Minor and Major Deformation Diagram.](image)

The major strain $\epsilon_1$ is calculated based on the definition of true strain as [2]

$$\epsilon_1 = \int_{L_0}^{L_1} \frac{dL}{L} = \ln \left( \frac{L_1}{L_0} \right)$$

(1)

where

- $L_0$ = Original diameter of circles on the circle grid before deformation.
- $L_1$ = Larger diameter of the ellipse after deformation.

The major strain $\epsilon_2$ is calculated based on the definition of true strain as
where \( L_2 \) = Smaller diameter of the ellipse after deformation.

In general, percent strain is defined in terms of final and original diameters as

\[
\varepsilon = \frac{\ln \left( \frac{L_f}{L_o} \right)}{100}
\]

(3)

where

\( L_f \) = Final diameter after deformation.

\( L_o \) = Original diameter before deformation.

As shown in table 3, for a circle grid of 0.2 in of original diameter, different final diameters are calculated for different percent strains based on equation (4).

\[
L_f = e^{\frac{\varepsilon}{100} \ln \left( \frac{L_f}{L_o} \right)}
\]

(4)

<table>
<thead>
<tr>
<th>Initial Diameter (in)</th>
<th>Strain (%)</th>
<th>Final Diameter (in)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.2</td>
<td>10</td>
<td>0.221</td>
</tr>
<tr>
<td>0.2</td>
<td>20</td>
<td>0.244</td>
</tr>
<tr>
<td>0.2</td>
<td>30</td>
<td>0.270</td>
</tr>
<tr>
<td>0.2</td>
<td>40</td>
<td>0.298</td>
</tr>
<tr>
<td>0.2</td>
<td>50</td>
<td>0.330</td>
</tr>
<tr>
<td>0.2</td>
<td>60</td>
<td>0.364</td>
</tr>
<tr>
<td>0.2</td>
<td>70</td>
<td>0.403</td>
</tr>
<tr>
<td>0.2</td>
<td>80</td>
<td>0.445</td>
</tr>
<tr>
<td>0.2</td>
<td>90</td>
<td>0.492</td>
</tr>
<tr>
<td>0.2</td>
<td>100</td>
<td>0.544</td>
</tr>
</tbody>
</table>

Table 3 Final Diameters of deformed circles for different Percent Strains.

After deformation, the final diameters of the resulting ellipses can be measured by a flexible film strip called Mylar tape, which is designed and calibrated to read the strains directly. As shown in figure 5, Mylar tape can be aligned to the major and minor axes of the resulting deformed ellipses between its guidelines to read the strains. The Mylar tape depicted in figure 5 is designed
for circle grid of 0.2 in of original diameter based on the final diameters presented in table 3 for the associated percent strains.

Figure 5 Mylar Tape Used for Strain Measurement of Deformed Circles.

Design Objective
The objective of this project is to design a power supply that provides capability of etching grid patterns on sheet metal based on electrochemical marking process.

Design Requirements
The customer is in need of the following requirements:

- A variable power supply that outputs 1-30 VDC and 2 mA matching with industry standard.
- The power supply provides capability for etching of grid patterns on sheet metal.
- Steel and aluminum sheet metal are intended.
- Circle grids of 0.2 in of diameter on a 0.5 square inch of sheet metal are desired.
- The power supply should be compatible with 6 in roller marker.
- Once the grids are etched on the metals, a pre-defined Mylar tape is used to measure the true strain of the deformed circles.

Design Constraints

- The power supply unit has to weigh less than 15-20 Lbs.
- The power supply has to use wall outlet of 120V, 60Hz.
- The entire system should cost not more than $350.00.

Design Approach
Given the design requirements and constraints, possible solutions are brainstormed and suitable ideas are generated to meet the design requirements. Faraday’s law of chemistry is implemented to analyze the electrochemical marking deposition for a given electrical current. An electrical circuit is designed as a power supply to deliver the required current. The initial design is based on simulation, but validated as a prototype is built. The performance of the system is evaluated with a number of testing which is conducted on different sheet metal. The design approach is summarized as follow:

- Define the design problem.
- Define the design requirements and constraints.
- Consider Chemistry Faraday’s law (or industry standard) for reasonable material deposition.
- Initial design of power supply circuitry to deliver the required current.
- Analyze the circuitry based on simulation.
- Build a model or prototype to validate the design.
- Conduct performance testing on sheet metal.
- Modify and refine the design.
- Document the design

Figure 6 depicts the design approach considered for this project.

**Circuit Design Approach**
A circuitry needs to be designed to operate with wall outlet and provides a selected steady voltage of 1-30 VDC. Figure 7 depicts the block diagram of the circuit to be designed.
As shown in figure 7, the following tasks are carried out by the circuitry:

- As required based on the design requirements, a 120 V input 28.5 V output transformer is implemented to receive the outlet voltage and then power the circuit.
- A bridge rectifier converts the AC voltage from the output of the transformer to a DC voltage.
- A smoothening capacitor provides a steady DC voltage without large levels of voltage variation.
- A voltage regulator is implemented to automatically maintain a constant voltage level.
- A potentiometer enables the operator to vary the DC voltage outputted from the voltage regulator in the range of 1-30 VDC as specified as the industry standard.
- The load is the resistance of the sheet metal specimen to be etched.

**Circuit Analysis**

Figure 8 shows the Multisim circuit simulation of the variable power supply. The transformer converts the AC power 120 V to 28.5 Vac. Then, the bridge rectifier converts the 28.5Vac to 28.5Vdc. The capacitor C1 that is in parallel with R3 is a low pass filter that cuts off the high frequency on the output of the bridge rectifier. The capacitor C2 smooth out the DC voltage before allowing it into the voltage regulator. The linear voltage regulator U1 is an integrated circuit chip that enables the DC voltage to stay at a constant voltage level. The capacitor C3 is connected in parallel with Vout and ADJ of the voltage regulator to rectify any voltage and current before allowing it into the load. D2 diode provides a discharge path for C3 when Vin of the voltage regulator is shut down preventing C3 for discharging through the regulator. D2-D3 diodes provide a discharge path for ADJ of the regulator. D2 and D3 diodes are implemented as protective diodes to protect regulator against reverse polarity at Vin and Vout. The voltage regulator controls the voltage through the rest of the circuit. Resistor R2 is implemented to limit the range of the potentiometer to meet the design requirements. Resistor R4 is utilized to limit the voltage drop of the voltage regulator while the 10kΩ potentiometer R1 is used to vary the final output voltage from 1-30V DC.

![Figure 8 Circuit Simulations using Multisim](image)

For the design to meet the output voltage of the specifications, the output voltage $V_{out}$ needs to be calculated. The output voltage is also calculated analytically based on the following equation.
\[ V_{\text{out}} = V_{\text{ref}} \left( 1 + \frac{R_1 \times R_2}{R_1 + R_2} \right) \]

where \( V_{\text{out}} \) is the output voltage from the voltage regulator, and \( V_{\text{ref}} \) is the voltage across resistor \( R_4 \), between the output of the voltage regulator and ADJ. \( V_{\text{ref}} \) is called reference voltage and is constant at 1.25V for the voltage regulator selected. Equation (5) is derived using circuit analysis of \( R_1 \), \( R_2 \) and \( R_4 \) circuitry.

In table 4, as the resistance of the potentiometer \( R_1 \) increases, the output voltage increases as well. The desired range of the output voltage (as targeted as design requirement) is generated as the resistance of potentiometer \( R_1 \) changes.

<table>
<thead>
<tr>
<th>( R_4(\Omega) )</th>
<th>( R_1 (\Omega) )</th>
<th>( R_2 (\Omega) )</th>
<th>( V_{\text{out}} ) (V)</th>
</tr>
</thead>
<tbody>
<tr>
<td>220</td>
<td>500</td>
<td>12000</td>
<td>3.98</td>
</tr>
<tr>
<td>220</td>
<td>1000</td>
<td>12000</td>
<td>6.49</td>
</tr>
<tr>
<td>220</td>
<td>2000</td>
<td>12000</td>
<td>10.99</td>
</tr>
<tr>
<td>220</td>
<td>3000</td>
<td>12000</td>
<td>14.89</td>
</tr>
<tr>
<td>220</td>
<td>4000</td>
<td>12000</td>
<td>18.30</td>
</tr>
<tr>
<td>220</td>
<td>5000</td>
<td>12000</td>
<td>21.30</td>
</tr>
<tr>
<td>220</td>
<td>6000</td>
<td>12000</td>
<td>23.98</td>
</tr>
<tr>
<td>220</td>
<td>7000</td>
<td>12000</td>
<td>26.37</td>
</tr>
<tr>
<td>220</td>
<td>8000</td>
<td>12000</td>
<td>28.52</td>
</tr>
<tr>
<td>220</td>
<td>9000</td>
<td>12000</td>
<td>30.47</td>
</tr>
<tr>
<td>220</td>
<td>10000</td>
<td>12000</td>
<td>32.24</td>
</tr>
</tbody>
</table>

Table 4 Calculations of \( V_{\text{out}} \) as the Resistance of the Potentiometer changes.

For the given potentiometer resistance of \( R_1 \), the simulation has been conducted. The simulation results are obtained and summarized in table 4. For the purpose of validation, a prototype is built.

**Prototype Power Supply**
As presented in figure 9, Multisim delivers a model for the Ultra-board circuit of the circuit designed, which is helpful when an actual prototype of the power supply is to be built.
Prototype of Circuitry
As shown in figure 10, based on the circuit designed and analyzed, a prototype circuit has been built.

The prototype circuit is powered up by the transformer, which stepped down the output voltage. Then, a full wave bridge rectifier converts the AC voltage to DC voltage. A smoothening capacitor provides a steady DC voltage without large levels of voltage variation. A voltage regulator automatically maintains a constant voltage level. Then finally, the potentiometer enables the operator to vary the DC voltage in the range of industry standard 1-30 VDC. Figure 10 and 11 show how the circuit elements are connected on the final board. The elements include the capacitors, diodes, resistors, and voltage regulator.
Circuit Simulation Results and Validation
The circuit simulation results presented in table 5 exhibits significantly high percentage of errors in current at locations 2 and 3. After careful reviews, it has been discovered that the main reasons for the high percent errors are due to the fact that the Multisim simulation is conducted using ideal parts. In contrast, the elements of the prototype are not ideal in reality. The elements are subjected to some practical tolerances. So with that in mind, practical percentage of tolerances are included to the Multisim model according to the prototype parts specifications tolerances.

<table>
<thead>
<tr>
<th>Location</th>
<th>Prototype Voltage</th>
<th>Current</th>
<th>Simulation Voltage</th>
<th>Current</th>
<th>Percentage Error</th>
</tr>
</thead>
<tbody>
<tr>
<td>Location 1</td>
<td>120 V-AC</td>
<td>~</td>
<td>120 V-AC</td>
<td>~</td>
<td>0%</td>
</tr>
<tr>
<td>Location 2</td>
<td>28.5 V-AC</td>
<td>2A</td>
<td>29.7 V-AC</td>
<td>2.8A</td>
<td>4.04%</td>
</tr>
<tr>
<td>Location 3</td>
<td>Surge Voltage 79.8 V-DC</td>
<td>13.75 mA</td>
<td>Surge Voltage 82 V-DC</td>
<td>29.8 mA</td>
<td>2.68% 53.80%</td>
</tr>
<tr>
<td>Location 4</td>
<td>Surge Voltage 79.8 V-DC</td>
<td>5.68 mA</td>
<td>Surge Voltage 82 V-DC</td>
<td>5.84 mA</td>
<td>2.68% 2.70%</td>
</tr>
<tr>
<td>Location 5</td>
<td>at 1 V-DC</td>
<td>2.84 mA</td>
<td>at 1 V-DC</td>
<td>2.82 mA</td>
<td>0% 0.70%</td>
</tr>
</tbody>
</table>

Table 5 Prototype and Simulation Comparison

The following practical tolerances are included in the Multisim simulation as shown in figure 12:
5% tolerance is considered to the input of the circuit.
The ratio of the transformer is changed to 4.2.
20% tolerance is considered for the capacitance of C1 and C3 capacitors.
5% tolerance is considered for the resistance of R2, R3 and R4 resistors.
Finally, 10% tolerance is considered for the capacitance of C2 capacitors.

Figure 12 Multisim Simulation with added tolerances.

With the tolerances included, the simulation is conducted again. The results are obtained and summarized in table 6.
As a result of the added tolerances, a significantly large improvement has been observed with the percentage of error.

**Design of Power Supply Casing**

The prototype circuit needs to be placed in a housing for permanent operation. Figure 13 (a) and (b) show the front and back view of the solid model of the power supply built in SolidWorks. As shown in figure 13 (a), the front view shows the voltage display, banana sockets, and knob that controls the voltage via the potentiometer. As depicted in figure 13 (b), the back-view shows the power switch and power outlet socket.

A two-piece sheet metal casing is designed to house the prototype circuit. The two pieces are screwed together in the final assemble. Figure 14 shows the exploded view of the power supply assembly on SolidWorks. This view shows the components used in the power supply. There are two wooden blocks inside of the housing. One wooden block is used to hold the transformer and the other one is used to hold the circuit in place and also to prevent it from shorting out with the casing of the power supply.
Figure 15 shows the final assembly of the power supply.

Based on the solid model designed, a sheet metal casing is prototyped. In figure 16, the circuit board, the input sockets, voltage display, potentiometer, the output connectors and transformer are being assembled into the casing prototype.
Figure 16 Assembling Power Supply

Figure 17 (a) shows the front panel of the power supply casing, which includes the voltage display, positive and negative banana sockets, and voltage adjustment. One of the banana sockets is connected to the roller marker wiring, and the other one is connected to the sheet metal specimen to be etched. The sheet metal specimen acts as ground in the circuit. Figure 17 (b) shows the back panel of the power supply casing, which includes AC power input and power switch. The AC input is where the AC power cord connects into. The power switch is used to turn on the power supply for etching process.

Figure 17 (a) Voltage Display and Voltage Adjustment; (b) AC Input and Power Switch of Power Supply

The entire weight of the power supply is found to be limited to 3.65 pounds, which is noticeably below the weight design constraint of 15-20 lbs.

**Solid Model of Entire System**
Figure 18 shows the final assembly of the electrochemical marking system. As shown in the figure, the positive terminal of the power supply output connects to the sheet metal specimen to be etched. As shown, the negative output terminal of the power supply connects to the roller marker.
Etching Components

Figure 19 depicts the chemical solutions to be used for electro-etching process. These solutions include Neutralyte and Electrolyte. Neutralyte is used to clean the sheet metal specimen before and after etching. Electrolyte is used to aid the flow of low voltage electric charge from the roller marker through the gap in the stencil onto the sheet metal specimen. Figure 19 shows the components needed for etching process. These components include Steel and Aluminum sheet metal specimens, a roller marker, a marker pad, stencil and the chemical solutions acting as electrolye and cleaning compounds.

Figure 19 The top-left is the Aluminum sheet metal specimen. The bottom left is the Stainless Steel sheet metal specimen. Top middle is the 6” Roller Marker. The middle bottom is the 1.25”x 6” Roller Marker Pad. Finally on the far right is the sample Stencil grid.
Operational Procedure for Etching Process
The students developed the operational process that an operator should follow in different steps to etch sheet metal specimen as:

1. Plug power unit into 110V or 220V outlet.
2. Turn power unit on.
3. Set voltage to 15V.
4. Plug cord set into front of the power unit. Attach red alligator clip, the ground wire, to the sheet metal specimen to be marked. Attach black cord to the roller pad marker. Attach the other end of the red and black wires to the banana sockets with the associated colors on the front panel of the power supply.
5. Position long life stencil on the sheet metal specimen to be marked.
6. Dip roller pad marker in electrolyte so that the pad is saturated, but not overly wet. Overly wet pad causes shortage to power supply when coming in contact with the sheet metal.
7. Bring roller pad marker down on top of the stencil that is positioned on the sheet metal specimen so that the pad is firmly pressed onto the stencil.
8. For best results, roll the marker with gentle pressure slowly for 60 seconds and then remove the marker and stencil. Marks will appear on the sheet metal specimen.
9. Neutralize marks properly using neutralyte to clean the sheet metal specimen.
10. Dry the sheet metal specimen.

Conducting Etching Process
Figure 20 (a) shows the power supply turned on and set to 15 V. The red wire connects to the sheet metal specimen and the black wire connects to the roller marker. Figure 20 (b) shows the pre-set up for the etching process by placing the stencil on top of the sheet metal specimen. Figure 21 (a) shows the next step in the process by connecting the power supply to the sheet metal specimen. The red wire connects to the sheet metal from the power supply. Figure 21 (b) shows the etching process as being conducted after the electrolyte is applied. The roller marker is connected to the ground and the sheet metal is connected to the power supply. During this process, the voltage and electrolyte pass through the stencil to etch the desired image on the sheet metal specimen. Figure 22 shows the stencil and the sheet metal specimen after the etching process has been finalized on the specimen.

![Figure 20 (a) Setting Power Supply to 15V; (b) Placing Stencil on top of the Sheet Metal Specimen](image1)

Figure 20 (a) Setting Power Supply to 15V; (b) Placing Stencil on top of the Sheet Metal Specimen
Performance of Power Supply Circuit Prototype
The power supply prototyped has been tested to verify if an acceptable etch can be achieved. The following considerations are taken into account during the performance testing:

Voltage: 20 VDC, Time Duration: 2 minutes, Chemical: Neutralyte and Electrolyte

The roller is completely soaked in Electrolyte for a clearer and deeper etch.

Marking Steel Sheet Metal with different Voltages
Figure 23 (a) and (b) show the power supply performance tested on a partial surface of Steel sheet metal at 5V and 10V, respectively. Similarly, figure 24 (a) and (b) show the power supply performance on a partial surface of Steel sheet metal tested at 15V and 20V, respectively.
All four voltages deliver reasonable etch marking on the Steel sheet metal. However, the marking resulted from 15V looks slightly better after visual inspection. Figure 25 shows the final etching on the entire Steel sheet metal specimen using 15 volts. On this sample, all of the circle grids appear complete and clear after the etching process completes.
Marking Aluminum Sheet Metal with different Voltages

Figure 26 (a) and (b) show the power supply performance tested on a partial surface of Aluminum sheet metal at 5V and 10V, respectively. Similarly, figure 27 shows the power supply performance tested on a partial surface of Aluminum sheet metal at 15V and 20V, respectively.

Figure 26 Circle Grids Etched on Aluminum Sheet Metal Using (a) 5 Volts and (b) 10 Volts.
Figure 27 Circle Grids Etched on Aluminum Sheet Metal Using (a) 15 Volts and (b) 20 Volts.

All four voltages deliver reasonable etch marking on the Aluminum sheet metal specimen. However, the marking resulted from 15V looks slightly better after visual inspection. Figure 28 shows the final etching on Aluminum sheet metal specimen using 15 volts. On this sample, all of the circle grids appear complete and clear.

Figure 3 Final Etching of Aluminum Sheet Metal Specimen using 15 Volts

**Project Cost**

Table 7 shows the electrical components needed for the power supply and the cost associated with each component.
Table 7 Power Supply Components and the associated Costs

<table>
<thead>
<tr>
<th>Part ID</th>
<th>Part Type</th>
<th>Description</th>
<th>Quantity</th>
<th>Price per Part</th>
</tr>
</thead>
<tbody>
<tr>
<td>LM317T</td>
<td>Power Supply</td>
<td>ADJUSTABLE-VOLTAGE REGULATOR LM317T</td>
<td>1</td>
<td>$3.14</td>
</tr>
<tr>
<td>276-150</td>
<td>Power Supply</td>
<td>MULTIPURPOSE PC BOARD WITH 417 HOLES</td>
<td>2</td>
<td>$2.48</td>
</tr>
<tr>
<td>271-011</td>
<td>Power Supply</td>
<td>1/8 WATT 220 OHM CARBON FILM RESISTORS</td>
<td>1</td>
<td>$1.49</td>
</tr>
<tr>
<td>NTE877</td>
<td>Power Supply</td>
<td>NTE877 1000V 5 AMP GENERAL PURPOSE SILICON DIODE</td>
<td>2</td>
<td>$4.98</td>
</tr>
<tr>
<td>Model: 273-1812</td>
<td>Power Supply</td>
<td>28.2V CT 2.0A HEAVY-DUTY CHASSIS-MOUNT TRANSFORMER WITH LEAD</td>
<td>1</td>
<td>$15.83</td>
</tr>
<tr>
<td>QWCC227</td>
<td>Power Supply</td>
<td>RES-1/4W 2.7K-OHM 5%</td>
<td>1</td>
<td>$1.68</td>
</tr>
<tr>
<td>8009QFU9H4</td>
<td>Power Supply</td>
<td>10K Ohm potentiometer &amp; black control Knob</td>
<td>1</td>
<td>$8.99</td>
</tr>
<tr>
<td>800GWDEQEF</td>
<td>Power Supply</td>
<td>Female Banana Socket 7mm Thread Binding Post Terminals</td>
<td>1</td>
<td>$4.99</td>
</tr>
<tr>
<td>800IDR28S</td>
<td>Power Supply</td>
<td>Blue LED Panel LED Display Voltage Meter Voltmeter</td>
<td>1</td>
<td>$7.99</td>
</tr>
<tr>
<td>80002ZPKEW</td>
<td>Power Supply</td>
<td>SPST Rocker Switch with Neon Lamp</td>
<td>1</td>
<td>$4.99</td>
</tr>
<tr>
<td>328713</td>
<td>Power Supply</td>
<td>Heat Sink 1 Hole</td>
<td>1</td>
<td>$0.99</td>
</tr>
<tr>
<td>11870</td>
<td>Power Supply</td>
<td>CASE,ALUMINUM, 4.0 INCH X3 INCH X2.8 INCH Aluminum Electrolytic</td>
<td>1</td>
<td>$7.95</td>
</tr>
<tr>
<td>B009QFU9H4</td>
<td>Power Supply</td>
<td>10K Ohm potentiometer &amp; black control Knob</td>
<td>1</td>
<td>$5.99</td>
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<tr>
<td>800GWDEQEF</td>
<td>Power Supply</td>
<td>Female Banana Socket 7mm Thread Binding Post Terminals</td>
<td>1</td>
<td>$4.99</td>
</tr>
<tr>
<td>800IDR28S</td>
<td>Power Supply</td>
<td>Blue LED Panel LED Display Voltage Meter Voltmeter</td>
<td>1</td>
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<td>$4.99</td>
</tr>
<tr>
<td>328713</td>
<td>Power Supply</td>
<td>Heat Sink 1 Hole</td>
<td>1</td>
<td>$0.99</td>
</tr>
<tr>
<td>11870</td>
<td>Power Supply</td>
<td>CASE,ALUMINUM, 4.0 INCH X3 INCH X2.8 INCH Aluminum Electrolytic</td>
<td>1</td>
<td>$7.95</td>
</tr>
<tr>
<td>ESMH800VNN</td>
<td>Power Supply</td>
<td>Aluminum Electrolytic Capacitors - Snap In 10KUF 80V</td>
<td>1</td>
<td>$5.92</td>
</tr>
<tr>
<td>103MA50T</td>
<td>Power Supply</td>
<td>1/8-WATT 10K OHM CARBON FILM RESISTORS (5-PACK)</td>
<td>1</td>
<td>$1.49</td>
</tr>
<tr>
<td>271-006</td>
<td>Power Supply</td>
<td>Bridge Rectifier</td>
<td>1</td>
<td>$2.69</td>
</tr>
<tr>
<td>R21-KR1806</td>
<td>Power Supply</td>
<td>.033uF Capacitor</td>
<td>1</td>
<td>$1.98</td>
</tr>
<tr>
<td>90333</td>
<td>Power Supply</td>
<td>KME35V8221 .033uF Capacitor</td>
<td>1</td>
<td>$1.98</td>
</tr>
<tr>
<td>KME35V8221</td>
<td>Power Supply</td>
<td>KME 220uf 56v 105C Radial Electrolytic Capacitor</td>
<td>1</td>
<td>$4.95</td>
</tr>
<tr>
<td>M10X12LL</td>
<td>Power Supply</td>
<td>3220-Point Solderless</td>
<td>1</td>
<td>$36.85</td>
</tr>
<tr>
<td>20812</td>
<td>Power Supply</td>
<td>Boardboard 7.3&quot;x7.5&quot;W</td>
<td>1</td>
<td>$36.85</td>
</tr>
<tr>
<td>592-312007-01</td>
<td>Power Supply</td>
<td>AC Power Cord</td>
<td>1</td>
<td>$4.65</td>
</tr>
</tbody>
</table>

| Sum      |             |                                     |          | $128.61         |
Table 8 shows the other items needed for the electrochemical etching system (besides power supply parts) and the cost associated with each item. These items include the roller marker, power cord, stencils, marking solutions for different sheet metals, Steel and Aluminum sheet metal specimens.

<table>
<thead>
<tr>
<th>Part ID</th>
<th>Part Type</th>
<th>Description</th>
<th>Quantity</th>
<th>Price per Part</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Etching</td>
<td>4394 roller marker 6”</td>
<td>1</td>
<td>$96.00</td>
</tr>
<tr>
<td></td>
<td>Etching</td>
<td>4394-1 roller marker pad</td>
<td>1</td>
<td>$16.00</td>
</tr>
<tr>
<td></td>
<td>Etching</td>
<td>4309-B-4’ Black cord only 4 feet</td>
<td>1</td>
<td>$6.25</td>
</tr>
<tr>
<td></td>
<td>Etching</td>
<td>P/S 9”x 9” grid photo-stencil</td>
<td>1</td>
<td>$9.00</td>
</tr>
<tr>
<td></td>
<td>Etching</td>
<td>5-PAK 5 - 4oz bot. marking solutions for various metals, includes cleaner</td>
<td>1</td>
<td>$20.00</td>
</tr>
<tr>
<td>1814161</td>
<td>Etching</td>
<td>Red Alligator Clip to Multi-Stacking Banana Plug</td>
<td>1</td>
<td>$6.25</td>
</tr>
<tr>
<td>ASTM A240</td>
<td>Etching</td>
<td>COLD ROLL STAINLESS 2B SHEET 316/316L 12”x 12”</td>
<td>2</td>
<td>$10.91</td>
</tr>
<tr>
<td>ASTM B209</td>
<td>Etching</td>
<td>ALUMINUM BARE SHEET 6061 T6 12”x 12”</td>
<td>2</td>
<td>$4.72</td>
</tr>
<tr>
<td>Sum</td>
<td></td>
<td></td>
<td></td>
<td>$311.51</td>
</tr>
</tbody>
</table>

Table 8 Other Items of the System and the associated Costs

The total cost for the entire system is $340.12, which includes both the power supply components and the other items listed. The project cost is below the targeted cost of $350 specified earlier as a design constraint. The amount is away below the commercial products available in the market.

Assessment of Student Outcomes

For the purpose of assessing this project, a few specific learning outcomes have been selected. These learning outcomes include 1) Design, 2) Experimentation, 3) Oral Communication, 4) Written Communication and 5) Teamwork. For each selected learning outcome, a set of performance indicators have been defined as metrics for assessment purposes. Table 9 summarizes the performance indicators that have been developed to assess each of the learning outcomes selected. For a given learning outcome, the performance of the participating students have been assessed on each of the performance indicators (associated with the outcome) using a four scale scoring system. The scoring system considers scores of 1-4 for student performance of unsatisfactory/need improvement/satisfactory or competent. The student performance is estimated in percentage for each performance indicator for any selected learning outcome.

Figure 29 shows the assessment results for Design learning outcome where student performance is depicted for each of the performance indicators associated with Design outcome. As seen, the students performed above 75% for all the performance indicators. It appears that student performance is the lowest in developing design strategy/planning/timeline along with design analysis using governing equations. These performance indicators will need further attentions for future projects.
<table>
<thead>
<tr>
<th>Performance Indicators</th>
<th>1) Design Outcome</th>
<th>2) Experimentation Outcome</th>
<th>3) Oral Communication Outcome</th>
<th>4) Written Communication Outcome</th>
<th>5) Teamwork Outcome</th>
</tr>
</thead>
<tbody>
<tr>
<td>Design requirements</td>
<td>Development of logical experimental procedure</td>
<td>Organization</td>
<td>Organization</td>
<td>Attendance in team meetings</td>
<td></td>
</tr>
<tr>
<td>Design constraints</td>
<td>Experiment planning</td>
<td>Clarity</td>
<td>Clarity</td>
<td>Preparation for team meetings</td>
<td></td>
</tr>
<tr>
<td>Design conceptualization</td>
<td>Selection of appropriate equipment/instrumentation</td>
<td>Sufficiency</td>
<td>Sufficiency</td>
<td>Contribution to team</td>
<td></td>
</tr>
<tr>
<td>Design strategy/planning/timeline</td>
<td>Ascertain performance of equipment/instrumentation</td>
<td>Flow/Sequence</td>
<td>Flow/Sequence</td>
<td>Interaction/ cooperation with others</td>
<td></td>
</tr>
<tr>
<td>Design analysis: (using governing equations)</td>
<td>Ability to operate equipment/instrumentation</td>
<td>Use of Charts/Graphs/Tables/…</td>
<td>Use of Charts/Graphs/Tables/…</td>
<td>Sharing information with others</td>
<td></td>
</tr>
<tr>
<td>Design analysis: (using modern tools)</td>
<td>Implementation of logical experimental procedure</td>
<td>Time</td>
<td>Proper English: (Grammar, spelling, writing Style, etc)</td>
<td>Listening to others</td>
<td></td>
</tr>
<tr>
<td>Design verification</td>
<td>Safe conduct</td>
<td>Presentation Soft Skills: (Eye contact, being heard, non-monotonic, body language, nervousness, not-blocking screen, etc)</td>
<td>Results</td>
<td>Respectfulness to others</td>
<td></td>
</tr>
<tr>
<td>Design modification/optimization</td>
<td>Time management</td>
<td>Professional appearance</td>
<td>Discussion of results</td>
<td>Encouraging others for participation</td>
<td></td>
</tr>
<tr>
<td>Cost analysis</td>
<td>Data collection</td>
<td>Proper English</td>
<td>Citation/References</td>
<td>Sharing credit with others</td>
<td></td>
</tr>
<tr>
<td>Design documentation</td>
<td>Data interpretation</td>
<td>Handling questions</td>
<td>Formatting</td>
<td>Accepting designated team roles</td>
<td></td>
</tr>
<tr>
<td>Physical/virtual prototype</td>
<td>Data analysis based on relevant theory</td>
<td>Error consideration</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Table 9 Summary of Performance Indicators used for Assessment for each Learning Outcomes
Figure 29 Assessment of Design Outcome; Student Performance (%) for different Performance indicators

Figure 30 Assessment of Experimentation Outcome; Student Performance (%) for different Performance indicators
Assessment of Oral Communication Outcome

Student Performance (%) for different Performance indicators

Assessment of Written Communication Outcome

Student Performance (%) for different Performance indicators

Figure 31 Assessment of Oral Communication Outcome; Student Performance (%) for different Performance indicators

Figure 32 Assessment of Written Communication Outcome; Student Performance (%) for different Performance indicators
Figure 33 Assessment of Teamwork Outcome; Student Performance (%) for different Performance indicators

Figure 34 Assessment of Learning Outcomes; Student Performance (%) for Learning Outcomes
Figure 30 shows the assessment results for Experimentation learning outcome where student performance is depicted for each of the performance indicators associated with Experimentation outcome. As shown, the students performed above 75% for all the performance indicators. It appears that student performance is the lowest in experiment planning, time management, data interpretation and data analysis. More attentions should be paid to these performance indicators in similar future projects. Figure 31 depicts the assessment results for Oral Communication outcome. While student performance for all performance indicators is above 75%, there is still room for improvements when it comes to presentations’ organization, clarity, use of proper English and handling questions. Similarly, Figure 32 shows the assessment results on Written Communication outcome. Although all the performance indicators have been assessed above 75%, the written reports’ clarity and proper English can be further improved. Figure 33 depicts the assessment results for Teamwork learning outcome. It is observed that student performance is above 85% for all the performance indicators associated with Teamwork outcome. Figure 34 summarizes the assessment results for all the learning outcomes. As shown, all the outcomes have been assessed above 80%, which is very encouraging.

Further Observations on Student Learning
1- The project exposed two students to design process of a real world electrochemical marking system for strain measurement application with realistic design requirements and design constraints.
2- The students developed a design approach to design the electrochemical etching system.
3- The students learned how to apply the fundamentals of mechanics of materials to measure and calculate plastic true strain using circle grid analysis.
4- The students gained hands-on experience working with Multisim as a modern simulation tool for design and analysis of complex circuitries in realistic conditions.
5- The students learned how to select and work with electrical elements and components such as resistors, capacitors, voltage regulators, bridge rectifier, diodes, transformer, and potentiometer to prototype circuitries.
6- The students gained valuable hands-on experience on how to design and conduct experiments to validate the performance of the system designed.
7- The students learned the importance of implementing multidisciplinary concepts for design purposes. In this case, the students designed an electrical system that utilizes a chemical process for a mechanical engineering application.
8- The students learned how to develop operational and safety manual for the system designed.
9- The students improved their oral communication skills by making weekly presentations to the audience of the senior design class and a faculty advisor.
10- The students improved their written communication skills by documenting the design, design verification, prototype fabrication, testing and validation.
11- The students had a chance to improve their project management skills by setting up project plans, time lines and etc.
12- The students had a chance to work in a team framework and experience the challenges associated with it.
**Students Feedback**
Faculty involved in this project received very positive feedback from the students who conducted the project. At the beginning of the project, the students thought that the topic was uncommon and unconventional. However, the students became interested in the topic as they read and learned more about the project. They were convinced that they had the opportunity to work on a design project, which involved them in applying engineering fundamentals toward the design of an electrochemical etching system. The students were satisfied that they gained practical experience with modern engineering tools and software. They were excited about the opportunity that they had to develop, prototype, and test the performance of their system. The students noticed that their oral and written communication skills have improved remarkably as a result of this project. The students viewed the project as a challenge since many tasks needed to be completed in a short period of time. The student realized that while the course materials offered throughout the curriculum are very helpful, they are not enough to conduct real world projects. To this end, they learned a great deal of extracurricular materials to successfully complete the project.

**Pedagogy**
The teaching style adopted for this project is project-based learning and learning-by-doing. The faculty member briefly introduces the design concepts and general terms for design requirements and constraints. The students gather information on their own, and define the project in a form of a design problem with very specific design requirements and constraints. On weekly basis, the students present (in a form of PowerPoint) their progress and future plans to the faculty member and an audience of students. The faculty member reviews the materials and provides detailed feedback interactively during the presentation. If further discussion is needed, the students meet with the faculty member during office hours. The faculty member acts as both customer and advisor and keeps track of the students’ progress and to-do items in a log sheet so he can follow up for the upcoming weeks. As the students make progress on their project, they are asked to submit a written report at three different milestones during the semester. Each revision of the report is graded thoroughly by the faculty member. The final report should be well-written, formatted, and free of technical errors. A final presentation is presented by the students and evaluated by the faculty member. Assessment data are collected throughout the semester.

**Conclusion**
- With a predefined sets of educational objectives, an Electrochemical Marking System for strain measurement applicable in sheet metal forming has been designed, prototyped and performance tested.
- The final design is in compliance with the design needs originally specified.
- The system designed is a variable power supply that outputs 1-30 VDC and 2 milliamps DC to etch circle grid pattern of 0.2in of diameter circles in a 0.5in square on Steel or Aluminum sheet metal.
- The power supply displays the output voltage and is compatible with 6 in roller marker.
- The design constraints have been met as the project costs $340.12 and the set up weighs only 3.66 pounds.
- To assess the projects, specific learning outcomes have been selected. Performance indicators have been developed for the learning outcomes selected. Assessment data have been
collected and presented in details. It has been shown that students met the learning outcomes in Design, Experimentation, Oral Communication, Written Communication and Teamwork.

- The students gained great deal of engineering knowledge along with hands-on experience.

References