Project Hulk: X-ray Dose Rate Detection for Material Irradiation

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***Abstract* — This engineering project presents a radiation dose-rate detection and visualization system designed for use with the precision X-ray 320 biological irradiator. The system combines radiation sensing hardware with embedded data processing to display X-ray dose-rate in real time. The radiation sensor converts the x-ray signals into electrical signals which are then refined by a custom circuit to create a readable voltage. The signal gets processed by a microcontroller into an accurate dose-rate value. The processed data is depicted in a real time graph on an LCD display. This system offers a compact and effective way to monitor and analyze radiation dose-rate in a lab setting.**

***Index Terms* — Microcontroller, LCD**

II. Introduction

Monitoring X-ray radiation dose is critical in medical imaging, radiation research, and materials testing environments to ensure accurate exposure levels and maintain safe operating conditions. This senior design project was developed based on research involving the use of photodiode sensors to monitor X-ray radiation. The project was initiated after the team was approached by Dr. Enxia Zhang to design and build a radiation dose rate measurement system for use with an X-ray machine in the Radiation Effects and Reliability Laboratory (RERL). The goal of the project is to develop a machine capable of measuring X-ray dose rate in real time, displaying the measurements on a screen, and logging the data for later analysis.

The system operates by using a photodiode to detect incident X-ray radiation, which produces a very small current proportional to radiation intensity. This current is converted into a voltage using an analog signal conditioning circuit consisting of a transimpedance amplifier and filtering stages. The conditioned signal is then read by a microcontroller, which processes the signal, displays the dose rate on a TFT display, and logs the data to an SD card for further analysis.

III. Previous Work

A. Development of a Silicon PIN Diode X-Ray Detector

The Silicon PIN Diode X-Ray Detector is a PCB designed to detect radiation output by monitoring dose rate. As x-ray flux passes through a diode a current is produced. This current can be used to calculate the flux which leads to the calculation of the radiation dose. This project consists of many shared qualities with the PCB we will design.

The PCB consists of an AC and DC circuit to measure radiation. The end goal for this project is to combine the AC and DC circuits to measure the pulses from the diodes at lower and higher dose rates respectively. The AC circuit was coupled to measure the radiation. A gamma ray is sent to a photodiode creating a photocurrent which is then sent through a high-pass filter coupled with a low-pass filter with a passband of 160 Hz to 18kHz.

In the DC circuit a high pass filter is placed in series with a non-inverting amplifier, two capacitors are also used to filter noise. This circuit worked and the output voltage measurements were taken at different distances from the source of the radiation. Using the Inverse Square Law and the known dose rates (at some of the distances), the dose rates at unknown distances were estimated. [1]

B. Experimental analysis of a novel and low-cost pin photodiode dosimetry system for diagnostic radiology

The system for diagnostic radiology is a two-stage amplifier to measure the photocurrent from the PIN sensor; this current is then processed to be displayed on an LCD screen. The first stage of this amplifier is a trans-resistive amplifier to measure current changes which are then converted to voltages and sent to the second stage, a voltage amplifier, to amplify the first stage output voltage to a range between 0V and 2.5V. The circuit design was found to be very sensitive to noise and was placed in a small metal box to shield it. To evaluate the signal changes a full-wave rectifier was used.

In addition to this circuit, in this project a Digital Processing Unit was used to process the data. The first block of this was an ADC to digitalize the voltage output from the circuit. A signal channel analyzer (SCA) is used to measure the noise sources; this is used as a trigger signal to activate the multichannel analyzer (MCA). When the SCA is active the MCA begins to capture the data from the input signal, when the SCA is not active the MCA uses the data collected to calculate the voltage. [2]

IV. Safety Standards

For the safety of users, we adhered to established radiation and electrical safety standards in the design of the X-ray dose rate measurement system.

Radiation safety standards for X-ray facilities are outlined in NCRP Report No. 147, which provides guidelines for shielding, exposure limits, and safe operation of X-ray equipment. The X-ray machine used in the Radiation Effects and Reliability Laboratory is a shielded cabinet system designed to limit exposure. The measurement system operates only when the cabinet is closed, ensuring compliance with radiation safety practices such as minimizing exposure time, maximizing distance, and using proper shielding.

Electrical safety standards were also considered in the system design. OSHA Electrical Safety Codes, particularly 29 CFR 1910.303 and 29 CFR 1910.305, outline requirements for safe wiring methods, grounding, and protection against electrical hazards. Voltage regulators, proper grounding planes, insulation, and decoupling capacitors were used in the design to ensure stable and safe operation of the electronic components.

PCB design standards such as IPC-2221A and IPCJ-STD-001J were also followed to ensure safe and effective board design in the project. IPC-2221A addresses requirements for overall board design requiring the PCB to have a thickness between 0.8mm and 2.4mm, components selected to be able to withstand a minimum temperature and humidity they might be exposed to during manufacturing or general use. IPCJ-STD-001J covers requirements for soldering temperatures, between 340- 380°C and requirements for the materials used in solder alloys and fluxes. These standards were taken into consideration when designing and producing our design. [3] [4]

V. Hardware System Components

A. Diode

The sensor used in this system is the AXUV20HS1 photodiode, which is specifically designed for detecting X-rays and ultraviolet radiation. This photodiode was selected because it has high sensitivity to X-ray radiation and produces a current proportional to radiation intensity, making it suitable for radiation dose rate measurement applications.

When X-ray photons strike the photodiode, they generate electron-hole pairs within the semiconductor material, producing a photocurrent. The output of the AXUV20HS1 is a current rather than a voltage, and this current is extremely small, typically ranging from approximately

10^{-10}A to 10^{-5} A depending on the radiation dose rate. Considering how the output current is so small, it cannot be measured directly by a microcontroller and must first be converted into a voltage via another PCB with analog circuitry.

The photodiode is connected to the signal conditioning circuit using a shielded coaxial cable. The coaxial cable helps reduce electromagnetic interference and noise pickup, which is critical because the signal being measured is extremely small and susceptible to noise.

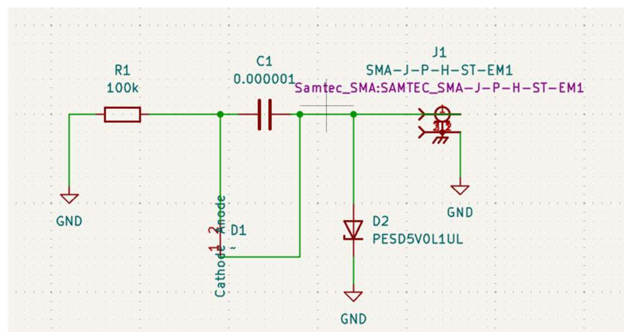

Fig. 1 Schematic showing the Diode PCB design

B. Signal Conditioning Filter

The photodiode produces a current output so a transimpedance amplifier (TIA) is used to convert the current into a measurable voltage. The TIA uses an operational amplifier with a feedback resistor to convert input current into output voltage according to the relationship where I_{pd} is photodiode current and Rf=100,000 is the feedback resistor

$$Vout = -I_{pd} \times (100{,}000). \qquad (1)$$

After the TIA stage, the signal passes through a low-pass filter. The purpose of the filter is to remove high-frequency noise and stabilize the signal before it is sampled by the microcontroller. Because the system is measuring very small signals noise could distort the measurement.

The filter circuit consists of resistor capacitor low-pass filter stages with a buffer amplifier placed between stages. The buffer amplifier prevents loading effects between filter stages and ensures that the signal is not unintentionally attenuated. The cutoff frequency of the filter is designed to be low enough to remove high-frequency noise while still allowing the slowly changing radiation signal to pass through.

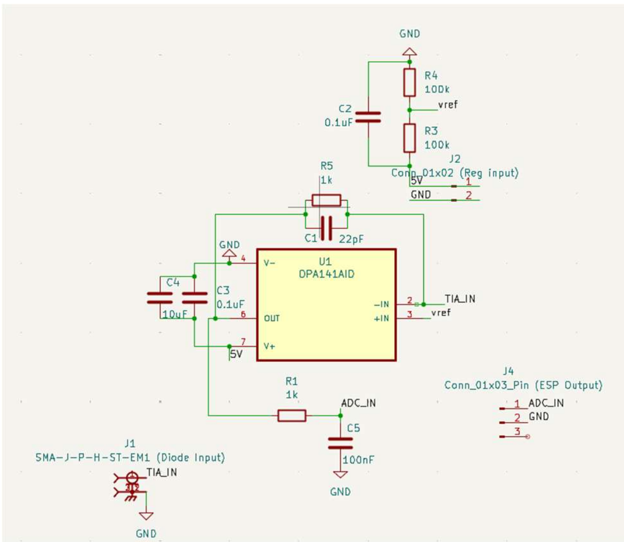

Fig. 2 Schematic showing the Filter PCB design

C. MCU

The microcontroller used in this project is the ESP-32-WROOM. This part was selected because it includes a built-in analog-to-digital converter (ADC) and communication interfaces required for the system that we needed. The ADC is used to measure the analog voltage output from the signal conditioning circuit and convert it into a digital value that can be processed to calculate radiation dose rate.

The ESP-32-WROOM also supports SPI communication, which allows it to interface with the TFT display and SD card module for real-time display and data logging. By using a microcontroller with integrated ADC and communication interfaces, the overall system complexity and cost of the part were reduced.

D. Buck Regulator

The regulator we will be using is the LM22680 6V to 3.3V and 5V buck regulator from Texas Instruments. The 3.3V regulator will need to take in the supplied voltage from the barrel jack of around 6V and drop it down to 3.3V to power our main PCB board. This regulator will be needed to power the ESP32 chip, the LCD display, and the SD card reader and will need to supply around 1.5A of current to the board. To account for this the regulator was designed to supply both a 3.3V output voltage and a 2A output current to allow for any additional current needs with the testing and growth of the design.

This LM22680 was chosen as the regulator integrated circuit for the design because of its efficiency, price, and ease of integration into the design. Another major draw of this regulator for our design was the ability to use this IC with only simple changes of the circuit components for the 5V regulator as well.

The design of the regulators and the PCB layouts were based mainly on the information found in the datasheet for the IC as well as found on Texas Instrument's WEBENCH Power Designer. All the components selected were at least a 0805 footprint and the inductor used was chosen because of the ability to handle up to 3A of current, which was large enough for our design.

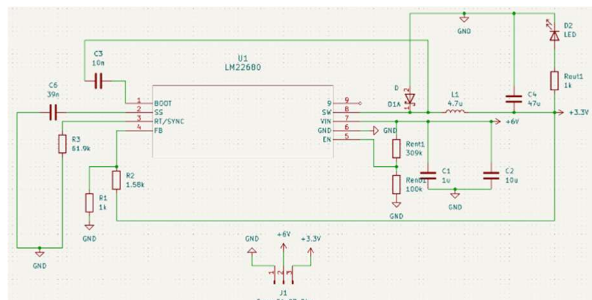

Fig. 3 Schematic showing the 3.3V Buck Regulator design

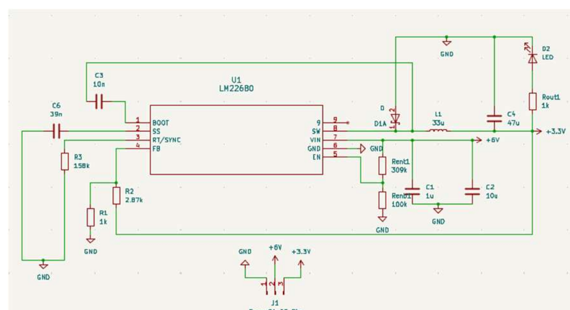

Fig. 4 Schematic showing the 5V Buck Regulator design

E. Main PCB

The core of this system is the ESP32-WROOM-32E microcontroller. It was chosen for its fast dual-core processor (up to 240 MHz) and built-in Wi-Fi and Bluetooth, which provide strong data processing and wireless connectivity. To support development and maintenance, the design includes a CP2102N USB-to-UART bridge, which offers a reliable connection for uploading firmware and debugging over a serial interface.

Real-time data is shown on a 2.4-inch TFT LCD (320x240), a display module tested and confirmed to work smoothly with the ESP32's SPI interface during prototyping. For long-term use, the system includes a 128GB SD card so users can store and access large amounts of historical dose-rate data. Power for all components comes from a 6V AC-to-DC wall adapter, which is stepped down by voltage regulators to provide 3.3V for the microcontroller and SD card, and 5V for the display.

The layout transition from schematic to PCB followed a hardware flowchart approach, ensuring optimal component placement for signal integrity and thermal efficiency.

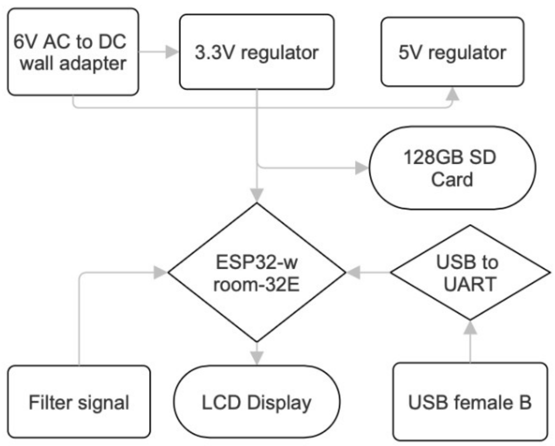

Fig. 5 Main PCB Block Diagram

The system is integrated onto a compact, 2-layered PCB designed to balance low-level analog acquisition with high-speed digital communication. Power is sourced from a 6V adapter and regulated into 3.3V and 5V rails, supporting the ESP32 microcontroller, SD card and LCD respectively. To maintain signal integrity for the sensitive radiation sensor, the analog front-end utilizes short signal paths, a common ground plane, and decoupling capacitors to minimize noise and electromagnetic interference.

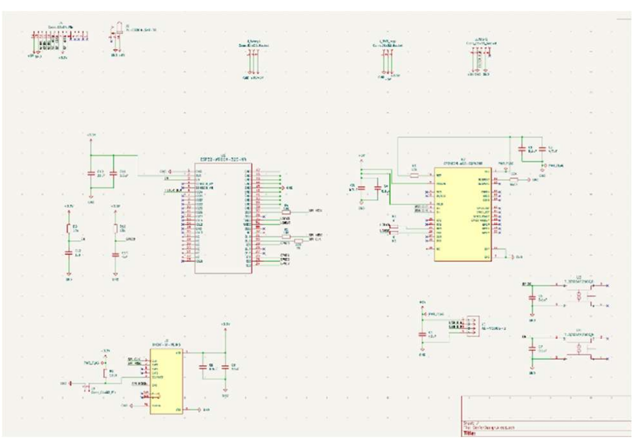

Fig. 6 Schematic showing the main PCB design

The ESP32 manages data processing and peripherals via SPI and UART, enabling real-time LCD visualization and continuous SD card logging. The resulting layout ensures a reliable, low-impedance environment for accurate dose-rate detection in a portable format.

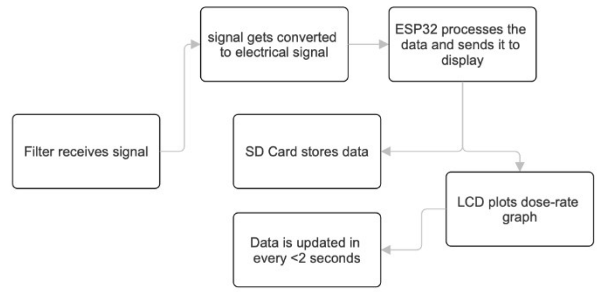

Fig. 7 Sensor Data Flowchart

The process begins as a radiation signal is captured and passed through a filter to remove interference and amplify the signal. This filtered input is then converted into an electrical signal to transform raw radiation strikes into measurable voltage.

Once digitized, the ESP32 microcontroller acts as the central hub, processing the raw data into meaningful dose-rate measurements. The ESP32 simultaneously manages two data paths: it logs the information to an SD card for long-term storage and transmits the data to an LCD display.

The system provides real-time feedback by plotting a dose-rate graph on the screen. To ensure accuracy and responsiveness, the entire data chain is refreshed with an update frequency of less than 2 seconds, allowing for near-instantaneous monitoring of radiation levels.

VI. Software System Components

A. *Software Design*

The software system is designed to acquire analog signals from the photodiode circuitry, process data, and compute the corresponding dose rate in real time on the display for the researchers. The implementation is divided between embedded firmware on the ESP32 microcontroller and a display interface on the TFT LCD. The ESP32 performs acquiring signal and computing, while the LCD provides visualization of the processed data.

The firmware is developed in C/C++ using the Arduino IDE due to its compatibility with the ESP32 platform and efficiency in terms of execution in embedded systems. The Arduino IDE was selected over lower-level development environments because it simplifies hardware interfacing, peripheral configuration, and rapid prototyping, while still allowing sufficient control for real-time embedded applications. Additionally, the availability of built-in libraries for SPI communication and display control reduces development complexity and improves reliability. Lower-level programming languages such as C/C++ are preferred in embedded systems because they provide improved execution speed and reduced memory overhead compared to higher-level alternatives Lower-level programming enables precise control over timing and hardware resources, which is necessary for real-time signal processing applications

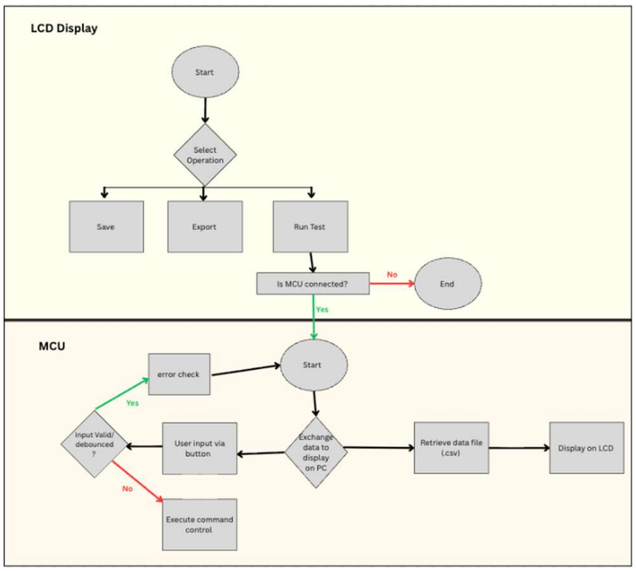

Fig. 8 Software design flowchart

B. Software Function

The ESP32 samples the analog output of the photodiode and transimpedance amplifier using its onboard ADC. To reduce the effects of noise, multiple samples are collected and averaged before further processing. The resulting digital values are converted into voltage and used as the input for dose rate computation.

The primary function of the software is to compute the radiation dose rate from the measured photocurrent. This calculation is implemented directly in the firmware using the relationship shown below:

$$D = \frac{I_{ph}}{Q} \cdot \frac{E_r(1-e^{-\left(\frac{\mu}{\rho}\right)\rho t})}{A \cdot t \cdot \rho} \qquad (2)$$

where Iph is the measured photocurrent, Q is the electron charge, Er is the photon energy, μ/ρ is the mass attenuation coefficient, ρ is the material density, t is the intrinsic thickness, and A is the active area of the detector. As shown in the provided equation (2), the dose rate is derived from both the measured electrical signal and known material properties.

Within the firmware, this equation is evaluated after each sampling cycle. The measured voltage is first converted to photocurrent, and the corresponding dose rate is then calculated using predefined constants for the detector material and radiation properties. This approach enables direct mapping from sensor output to physically meaningful dose-rate values.

Processed data is transmitted to the LCD using the Serial Peripheral Interface (SPI) protocol, selected for its high data transfer rate and reliability. The display presents both numerical values and graphs, allowing real-time observation of system behavior. Upon system initialization, the display is configured, communication is established, and continuous updates begin.

Overall, the software is structured to ensure accurate data acquisition, efficient computation, and reliable visualization. By directly implementing the dose-rate equation within the embedded system, the design enables real-time conversion of sensor measurements into meaningful radiation data.

VII. Testing

A. Photodiode Testing

The photodiode was connected to the system. The photodiode was placed inside the X-ray cabinet while the rest of the electronics remained outside the cabinet. When the X-ray machine was turned on, the output voltage of the signal conditioning circuit was monitored using an oscilloscope and a multimeter.

The output voltage increased as the X-ray dose rate increased, confirming that the photodiode was detecting radiation and that the system was successfully converting radiation intensity into a measurable voltage. Multiple measurements were taken at different X-ray machine settings to verify that the system produced consistent and repeatable readings.

B. LDO Regulator Testing

The low-dropout voltage regulators were tested to ensure that the op-amp in the filter would receive stable supply voltages. A DC power supply was used to simulate the battery input to the regulators. The input voltage of ±5V was applied to the regulators on a breadboard and a multimeter was used to measure the output voltage.

The regulators were also tested under load conditions using a DC electronic load to verify that the output voltage remained constant while supplying current. The output voltage was monitored to confirm that the regulators maintained a constant voltage and did not overheat during operation.

C. *Filter Circuit Testing*

The signal conditioning PCB, including the TIA and filter stages, was tested using a function generator to simulate the photodiode signal. Since the photodiode produces a very small current, a small input signal was applied to the input of the transimpedance amplifier to verify that the circuit produced the expected amplified output.

An oscilloscope was used to measure the output voltage of the amplifier and filter circuit. The frequency of the input signal was swept over a range of frequencies to observe the filtering behavior of the circuit. This allowed verification that the low-pass filter was attenuating high-frequency signals and passing low-frequency signals as expected.

D. *Buck Regulator Testing*

The regulators were designed using an extra load resistor and LED to have a visible signal of their functionality when connected to the power supply. With this quick test we can see that there is some voltage going from the input to the output of the buck regulators. To test the actual output voltage and current of the regulators the PCB was breadboarded with a 6V supply added into the input of the regulator. When probed the output voltage of the regulators were 3.3V and 5V which is as expected and shows proper function of the regulators and the design.

E. *Power Supply Testing*

To verify the integrity of the power delivery system, the main PCB was powered using a 6V AC-to-DC wall adapter, which serves as the primary source for the 5V and 3.3V regulators. Initial testing involved probing the adapter's output and ground pins with a multimeter, yielding a reading of approximately 6.6V. While slightly higher than the nominal rating, this value remains well within the safe operating input range for the selected regulators. To confirm that the ESP32and SD card were receiving stable power, the Vcc and GND pins were probed, consistently showing a precise 3.3Voutput. Finally, the TFT LCD was connected to the 5V rail; the display initialized immediately upon power-up, confirming that the 5V regulator was functioning as expected and providing sufficient current for the visualization hardware.

VIII. Results

The performance of the system was evaluated based on two of the primary specifications: display initialization time and measurement accuracy. These metrics were selected to assess both responsiveness and reliability of the data.

The display initialization time was measured across ten independent trials. In these trials the power to the system was turned on at the same time as a timer which was stopped once the display was fully on. The recorded times ranged from 1.11 s to 1.68 s, with an average initialization time of 1.323 s. This result demonstrates consistent system startup behavior with minimal variation between trials. This indicates stable performance of the software and communication between the ESP32 and LCD during initialization.

Run	Timer
1	1.13
2	1.50
3	1.40
4	1.33
5	1.36
6	1.68
7	1.28
8	1.11
9	1.26
10	1.18
	Average: 1.323

Fig. 9 Chart of startup time for the system performed while testing

Measurement accuracy was evaluated by comparing voltage readings displayed on the LCD with corresponding values obtained from a digital multimeter. Ten test points were recorded across the operating range of the system. The results show strong agreement between the measured and displayed values, with only minor deviations observed at higher voltage levels. The total measured voltage from the multimeter was 14.636 V, while the total displayed voltage was 14.570 V.

The accuracy was calculated using the ratio of displayed values to measure values, yielding an accuracy of 99.54%. This high level of accuracy confirms that the signal processing and calibration implemented in the software effectively translate analog input signals into reliable digital outputs.

Run	Multimeter reading (V)	LCD Reading (V)
1	190m	0.19
2	306m	0.30
3	0.51	0.51
4	0.75	0.75
5	1.00	1.00
6	1.52	1.51
7	2.00	1.99
8	2.50	2.49
9	2.75	2.73
10	3.11	3.10
	Total: 14.636	Total: 14.570

Fig. 10 Chart of displayed voltage values while testing

IX. Conclusion

Project HULK is a Dosimetry readout machine designed for and sponsored by Dr. Enxia Zhang and the Radiation Effects and Reliability Laboratory (RERL). This machine is connected to the PIN photodiode selected by the lab which is placed in the X-Ray 320 machine. The design takes the current generated by the photodiode and by using the signal conditioning filter this current is converted into a voltage which is sent to the analog to digital converter of the ESP32. Using a series of equations provided by the lab, this voltage is converted to a graph displaying the dosimetry of the X-Ray machine onto the TFT LCD display. This data is also saved to a microSD card using the card reader to allow for ease of data storage and useability while further analyzing the data shown.

Biography

Labiba Ibrahim is a senior Electrical Engineering Student who is graduating in May of 2026. She has completed 1 internship with Texas Instruments and will be working as a full-time Electrical Engineer in Mortenson.

Madeline Moran is a senior Electrical Engineering Student who is graduating in May of 2026. She plans to continue her education by pursuing a Masters degree in Electrical Engineering.

Janani Nagaraj is a senior Electrical Engineering student who is graduating in May of 2026. She has completed 1 internship with Lockheed Martin and 1 with Texas Instruments and will be continuing to work there in the Fall.

Myesha Rahman is a senior Electrical Engineering student

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