MACHINE VISION APPLICATION FOR DAMAGED SOLAR PANELS DETECTION

FINAL REPORT

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EPRI SPONSORED PROJECT

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EXECUTIVE SUMMARY

Photovoltaic (PV) power plants provide an excellent solution to supplying communities with efficient and clean energy. However, some technological issues have become apparent with the increased availability and affordability of solar panels as an alternative energy source. Like any other energy source, solar panels require maintenance and monitoring to maintain their effectiveness. Still, by the nature of their construction, solar panels are susceptible to damages from various environmental factors like visual obstructions (e.g., dirt and other foreign matter), cracks and scratches from objects like hail and rocks, and warping from strong winds and unanticipated high-heat. This project aims to develop an AI-powered drone system that detects defects in solar panels. The system consists of several components: an image dataset, an AI model, a drone equipped with a camera, and a user interface. The image dataset includes images of solar panels with different types of defects, such as cracks, hotspots, and dirty panels. The AI model is trained using TensorFlow and Keras libraries in Python and can classify the defects in solar panel images. The drone captures images of solar panels, which are then fed into the AI model for analysis. The user interface provides an easy-to-use interface for interacting with the system and analyzing the results. The system's safety and ethics are considered, and guidelines are provided to ensure safe and ethical use of the system. This document also provides troubleshooting tips and recommendations for improving the dataset and AI model, including using instance segmentation to improve accuracy.

INTRODUCTION

Problem Statement

One concern about using photovoltaic (PV) technologies is their susceptibility to damage from various environmental factors [1]. Once the panels leave the manufacturing facility and are installed in their respective solar plants, panels can exhibit damages including but not limited to:

- Scratches, cracks, and other glass damage
- Obscured panels from foreign matter (e.g., bird excrement or dust)
- Warping from environmental factors like wind and heat
- Yellowing, front coating degradation, and other time-related defects

This project aims to incorporate an AI-based detection script into a functional product, potentially expanding its accessibility. The AI can be helpful to various clients, allowing them to work remotely and only be present if errors are detected. The main objective of this AI project is to fully train a drone to detect damaged solar panels and take high-definition photos without human intervention on site. A functional script will be created using the programming language Python. Pictures of solar panels (damaged and non-damaged) will be acquired and compiled into a language that the drone can understand, and the drone will be trained to follow a specific path.

Python will be the language of choice for the program to allow for ease of adaptability to potential applications, in addition to the provided software interface. The team is optimistic that this design will lead to advancements in the affordable detection of solar panel defects using AI-based image processing. This will open new opportunities for remote work and reduce manpower for the same tasks. The ideal benefits for the client are expected to be cost savings from reduced manpower and the ability to focus on more critical tasks.

Background

A history of steady advances in PV technologies implies an increased demand for improvements in maintaining and repairing them. Given the age of this technology, it should surprise no one that this area of research and project implementation is not barren. Multiple teams have approached the prospect of detecting defects, faults, and other issues in solar panels' mechanical and electrical properties. Given the nature of drones, the defects must be detectable from an aerial view. One objective of this project is to develop an affordable method to detect any imperfections in solar panels effectively. Some of the most common methods available based on current research appear to be through image processing (both visual and infrared) using artificial intelligence [4][5][6], as is the case for this project. Other teams opted for a manual approach, either manually checking images taken from an ultra-violet fluorescence test [7] or using mathematical models to calculate potential imperfections based on the expected output of solar panels [8].

The journal articles most similar to this project are those from Zou et al. and Patel et al. In the former, the team uses a combination of artificial intelligence, thermal imaging, and a convolution neural network to detect defects in solar panels which are then sent back to a ground station via 5G wireless technology, all in real time. The latter article deals with a similar concept but is identical in scope to this design in that it used an unnamed aerial vehicle (UAV) with what is assumed to be its built-in camera. The authors then used various image manipulation and processing techniques to determine solar panel defects. While similar in scope to this project, infrared cameras can be relatively expensive and subject to varying environmental conditions like rain (if the customer opts to waterproof their drone), temperature fluctuations, and unintended thermal reflections like the drone itself, the sun, or other objects.

The other articles worthy of note are from Gabor et al. and Pourhossein et al. The former is particularly worthy of note because they analyze solar panel defects using an ultraviolet imaging system that is particularly effective at finding defects that would be undetectable from a standard RGB camera. The downside to this technique is that it misses many other essential factors and is supposedly not compatible with newer PV technologies. The latter paper used a purely theoretical approach to approaching this issue. By modeling an AC equivalent to a PV module, Pourhossein's team developed a simulation and various elements in a circuit to determine what type of anomaly might be affecting the solar panel. This document was necessary to mention because smart devices are currently used in modern solar plants for detecting faults in this fashion. The downside of technologies like this is that the panels must be visually examined for what caused the faults in the first place, thus taking longer than the solution presented in this proposal.

DESIGN DESCRIPTION

The AI Python program trains the AI model using the TensorFlow 2, Keras, Pillow, and OpenCV libraries. The program includes the ImageRenamer, Data Augmentation, Resize Images, Train Images, and Predict Image functions. The ImageRenamer is used to rename images according to their category and ensure they are organized correctly for training. The Data Augmentation program is used to increase the size of the training dataset by applying transformations to the original images. The Resize Images program resizes all images in the prediction folders to the required size. The Train Images program trains the AI model using augmented and resized images. Finally, the Predict Image program uses the trained AI model to predict the defects category in new images.

A live detection example was created using ModelPredict, which uses the preprogrammed ESP32 Web Video Server available through the Arduino library. This model only works for two categories, so it will not work in the real world. However, it gives an idea of how to use it for real-world applications.

The design concludes with recommendations for improving the model's accuracy, such as using instance segmentation to extract relevant features from images and taking more original pictures of good and dirty solar panels.

System Block Diagram

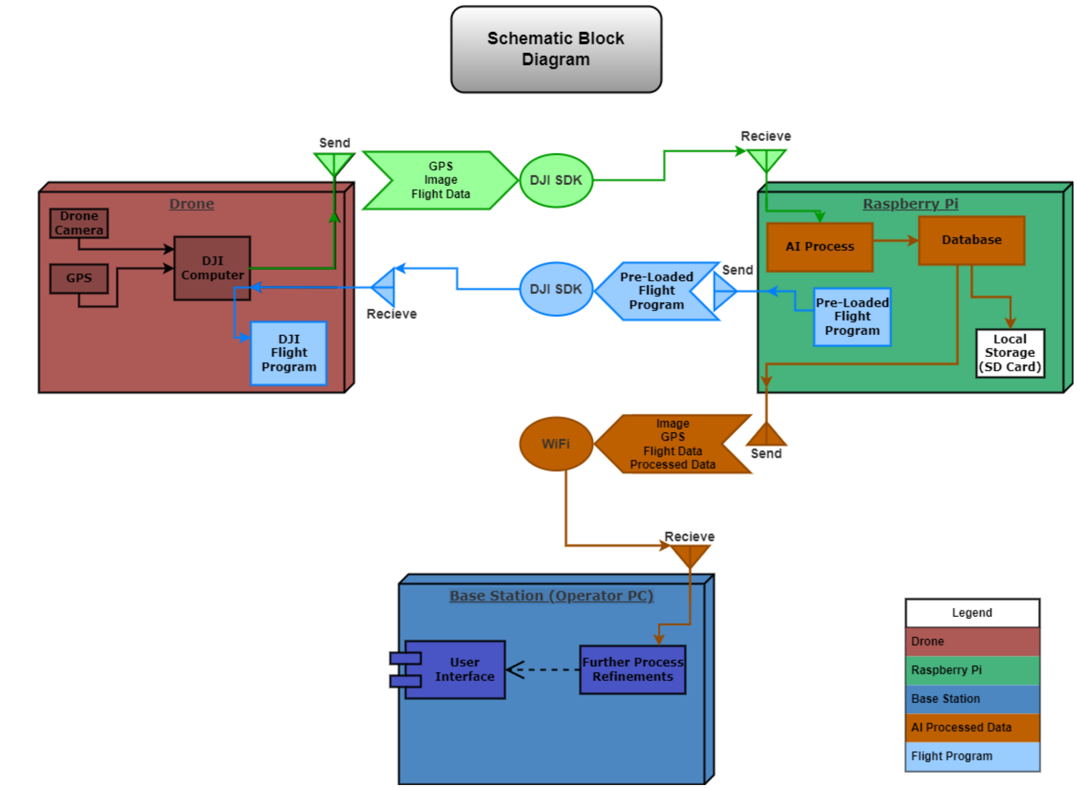

Fig. 1 - Theoretical Subsystem design

Methods

Using a supervised learning approach, a dataset was collected from various archives available from multiple sources; these images were manually organized into the classes expected to be encountered. Using 512x512 images, the data set was trained with 80% training and 20% validation split from the original data. Only the training images were augmented, and the validation data remained the same. Predictions were then made on the original dataset to verify accuracy.

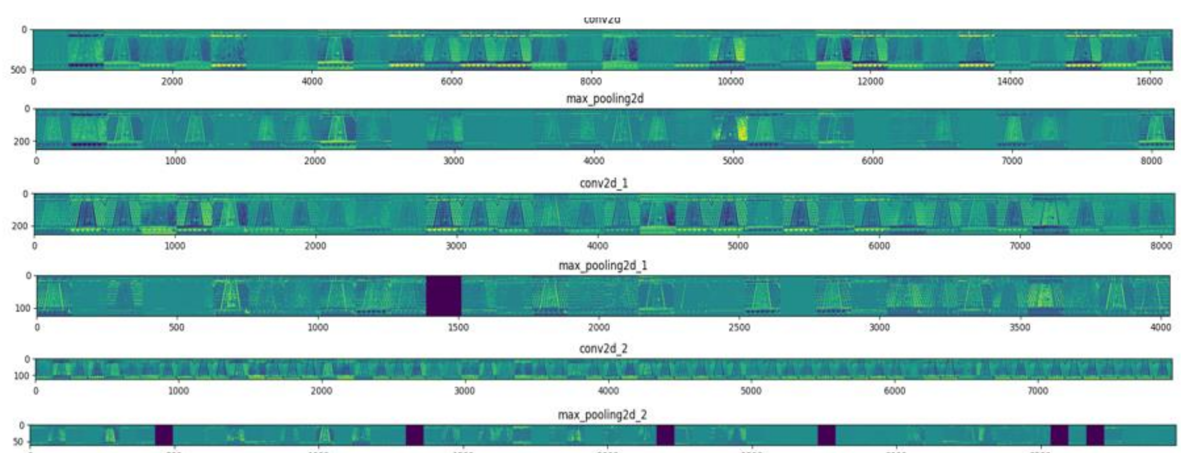

Fig. 2 - Visualization of how the model uses layers to extract features from a broken panel image

RESULTS

Given the limited training set, the final model is restricted in how well it can determine if a panel is covered in dust, pollen, and other debris. The model exhibits high accuracy for broken panel detection, hot spot, and microcrack detection, but this may be a result of overfitting due to the lack of available images to train these categories. This model would greatly benefit from methods such as instance segmentation or collecting more data on solar panel defects.

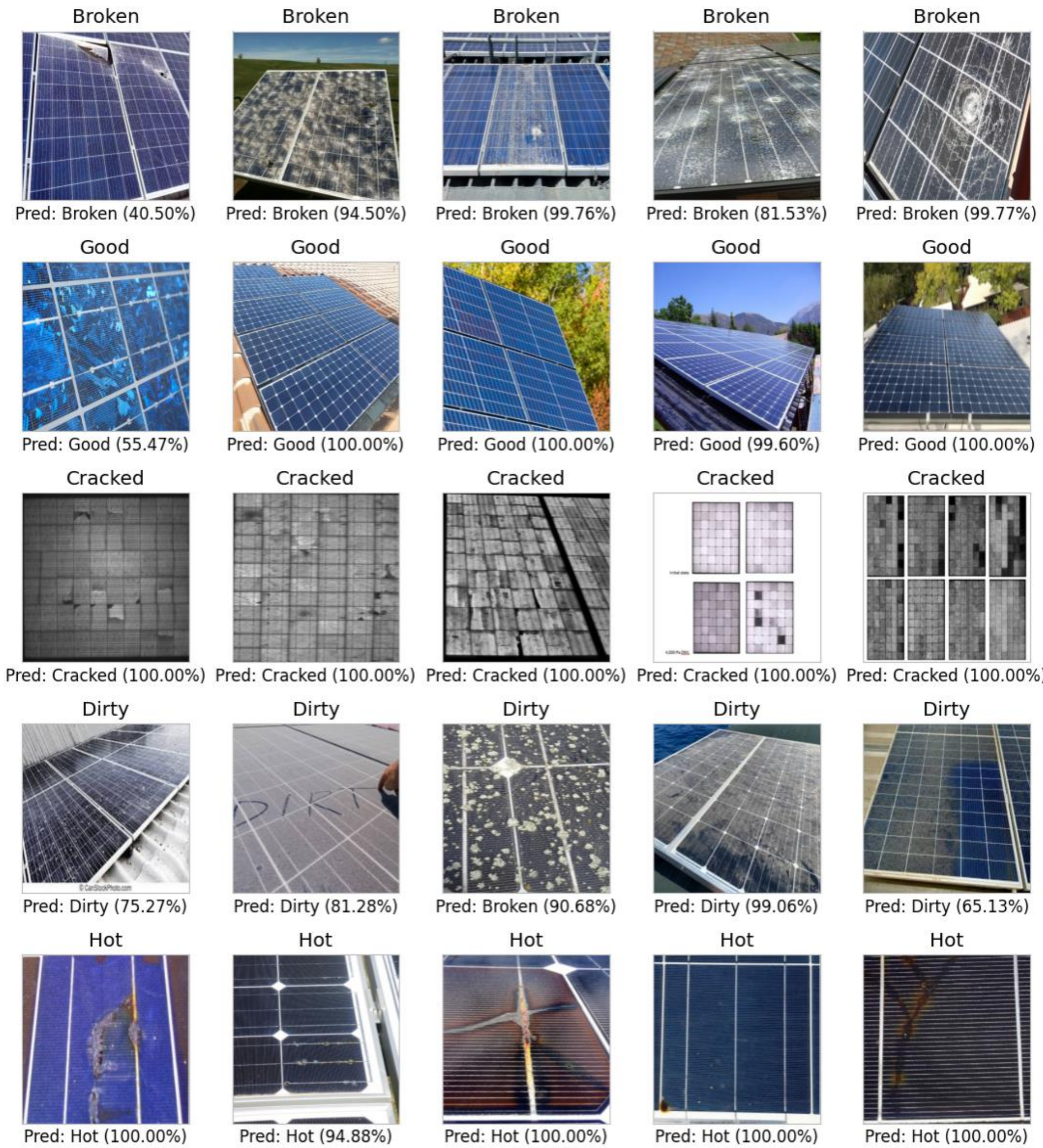

Fig. 3 - Results of the program predicting 5 random images from each category

Future work could involve implementing those methods and determining how to gather data for less commonly found images like hot spots and microcracks.

ETHICS AND SAFETY

Ethics

One ethical concern that arises in AI-based projects is the potential for bias in the system. Bias can occur when the data used to train the AI model is not representative of the real-world data, leading to incorrect or unfair predictions. It is important for the team to ensure that they are using diverse and representative data sets when training the AI model to avoid any potential bias.

Another ethical consideration is accessibility. The project proposal mentions that the AI-based detection script could expand its accessibility, allowing various clients to work remotely and only be present if errors are detected. However, if the system is not designed to be user-friendly or accessible, it could exclude certain groups of people from benefiting from the technology. Therefore, the team needs to ensure the user interface is intuitive and easy to use, making the technology accessible to all who could benefit from it.

Safety

The first concern is related to the regulations set by the Federal Aviation Administration (FAA) in the United States. Flying a drone beyond the visual line of sight (BVLOS) requires a special waiver from the FAA. If the drone is flown too high without a drone license or proper clearance, the FAA can penalize the operator. The team needs to ensure they are following all relevant regulations and obtaining any necessary permits or waivers to avoid legal or financial penalties.

Solar panels are typically installed in solar plants where high-voltage equipment is used to convert the DC power generated by the panels into AC power for use in the electrical grid. The second concern is the potential risks of flying drones around high-voltage equipment. If the drone is not properly trained or the operator is not properly trained, it could pose a danger not only to the drone but also to the equipment and personnel in the area. Therefore, it is important for the team to ensure that they have the proper training and take necessary precautions to ensure the safety of all involved.

ENGINEERING SPECIFICATION VERIFICATION

AI Capability Specifications

The AI program should prioritize the following capabilities in descending order:

- Detecting solar panels with broken glass and solar panels without broken glass.
- Detecting if solar panels have particulate matter (such as dust, pollen, bird droppings, etc.) on their surface.
- Detecting if large objects are obstructing the panels.
- Detecting if shadows are obstructing the panels.

Verification Status: *Partial Success*

The model was tested against the original, unaltered dataset and accurately predicted defects. However, how the model will react to large obstructing panels is unknown. Likely, it will pick whichever category the obstruction most closely matches, which may show up as broken or hot spots, depending on the scenario.

User Interface (Software) Specifications

The user interface should have two options: setup and download.

- Setup:
  Enables users to set up the drone pathing, scripting, and scan criteria and view a Google map with an overlay of the flight path.
  - Input Flight Path:
    - A file with coordinates for the drone to follow.
  - Select Drone to Control:
    - Multiple drones may be available, so the interface must be able to select between different drones within range.
- Download:
  Enables users to download data and analyze information scanned by the drone.
  - Display Image/Data of Broken Panels.
  - AI Software to Analyze Downloaded Data.
  - Live Analysis of Data from Data Stream (Secondary).

Verification Status: *Partial Success*

The verification process for ensuring that the User Interface was relatively simple uses the click button options to make different selections.

Compatibility (Hardware) Specifications

- Drones can give camera feed and flight path access to the user.
- DJI camera requirements.
- Flight time of at least 25 minutes.
- Weight/lift requirements Raspberry Pi and camera (Contingency).

Verification Status: Successful

Although the flight path access was not available to test, it is verified that 3rd party apps allow for control of automated flight paths. The camera feed of the drone is available through the RTMP server protocol. The DJI drone used during this project meets the rest of the specs listed.

Drone Flight Limits (Legal) Specifications

- Visual range or farther with a waiver.
- Unless the FAA has granted special clearance, licensed personnel should be on site 100% of the time.

Verification Status: *Successful*

Part 107 UAV License was acquired by one team member during the project and accompanied any test flights.

Drone Flight Navigation Specifications

- GPS navigation of the drone should be in sync with a device that can track it at all times.
- Ability to log GPS data and record its location for a given time (Contingency).

Verification Status: *Not Performed*

The specs were never met as the drone was never fully implemented. If a DJI drone is to be used, a method will need to be determined to gather GPS data live through a 3rd part app or the DJI SDK. Otherwise, a microcontroller with GPS capabilities will need to be attached.

Data Transmission/Storage Specifications

- Live data transmission from the drone or downloaded from a flash drive.
- GPS coordinates need to be tagged to each image.
- A database is needed to attach GPS, Images, Damaged tags, etc.
- Resolution (requires testing) and frequency of image captured.

Verification Status: *Partial Success*

Using an ESP32 video web server, images could be transmitted live to the program. RTMP transmission tests were also successful, though never implemented. GPS data was not accessible using the standard DJI app, but it may be possible with the DJI SDK or 3rd party apps.

Raspberry Pi/ESP-32 Specifications

- Capable of recording video/images at around 20 Frames per second (FPS).
- It needs to store 1 hour of data.
- It can connect to a PC for viewing.
- Ability to send images live (with a latency of 0-2 seconds) back to the operator's PC (will not be used to pilot the drone).

Verification Status: *Successful*

Using the ESP32 video web server, 20FPS can realistically be obtained but relies on a good network connection. ESP32 microcontrollers have the option of incorporating a better antenna to improve this. Video storage is possible through the Python program that records the images from the web server. Prediction results can be viewed live from a PC at reasonable latency after acquiring and predicting the image.

CODES AND STANDARDS

The following list is a collection of standards that pertain to the project and help determine some guidelines to follow in this project

- Python program – PEP 8, IEEE 2050-2018 [10]11]
- Operating drone – CFR Title 14 Part 107, IEEE 1936.1-2021 [12][13]
- Using drone for solar panel inspection – IEEE: 1262-1995, 1937.1-2020, 1939.1-2021, 2821-2020 [14-17]
- Drone docking/recharging station – 2020 NEC Article 480 [18]
- General photovoltaic system installation Guidelines – 2020 NEC Article 690, 691
- Documentation – IEEE: 307-1969, 610.4-1990 [19][20]

CFR Title 14 Part 107

This section of standards pertains to the regulation through the Federal Aviation Administration (FAA) in the United States for regulating the flight of small unmanned aircraft systems. Since this project involves the flight of such a device, particularly for what could be considered commercial applications, a commercial license is required, where regulations of Part 107 must be followed. Since this legislation does not approve beyond visual line-of-sight (BVLOS) flights, an operator must be present for the scheduled flight over the area. This would negate the idea of having a base station for charging the drone. One option is to fill out waivers to send to the FAA for each unsupervised flight. Another option is the potential for changes in legislation relatively soon, as a company called American Robotics Inc. recently received FAA approval to fly autonomous drones BVLOS and from offsite locations under 400 feet above ground level [21].

IEEE 1936.1-2021

IEEE created this document as a general framework for any drone application. It identifies potential application scenarios for use in different application types and standardizes drone safety, results, and facility requirements. This document likely acts as the basis for any other IEEE standard relating to unmanned aerial vehicles (UAVs). In relation to this project, it can be useful for determining the base parameters in designing the fault detection process, including the operation and programming of the drone. This document encourages using qualified personnel with the relevant licenses and drone insurance in the case of an accident.

IEEE 1262-1995

This standard is useful for determining what officially qualifies as a faulty solar panel. Using the visual inspection procedure outlined in section 5.1, there are multiple visual inspections that can be performed, such as cracks, shipping damage, bubbles/delamination, warping, insulation deterioration, and other factors. This document also provides procedures for various levels of visual inspection in addition to classifications of certain faults. This pertains to the project in a massive way, as it gives a guideline for classifying different faults and their severity according to expected standards for power-generating photovoltaic systems.

IEEE 1937.1-2020

Since this project may potentially use a payload, the Raspberry Pi, standards must be followed to ensure that a proper interface to the drone is designed to comply with expected standards. The interface must be resilient to various environmental factors like temperature, humidity, water and dust, vibration and shock, mold, and salt spray. The mechanical interface should also have a locking mechanism and contain whatever electrical connection is necessary.

For data transmission, the Raspberry Pi must be made a certified payload; otherwise, there is potential for unauthorized access to the command and control functions of the drone or payload. The data transmission standard demands at least one low-speed communication protocol like UART or CAN and one high-speed protocol such as ethernet and USB. If the drone can sufficiently supply power to the payload, it shall supply that power through the electrical interface and should not produce significant temperature rises of 20°C or more.

IEEE 1939.1-2021

When using a UAV, in this case, a drone, it may be required to verify its position in relation to other low-altitude airspace traffic. This documentation seeks to set standards for this, including gridding, remote sensing, communication and networking, path planning, and operations. The grid system could be implemented in this project, especially if the ability for BVLOS flight becomes a possibility, and because DJI provides the GPS coordinates for tracking the three-dimensional space from the Earth reference spheroid. By providing a three-dimensional grid map of the airspace in conjunction with flight path planning, an efficient mode of communication to nearby aircraft is possible.

IEEE 2821-2020

This description of standards establishes a guide for UAV-based inspection systems, particularly for transmission lines. This document outlines various methods for proper inspection procedures in addition to UAV requirements and tests. The UAV should have a self-check system to ensure proper performance during the planned mission and flight path. According to this document, technologies and emergency procedures are not mature enough for fully autonomous inspection modes. Given this, the autonomous inspection of solar power plants should not be performed until technology and legislation improve the safety and effectiveness of these procedures. The UAV tests outlined in section 7 are vital for testing the drone for this project and should be incorporated into the documentation and prototyping phases.

PEP 8

Though this standard is not necessarily needed for safety purposes, it does allow for a program layout to be universally understandable. Much of this documentation is regarding the readability of the code, which can range from aspects such as white space and other formatting, naming conventions, and interface recommendations. Since this project aims to be open-source to encourage the efficient operation of photovoltaic power plants, this document is vital to making code readable and understandable to the majority of people that may use the software. For instance, one of the recommendations in regard to inline comments is to not state the obvious, rather, it is better to explain what that "obvious" variable declaration is doing in the program.

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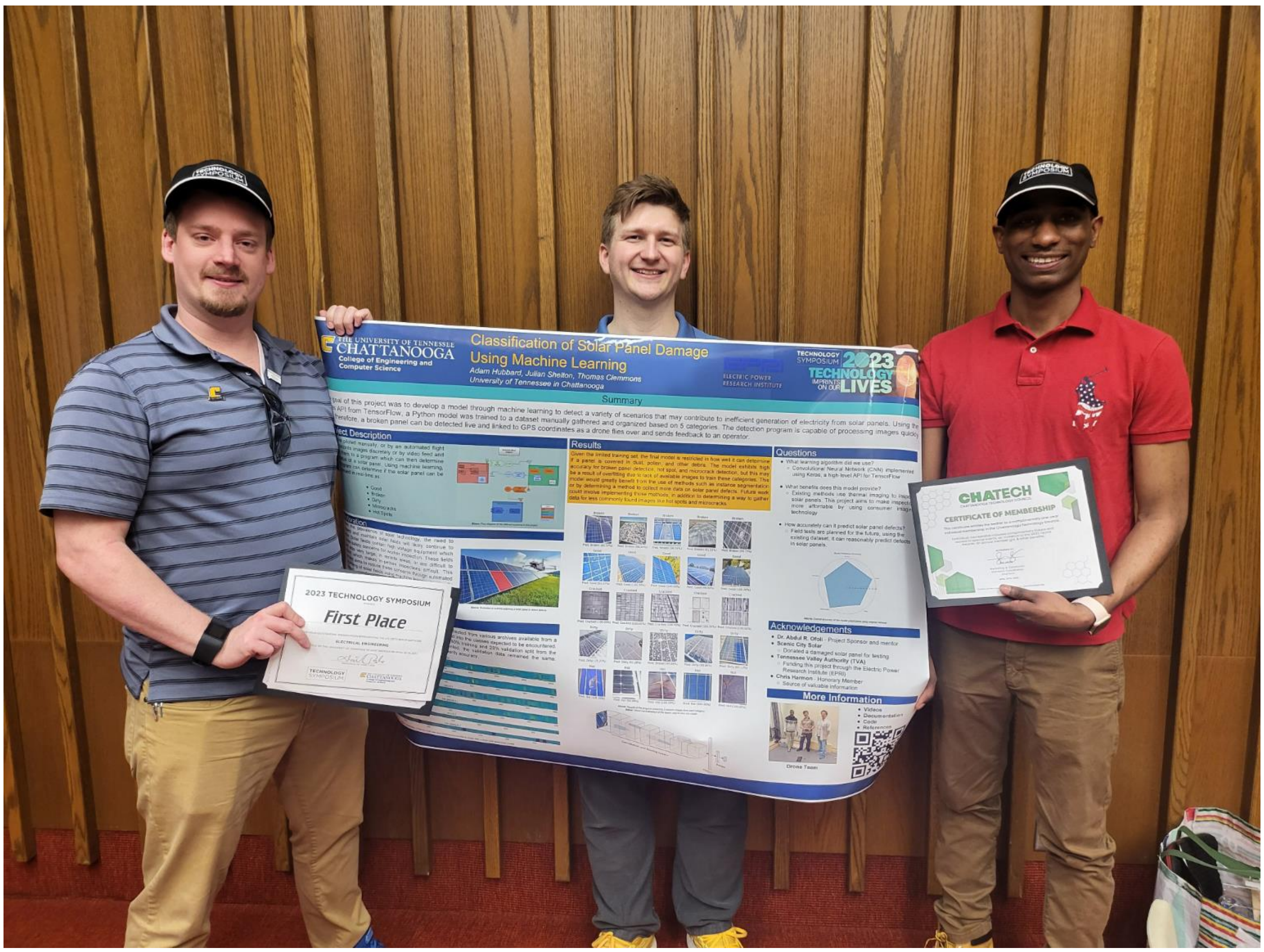

REFERENCES

[1] E. Suresh Kumar and B. Sarkar, "Investigation of the common quality and reliability issues in the photovoltaic panels," 2013 International Conference on Energy Efficient Technologies for Sustainability, 2013, pp. 320-325, doi: 10.1109/ICEETS.2013.6533402.

[2] C. Schuss et al., "Detecting Defects in Photovoltaic Cells and Panels and Evaluating the Impact on Output Performances," in IEEE Transactions on Instrumentation and Measurement, vol. 65, no. 5, pp. 1108-1119, May 2016, doi: 10.1109/TIM.2015.2508287.

[3] C. Schuss et al., "Estimating the impact of defects in photovoltaic cells and panels," 2016 IEEE International Instrumentation and Measurement Technology Conference Proceedings, 2016, pp. 1-6, doi: 10.1109/I2MTC.2016.7520345.

[4] A. V. Patel, L. McLauchlan and M. Mehrubeoglu, "Defect Detection in PV Arrays Using Image Processing," 2020 International Conference on Computational Science and Computational Intelligence (CSCI), 2020, pp. 1653-1657, doi: 10.1109/CSCI51800.2020.00304.

[5] J. -T. Zou and R. G. V, "Drone-based solar panel inspection with 5G and AI Technologies," 2022 8th International Conference on Applied System Innovation (ICASI), 2022, pp. 174-178, doi: 10.1109/ICASI55125.2022.9774462.

[6] M. Alsafasfeh, I. Abdel-Qader and B. Bazuin, "Fault detection in photovoltaic system using SLIC and thermal images," 2017 8th International Conference on Information Technology (ICIT), 2017, pp. 672-676, doi: 10.1109/ICITECH.2017.8079925.

[7] A. M. Gabor and P. Knodle, "UV Fluorescence for Defect Detection in Residential Solar Panel Systems," 2021 IEEE 48th Photovoltaic Specialists Conference (PVSC), 2021, pp. 2575-2579, doi: 10.1109/PVSC43889.2021.9518884.

[8] K. Pourhossein and M. Asadi, "Identification of Internal Defects of Solar Panels Using Equivalent Circuit," 2019 54th International Universities Power Engineering Conference (UPEC), 2019, pp. 1-3, doi: 10.1109/UPEC.2019.8893609.

[9] "14 CFR Part 107 -- Small Unmanned Aircraft Systems," www.ecfr.gov. https://www.ecfr.gov/current/title-14/chapter-I/subchapter-F/part-1

[10] G. van Rossum and N. Coghlan, "Python enhancement proposals," *PEP 8 – Style Guide for Python Code*, 05-Jul-2001. [Online]. Available: https://peps.python.org/pep-0008/#programming-recommendations. [Accessed: 20-Nov-2022].

[11] "IEEE Standard for a Real-Time Operating System (RTOS) for Small-Scale Embedded Systems," in IEEE Std 2050-2018 , vol., no., pp.1-333, 24 Aug. 2018, doi: 10.1109/IEEESTD.2018.8445674.

[12] “Code of Federal Regulations,” *PART 107 - SMALL UNMANNED AIRCRAFT SYSTEMS*, 28-Jun-2016. [Online]. Available: https://www.ecfr.gov/current/title-14/chapter-I/subchapter-F/part-107. [Accessed: 20-Nov-2022].

[13] "IEEE Standard for Drone Applications Framework," in *IEEE Std 1936.1-2021* , vol., no., pp.1-28, 17 Dec. 2021, doi: 10.1109/IEEESTD.2021.9652498.

[14] "IEEE Recommended Practice for Qualification of Photovoltaic (PV) Modules," in *IEEE Std 1262-1995* , vol., no., pp.1-32, 12 April 1996, doi: 10.1109/IEEESTD.1996.80822.

[15] "IEEE Standard Interface Requirements and Performance Characteristics of Payload Devices in Drones," in *IEEE Std 1937.1-2020* , vol., no., pp.1-30, 12 Feb. 2021, doi: 10.1109/IEEESTD.2021.9354136.

[16] "IEEE Standard for a Framework for Structuring Low-Altitude Airspace for Unmanned Aerial Vehicle (UAV) Operations," in *IEEE Std 1939.1-2021* , vol., no., pp.1-94, 1 Dec. 2021, doi: 10.1109/IEEESTD.2021.9631203.

[17] "IEEE Guide for Unmanned Aerial Vehicle-Based Patrol Inspection System for Transmission Lines," in *IEEE Std 2821-2020* , vol., no., pp.1-49, 25 Nov. 2020, doi: 10.1109/IEEESTD.2020.9271964.

[18] *NFPA 70: National Electrical Code 2020*. Quincy, MA: National Fire Protection Association, 2019.

[19] "IEEE Standard Definitions of Terms For Solar Cells," in *IEEE Std No.307* , vol., no., pp.1-4, 11 Nov. 1969, doi: 10.1109/IEEESTD.1969.120580.

[20] "IEEE Standard Glossary of Image Processing and Pattern Recognition Terminology," in *IEEE Std 610.4-1990* , vol., no., pp.0_1-, 1990, doi: 10.1109/IEEESTD.1990.94600.

[21] A. Sarkar, “American robotics gets FAA nod to fly fully automated drones,” *Reuters*, 16-Jan-2021. [Online]. Available: https://www.reuters.com/world/us/american-robotics-gets-faa-nod-fly-fully-automated-drones-20 21-01-16/. [Accessed: 20-Nov-2022].