Artificial Intelligence Technology for Photovoltaic Monitoring

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COST Action PEARL PV Conference

Enabling The PV Terawatt Transition

Enschede, University of Twente, The Netherlands

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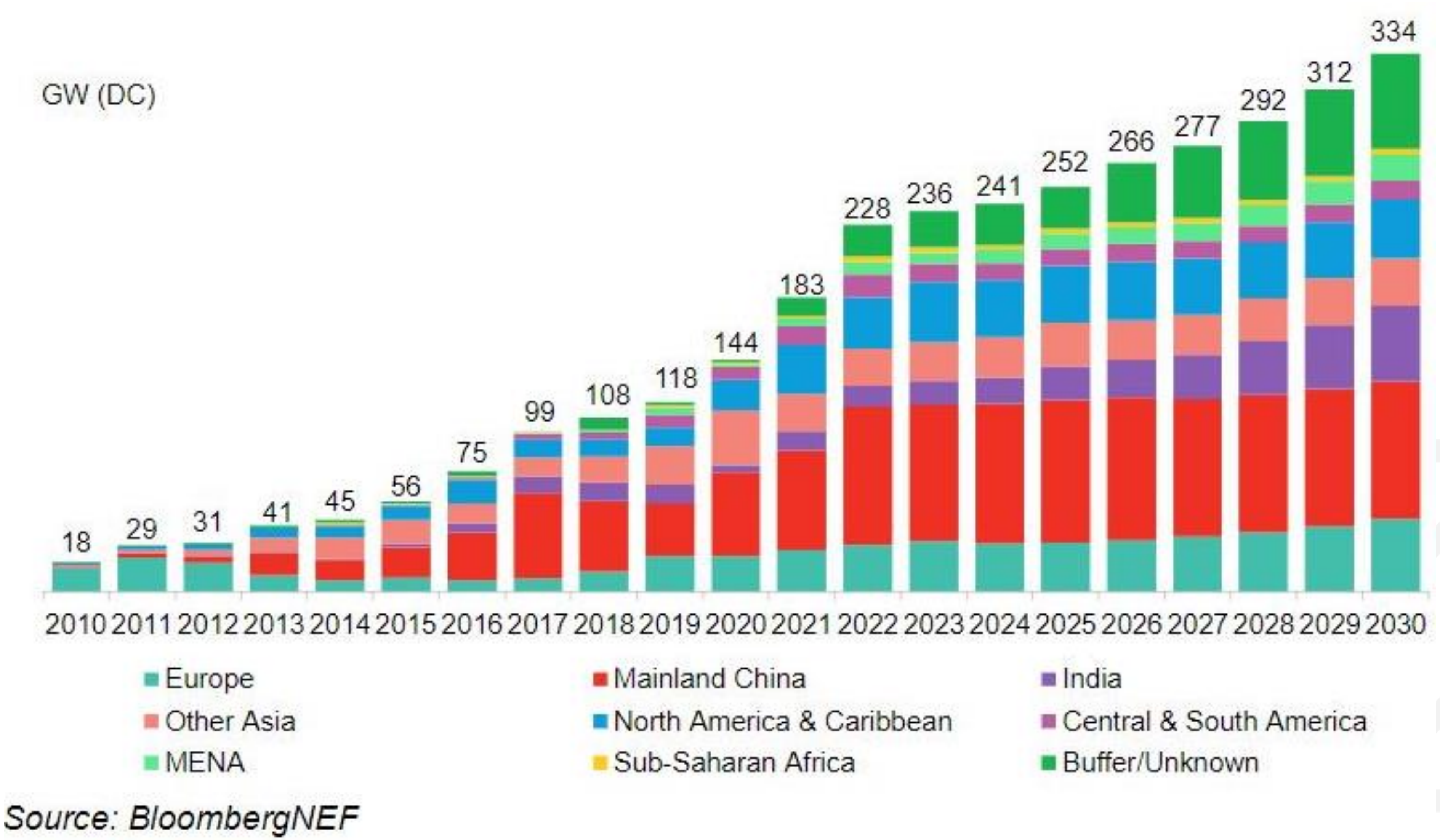
Overview

- Why intelligent monitoring for PV system is important?
- Failures in PV modules, components and systems
- Artificial intelligence technology
- Artificial Intelligence (AI) techniques in PV monitoring
- Electrical faults (DC side) detection/classification in PV systems using machine learning techniques
- Failures (IR) detection in PV strings using convolutional neural network (CNN)
- RoboPV Software Platform
- Summary & Take-Home Messages

Why intelligent monitoring for PV system is important?



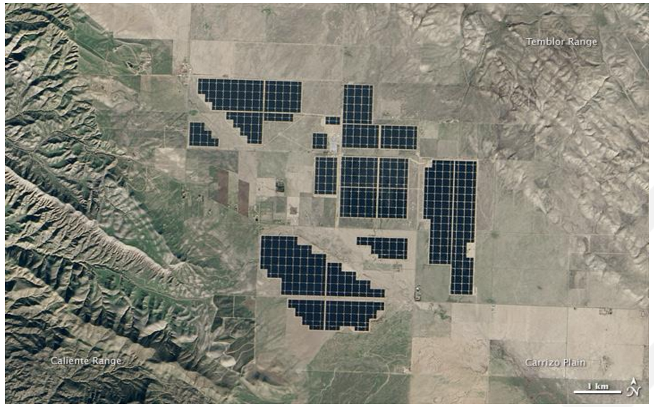
https://www.pv-magazine.com/2022/02/01/bloombergnef-says-global-solar-will-cross-200-gw-mark-for-first-time-this-year-expects-lower-panel-prices/

Why intelligent monitoring for PV system is important?

648 MW PV, Kamuthi, Tamil Nadu, India

850 MW PV, Longyangxia Dam Solar Park, Tibetan Plateau in China

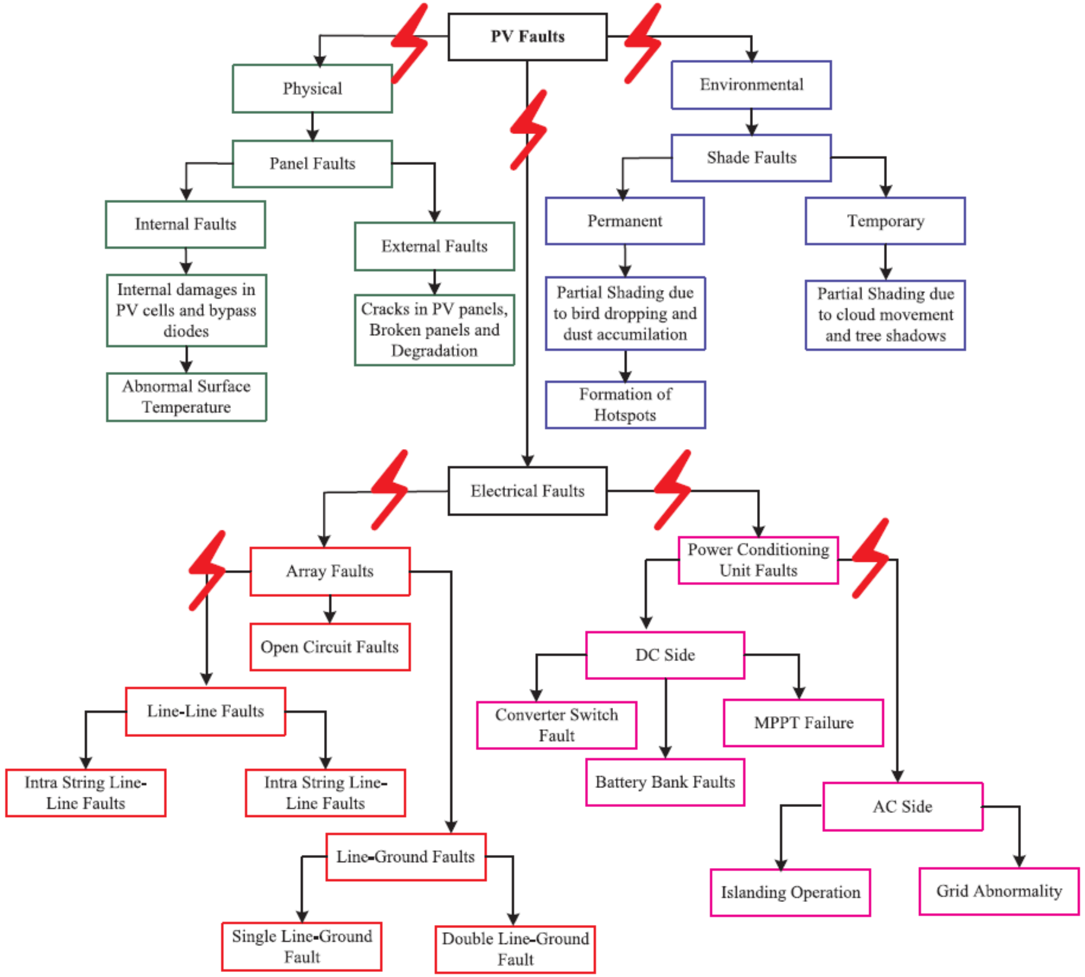
500 MW PV (bifacial), Oman

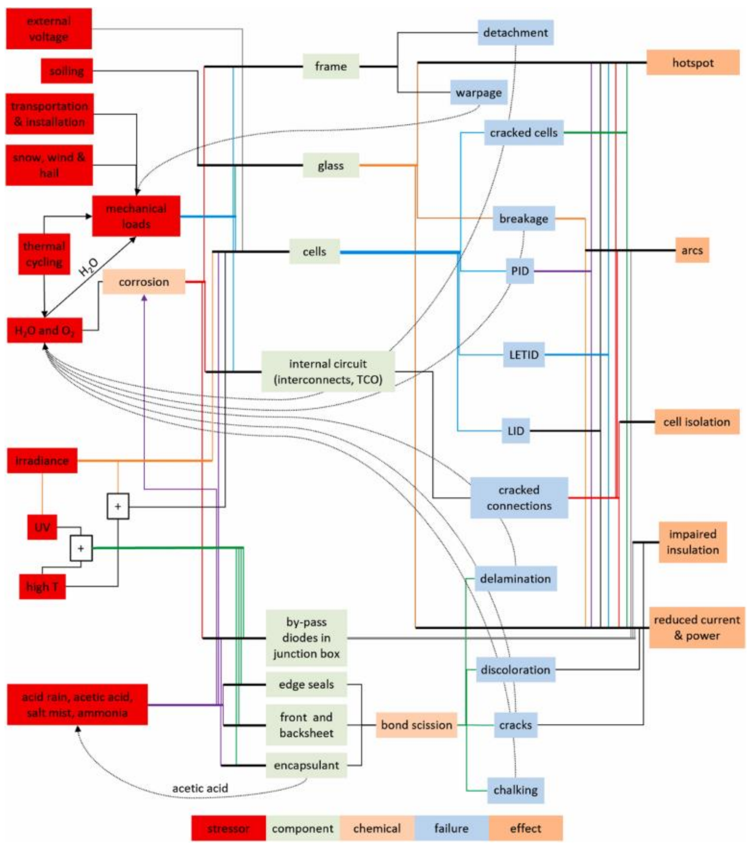


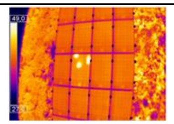
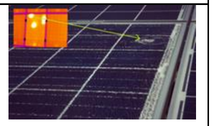
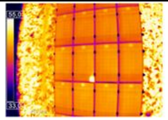
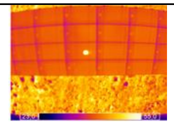
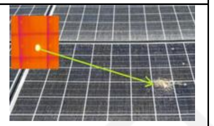
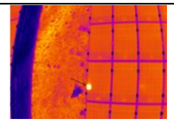
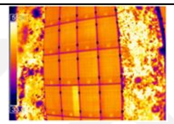
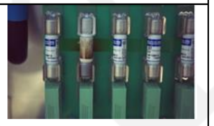
550 MW PV (CdTe), southern California, US

-https://www.originenergy.com.au/blog/lifestyle/5-largest-solar-farms-in-the-world.html
-https://www.financialexpress.com/world-news/longyangxia-dam-solar-park
-https://visibleearth.nasa.gov/view.php?id=89668
- https://www.pv-magazine.com/2022/01/24/oman-inaugurates-500mw-ibri-2-solar-field/

Defects and Failures in PV modules, components and systems



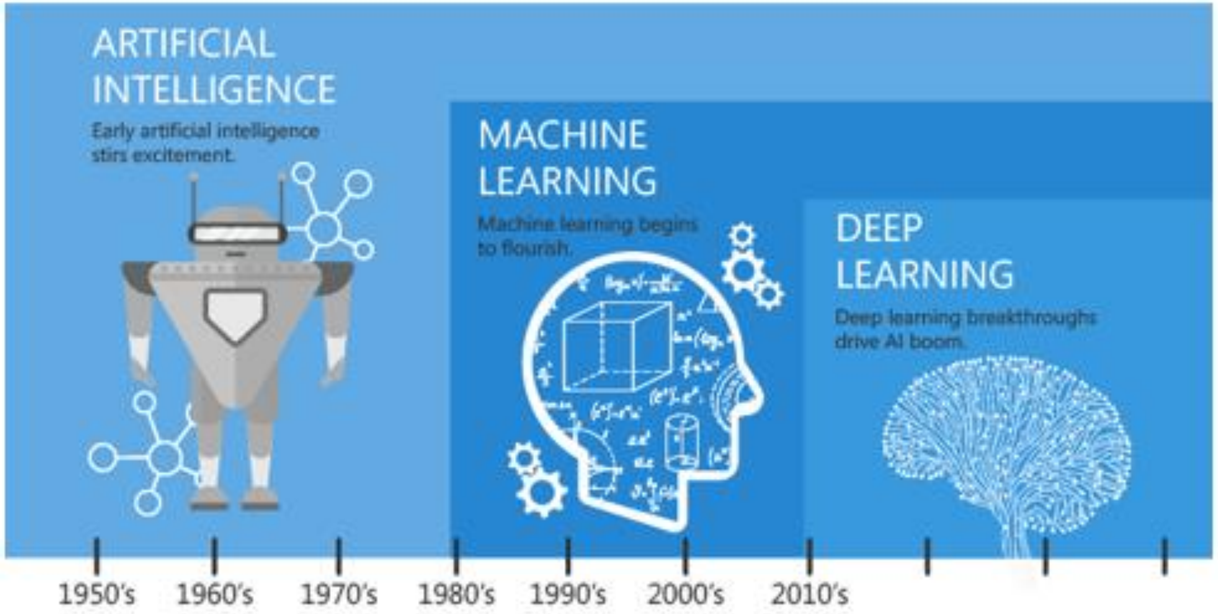


Defect	Low altitude aerial image (IR)	Ground Truthing (visual)
Severe glass and cell fractures		
Cracked cell		
Excessive soiling and dirt, resulting in severe hot spots and power losses		
Shading by adjacent vegetation, resulting in electrical mismatch, hot spot and power losses		
PV modules diagnosed with bypass diode failures. Hard to detect on the ground but clearly identifiable from the air.		

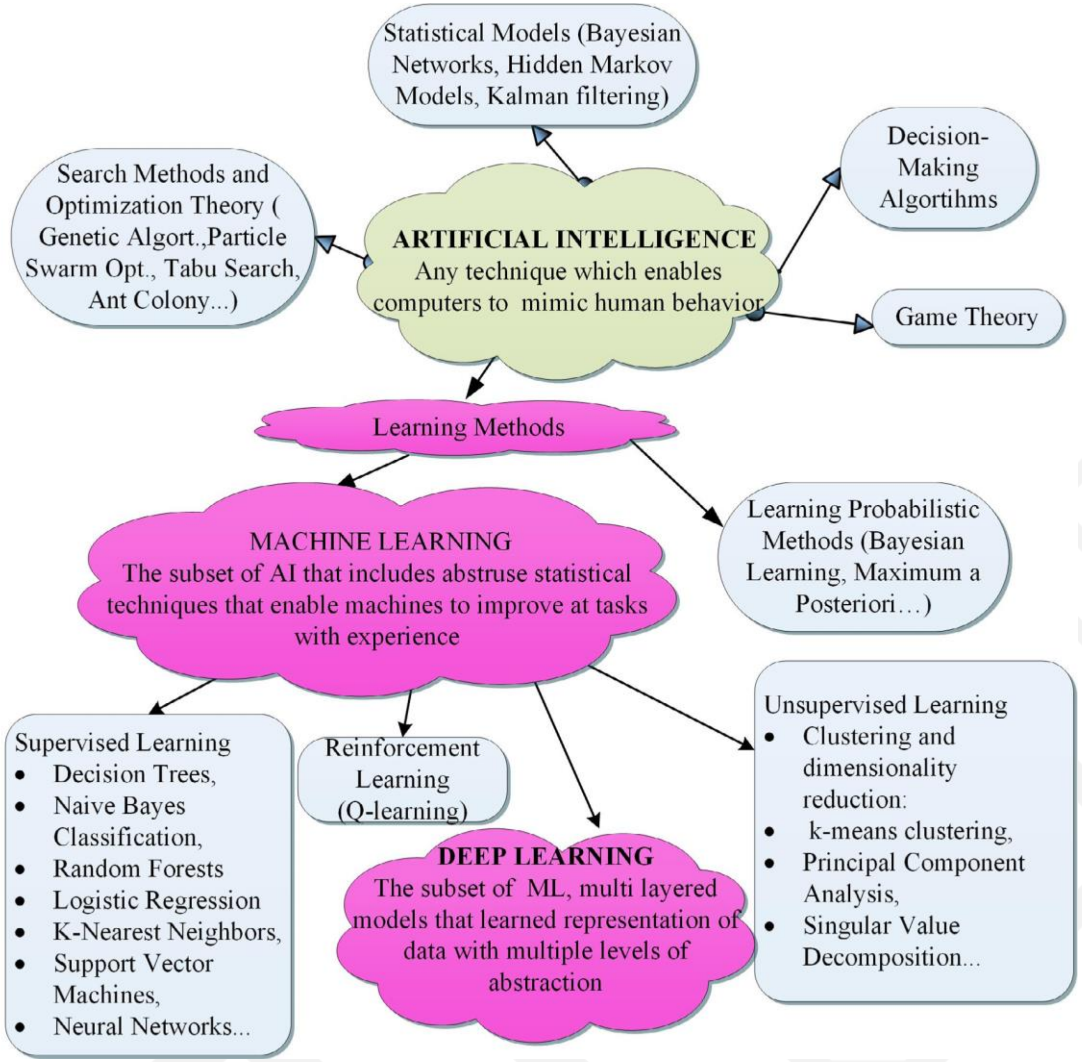
Environmental conditions, Human errors, Shading, Soiling, Inverter clipping, Power factor correction, Module/string faults, Degradation and etc.

- D. S. Pillai and N. Rajasekar, "A comprehensive review on protection challenges and fault diagnosis in PV systems," Renewable and Sustainable Energy Reviews. 2018.
- A.K. Oliveira, M. Aghaei, R.Ricardo, Aerial infrared thermography for low-cost and fast fault detection in utility-scale PV power plants, Solar Energy, 2020.
- A.Eskandary, J. Milimonfared, M. Aghaei, "Line-to-Line Faults Detection for Photovoltaic Arrays Based on I-V Curve Using Pattern Recognition", 46th IEEE PVSC, Chicago, USA, June, 2019.
- IEA-PVPS, Subtask 3.2: Good Practice Recommendations to Qualify PV Power Plants using Mobile Devices, 2021.
- M.Aghaei et al. Review of degradation and failure phenomena in photovoltaic modules, Renewable and Sustainable Energy Reviews, 2022.

Artificial Intelligence (AI) Technology



Development and milestones of Artificial Intelligence



- Yaguo Lei et al. Applications of machine learning to machine fault diagnosis: A review and roadmap, Mechanical Systems and Signal Processing, 2020.
- https://serokell.io/blog/how-to-choose-ml-technique, access: 5th July 2021.
- A. K. Ozcanli, F. Yaprakdal, and M. Baysal, "Deep learning methods and applications for electrical power systems: A comprehensive review," Int. J. Energy Res., vol. 44, no. 9, pp. 7136–7157, 2020.

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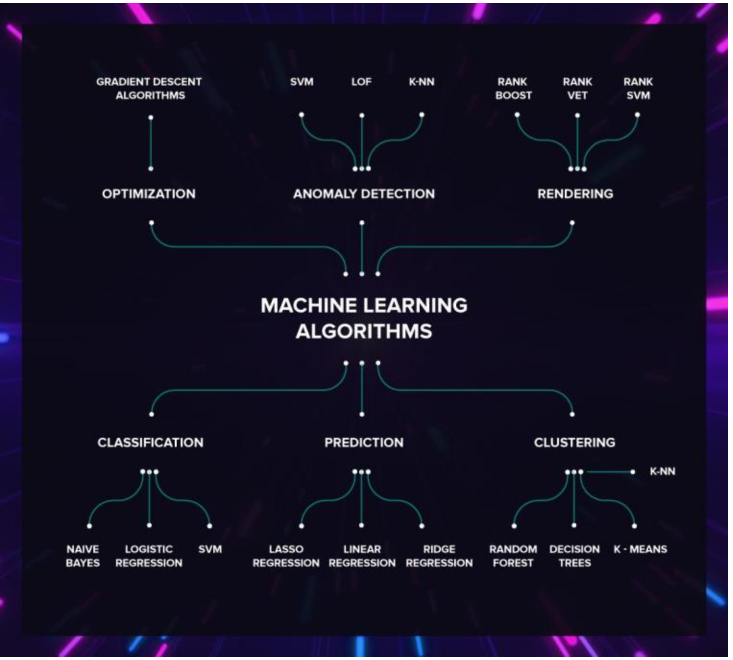

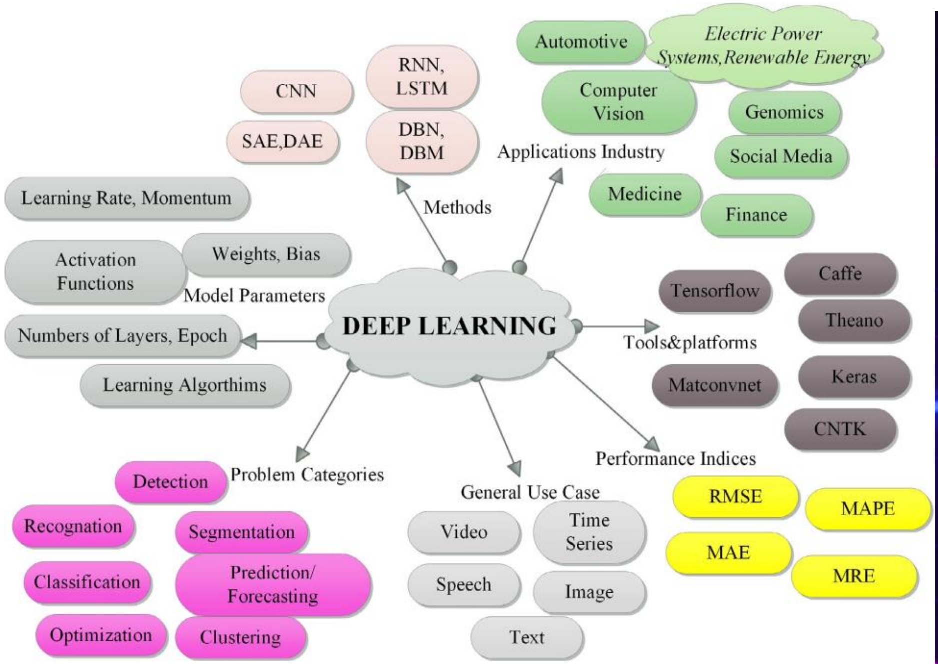

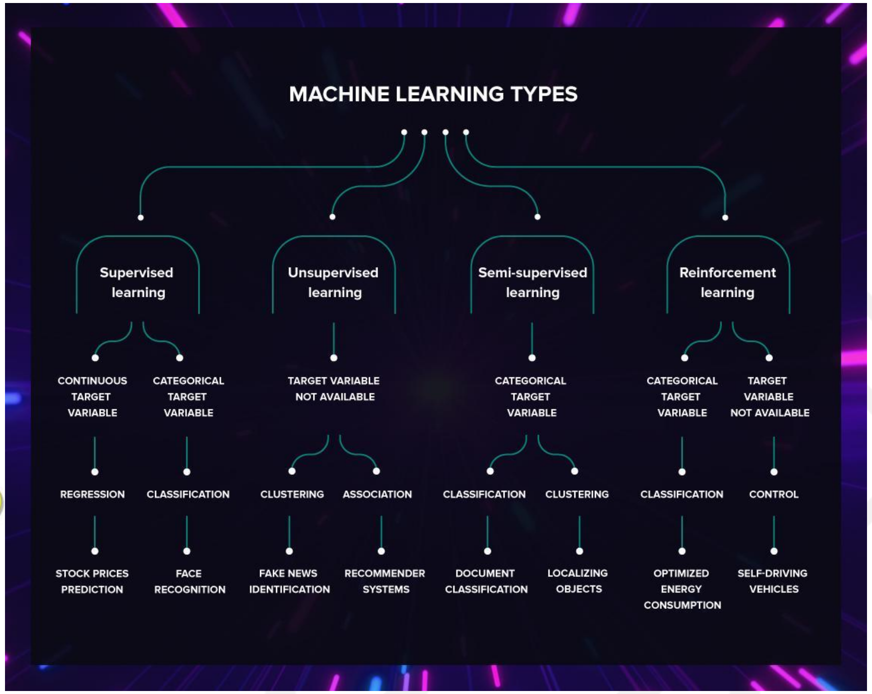

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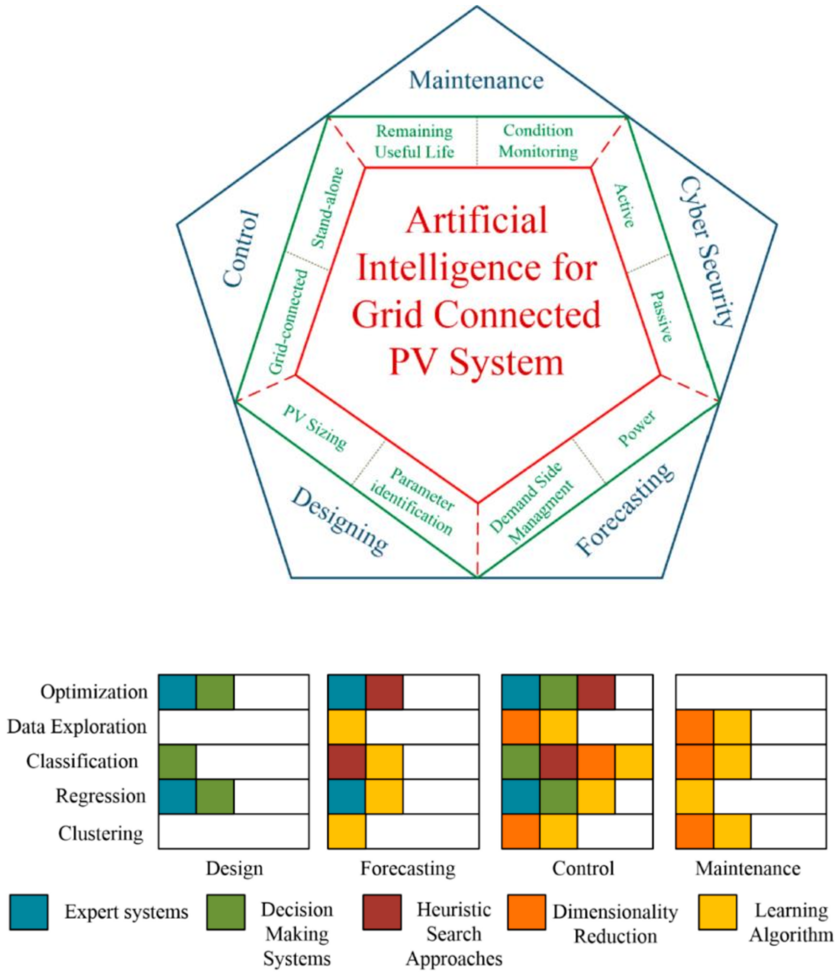
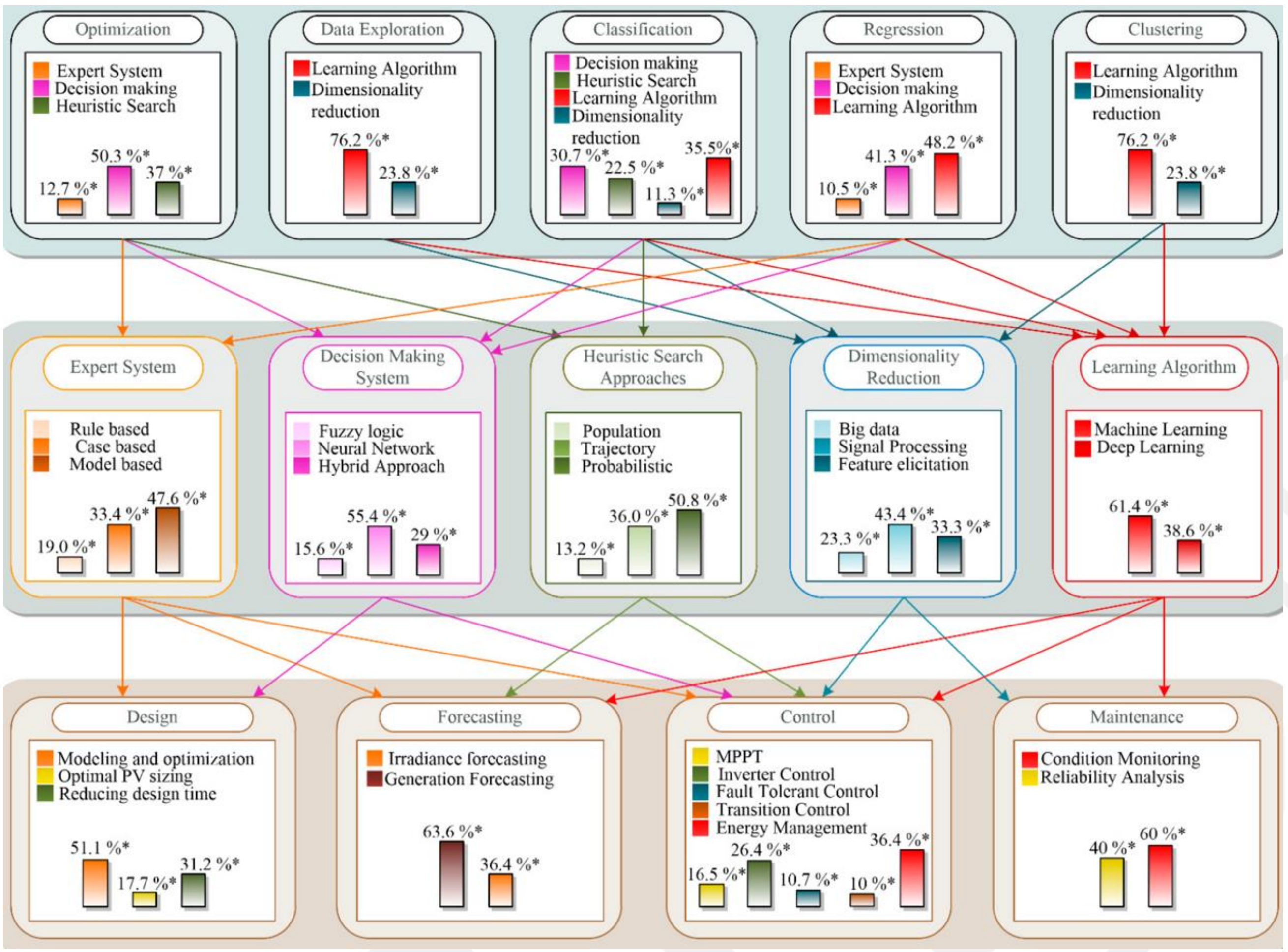
- https://serokell.io/blog/how-to-choose-ml-technique, access: 5th July 2021.
- A. K. Ozcanli, F. Yaprakdal, and M. Baysal, "Deep learning methods and applications for electrical power systems: A comprehensive review," Int. J. Energy Res., vol. 44, no. 9, pp. 7136–7157, 2020.
- https://medium.com/alumnaiacademy/what-is-deep-learning-basics-that-every-beginner-should-know-a39ae52cd4e4

Artificial Intelligence (AI) techniques in PV monitoring



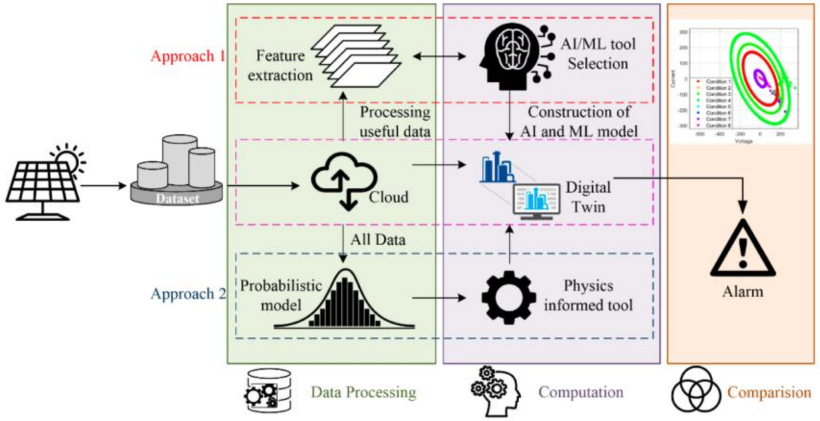
different AI applications for the design, control, forecasting and maintenance of grid-tied PV systems.

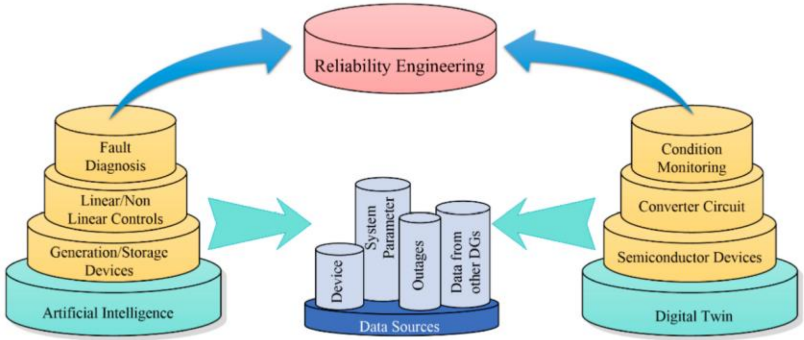


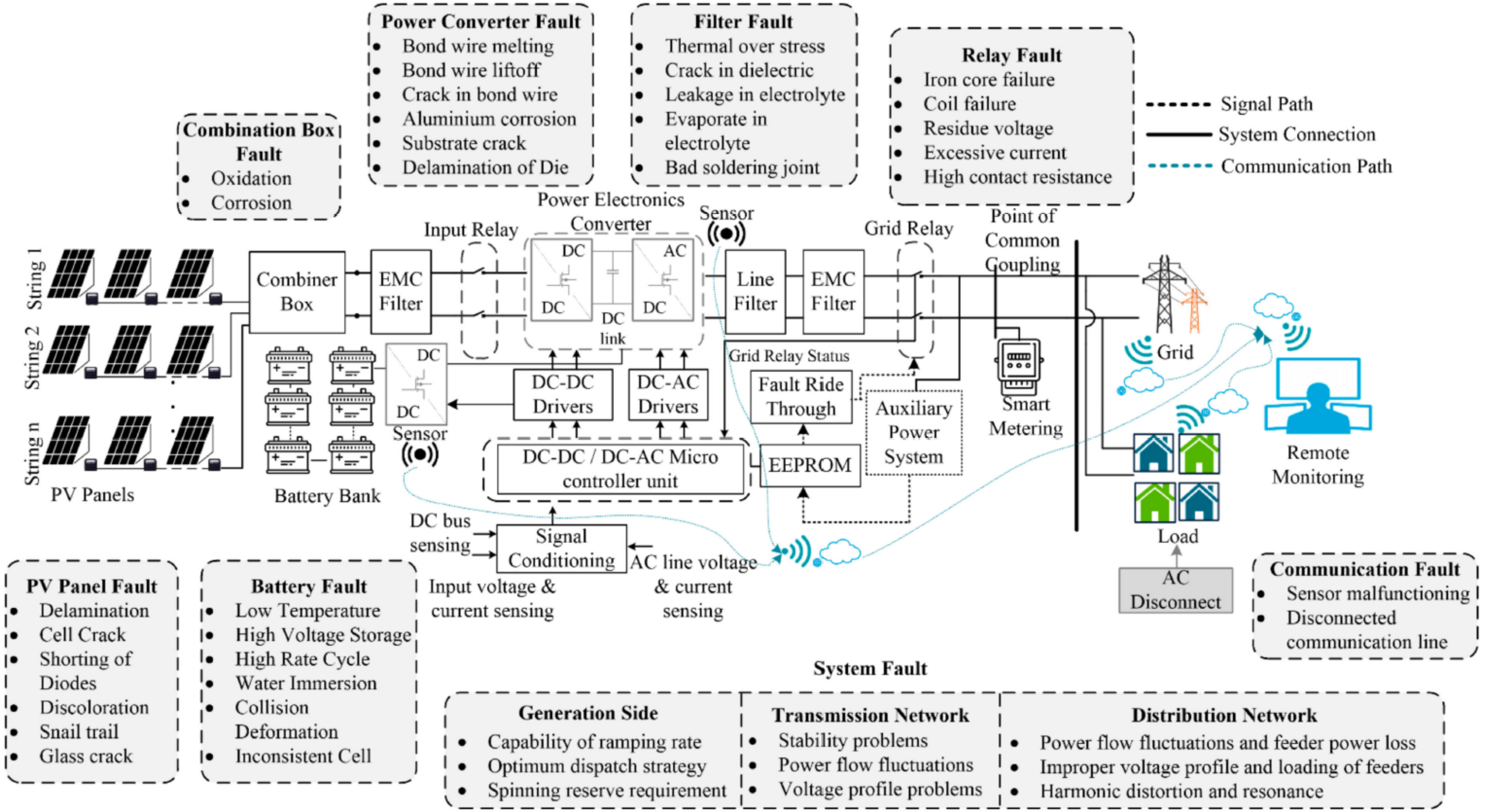
AI framework for different functions, and techniques in application with PV systems.

- V. S. B. Kurukuru et al. A Review on Artificial Intelligence Applications for Grid-Connected Solar Photovoltaic Systems, Energies, 2021

Artificial Intelligence (AI) techniques in PV monitoring



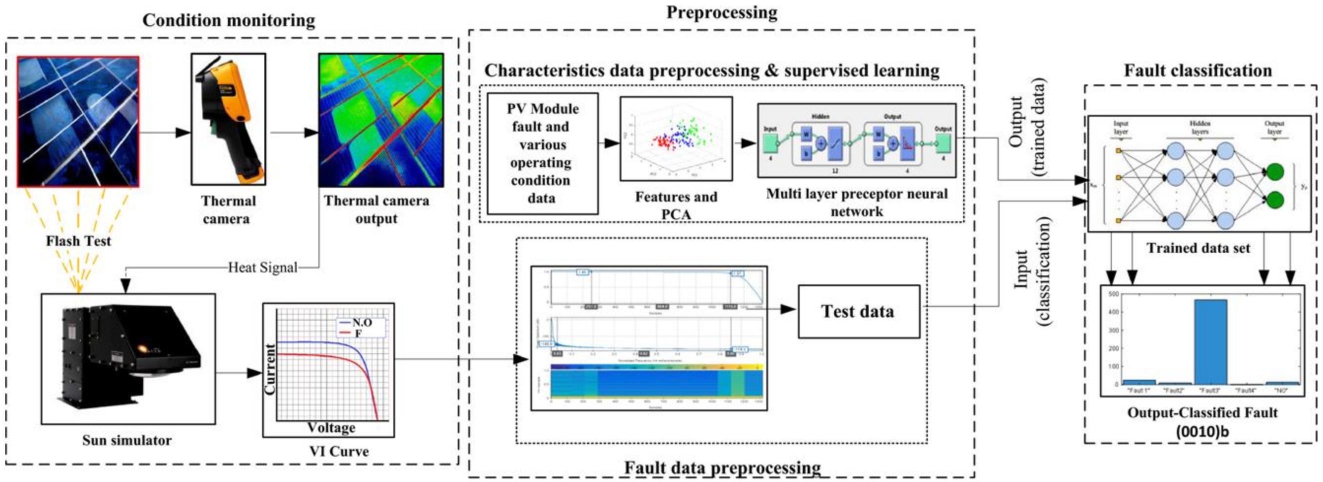


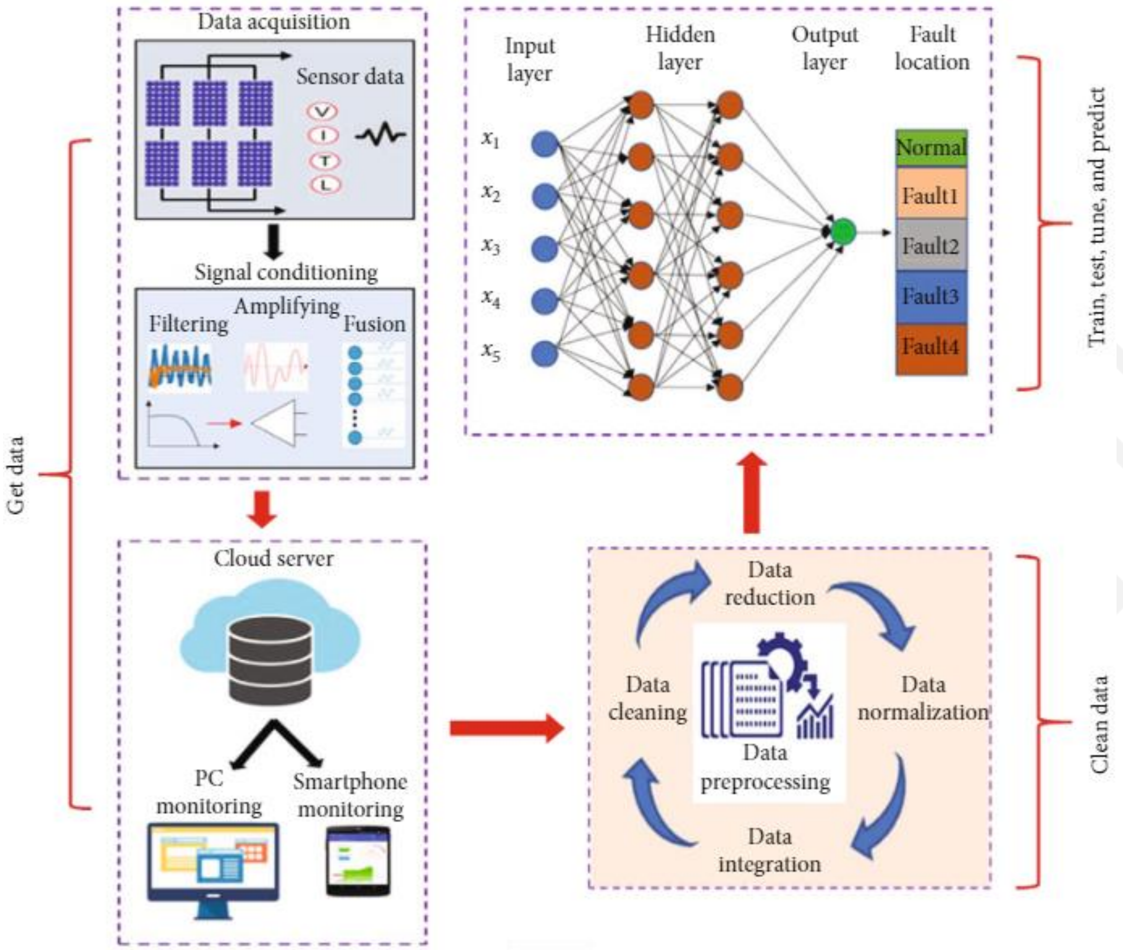


Fault layout for grid-connected PV system

- V. S. B. Kurukuru et al. A Review on Artificial Intelligence Applications for Grid-Connected Solar Photovoltaic Systems, Energies, 2021

Artificial Intelligence (AI) techniques in PV monitoring

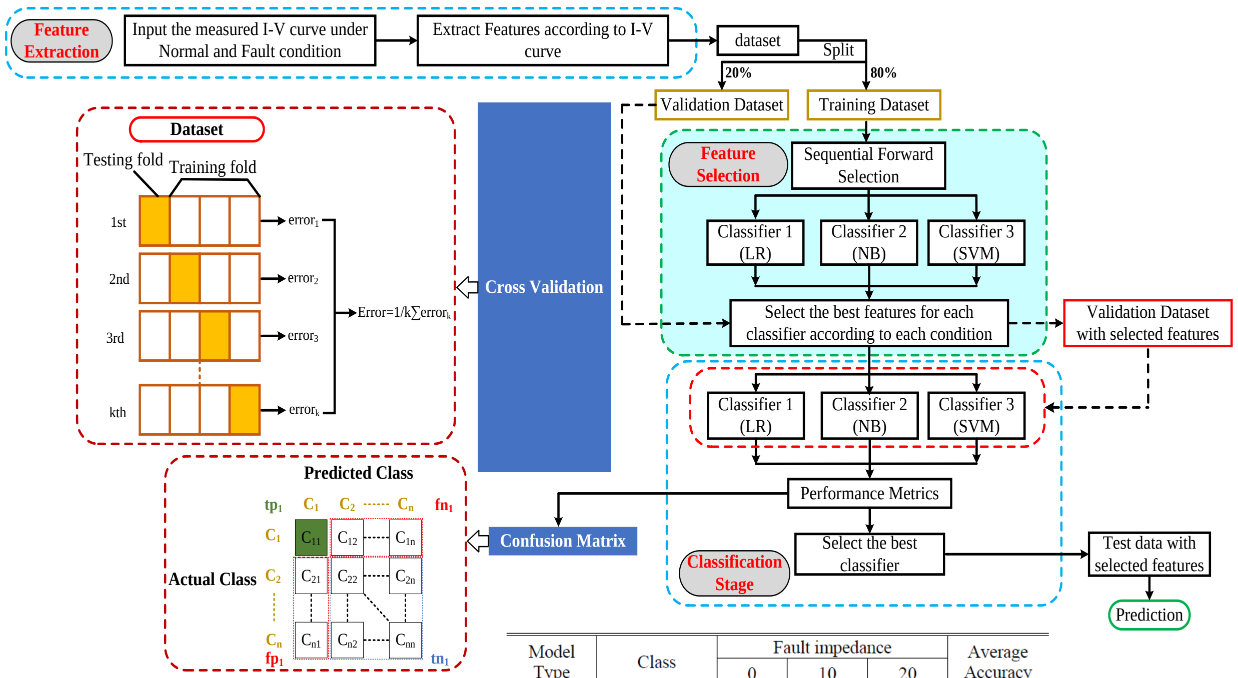




-Basnet B, Chun H, Bang J. An intelligent fault detection model for fault detection in photovoltaic systems. J Sensors 2020.
-Haque A, Bharath KVS, Khan MA, Khan I, Jaffery ZA. Fault diagnosis of Photovoltaic Modules. Energy Sci Eng 2019.
-https://centricconsulting.com/blog/machine-learning-a-quick-introduction-and-five-core-steps/

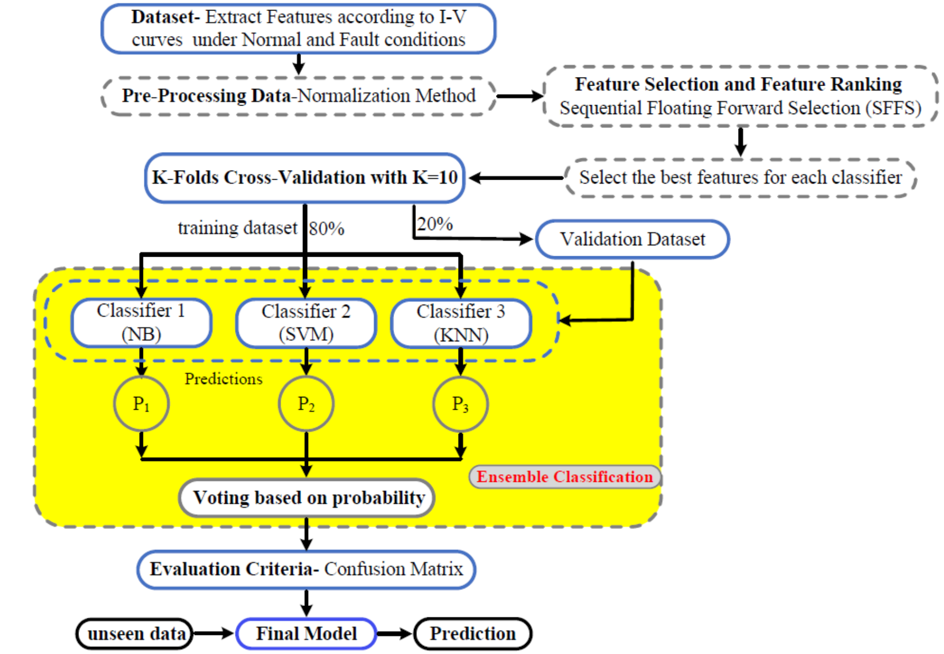
Electrical faults (DC side) detection/classification in PV systems using ML techniques

- Automatic electrical fault detection and classification for PV Systems using various machine learning techniques.
  Datasets: 1200 L-L and L-G fault and also normal events.
  Accuracy: 97%.



Model Type	Class	Fault impedance			Average Accuracy
		0	10	20	
1	Fault	40/40	40/40	38/40	98.33%
2	LL	20/20	20/20	18/18	100%
	LG	20/20	19/20	18/20	95%
3	LL- 16.67%	10/10	10/10	8/8	100%
	LL- 33.3%	10/10	10/10	10/10	100%
4	LG- 66.67%	10/10	10/10	7/9	93.1%
	LG- 50%	10/10	9/9	9/9	100%
Final Success	LL	58/60			96.66%
	LG	55/60			91.66%

Based on Hierarchical Classification and MLT (Naive Bayes classifier, Support-vector machine, Logistic regression)



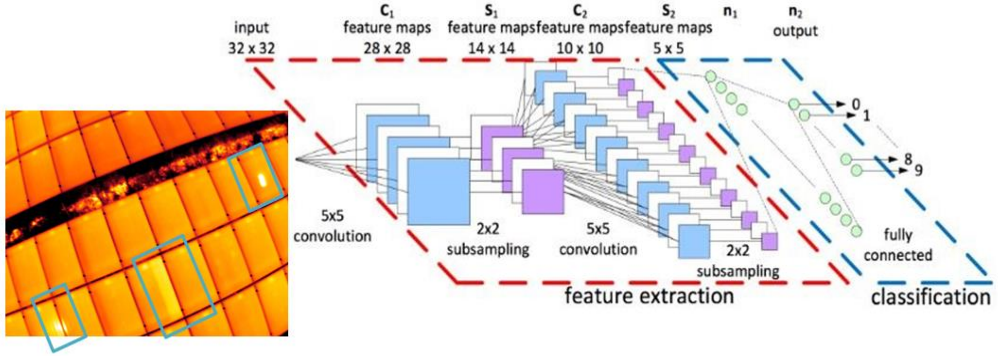
Model Type	Training accuracy (standard deviation)	Confusion matrix	Testing accuracy
FD	98.88% (0.63%)	$\begin{bmatrix} 60 & 0 \\ 1 & 71 \end{bmatrix}$	99.24%
LLC	99.06% (0.677%)	$\begin{bmatrix} 24 & 0 & 0 \\ 0 & 24 & 0 \\ 0 & 0 & 24 \end{bmatrix}$	100%

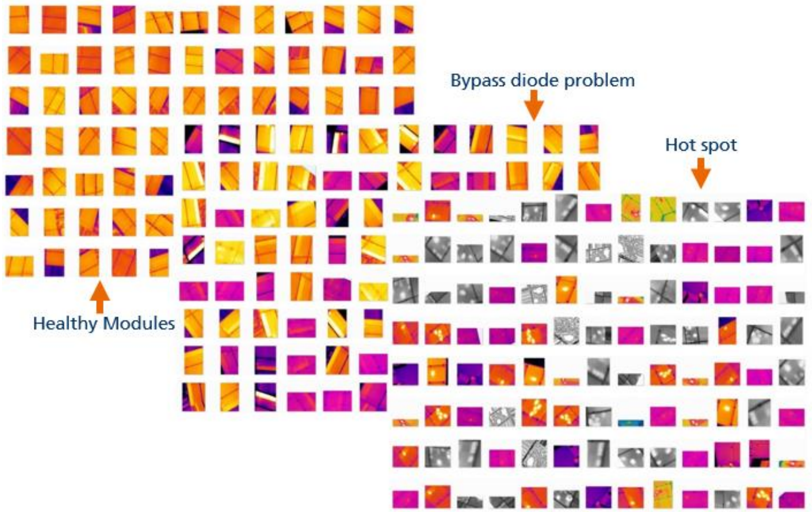
Based on Ensemble learning (Support Vector Machine (SVM), Naive Bayes (NB), and k-Nearest Neighbors (KNN))

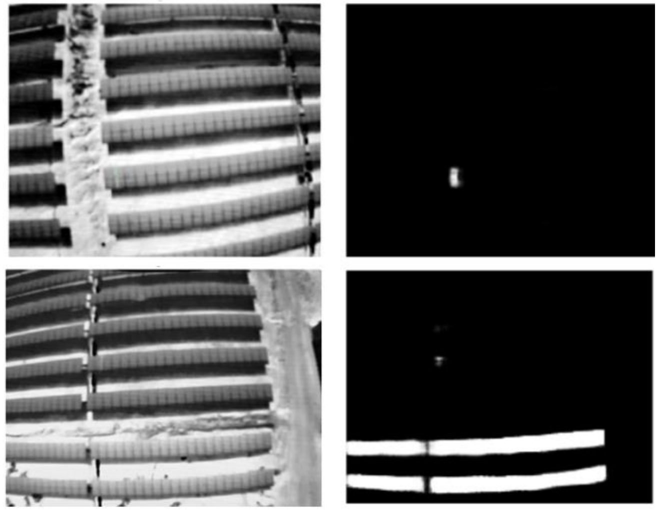
-A. Eskandari, J. Milimonfared, and M. Aghaei, "Fault Detection and Classification for Photovoltaic Systems Based on Hierarchical Classification and Machine Learning Technique," IEEE Trans. Ind. Electron., 2020.
-A. Eskandari, J. Milimonfared, and M. Aghaei, "Line-Line Fault Detection and Classification for Photovoltaic Systems using Ensemble Learning Model Based on I-V Characteristics," Sol. Energy, 2020.
-A Eskandari, J. Milimonfared, M. Aghaei, and A. H. M. E. Reinders, "Autonomous Monitoring of Line-to-Line Faults in Photovoltaic Systems by Feature Selection and Parameter Optimization of Support Vector Machine Using Genetic Algorithm," Appl. Sci., 2020.

Failures (IR) detection in PV strings using convolutional neural network (CNN)

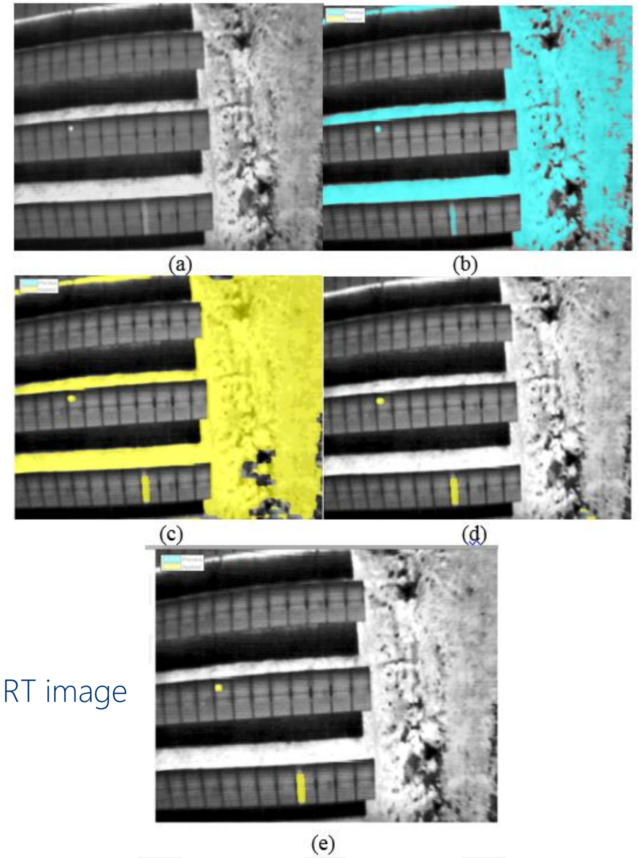
- Automatic fault detection procedure by CNN during Aerial Infrared Thermography.
  Dataset: more than 3300 aerial IR images.
  Accuracy: 90%.







Steps of the segmentation of faults in an aIRT image



-A.K. Oliveira, M. Aghaei, R.Ricardo "Automatic Fault Detection of Photovoltaic Array by Convolutional Neural Networks during Aerial Infrared Thermography", 36th EUPVPES, France, September, 2019.

M. Aghaei, A. Eskandari, and A. H. M. E. Reinders, "Autonomous Monitoring and Analysis of PV Systems by Unmanned Aerial Vehicles, Internet of Things and Big Data Analytics," in 37th EUPVSEC, 2020

RoboPV Software Platform

Boundary Detection

The boundary area of the PV plant is extracted by an accurate trained encoder-decoder network.

Fault Detection

RoboPV extract feature maps of target defects and failures on the PV modules for an accurate position localization.

Path Planning

An optimal flight path with the shortest total distance is designed to guarantee the full coverage of entire PV plant's areas.

Maneuvering

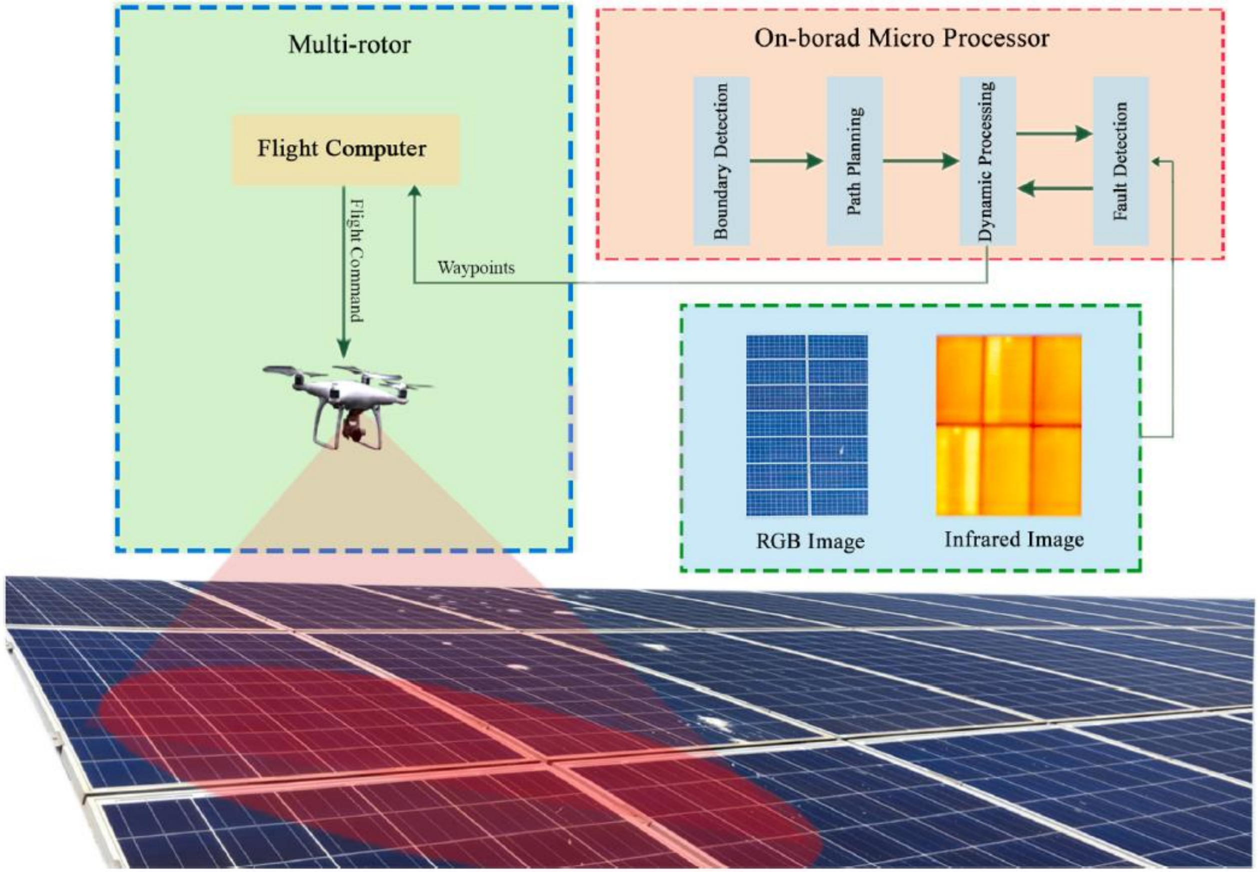
In a case of failure detection, RoboPV commands Pixhawk to maneuver on the possibly faulty region for further investigations.

Dynamic Processing

RoboPV monitors all flight data to take remedial action upon defined decision-making algorithms.

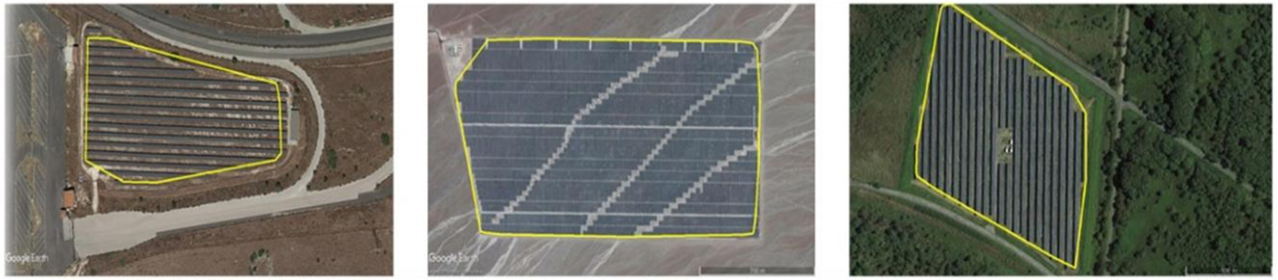
Decision-Making

After each maneuver, RoboPV examines the multi-rotor's ability to complete the mission and in the case of necessity, an optimal path is re-planned for the rest of the mission.

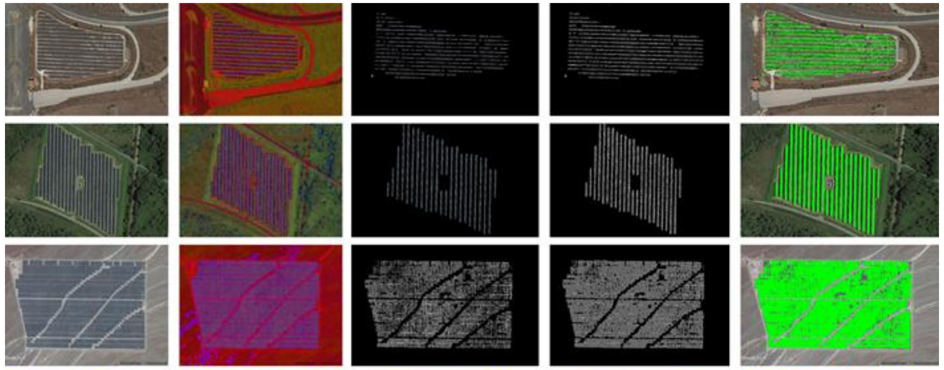


-A. Moradi, S. M. Esmailifar, M. Aghaei, "RoboPV Monitoring: An Integrated Aerial Robotic Platform for Autonomous Monitoring of Large-Scale PV Plants", Energy conversion and management, 2022.

Boundary Detection

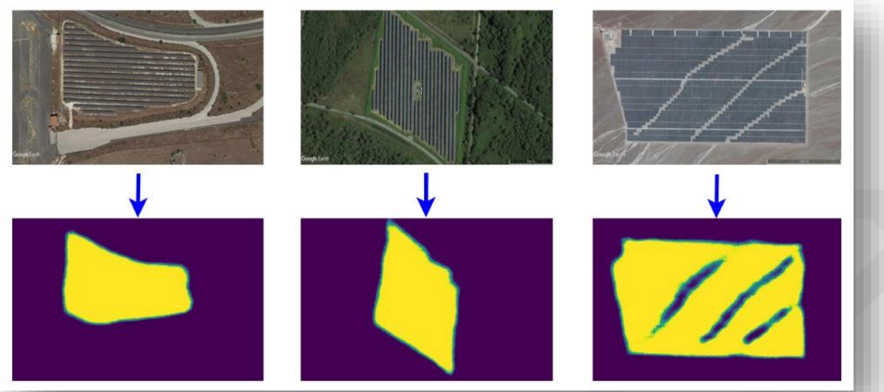


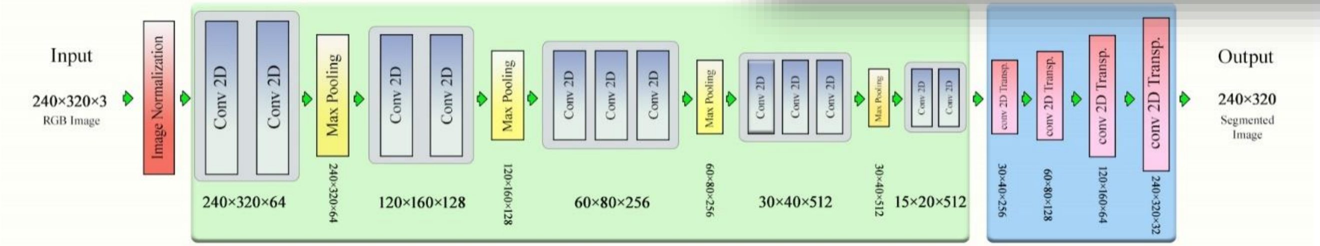
DIP



Guassian Filter | HSV Color-Space | Blue Channel Filter | Edge Detection | Contour Features

CNN





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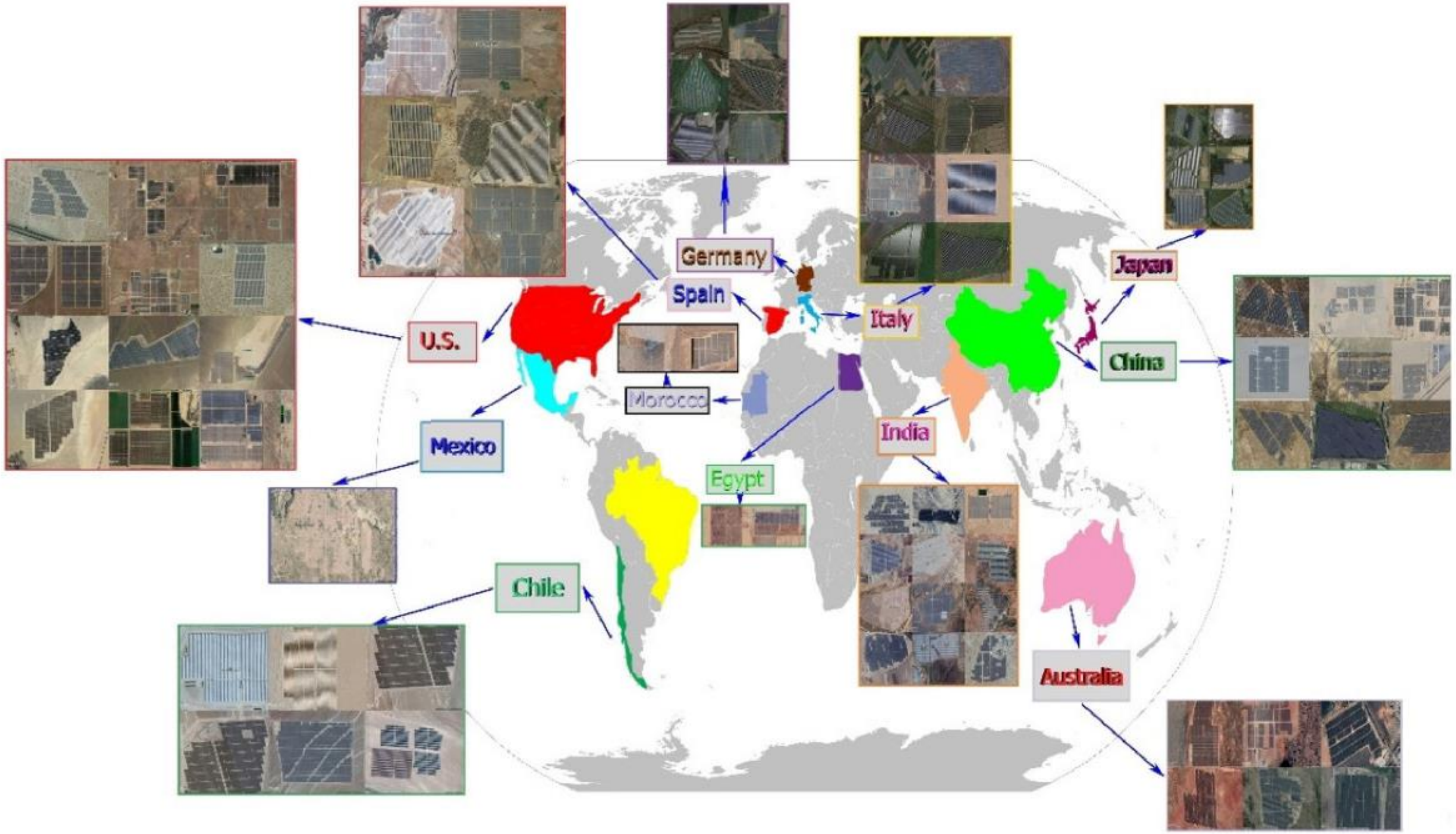
- A. M. Moradi Sizkouhi, M. Aghaei, and S. M. Esmailifar, "Aerial Imagery of PV Plants for boundary detection," IEEE Dataport, 2020, doi: 10.21227/g2bb-ms79.
- A. M. Moradi Sizkouhi, M. Aghaei, S. M. Esmailifar, M. R. Mohammadi, and F. Grimaccia, "Automatic Boundary Extraction of Large-Scale Photovoltaic Plants Using a Fully Convolutional Network on Aerial Imagery," IEEE J. Photovoltaics, 2020.

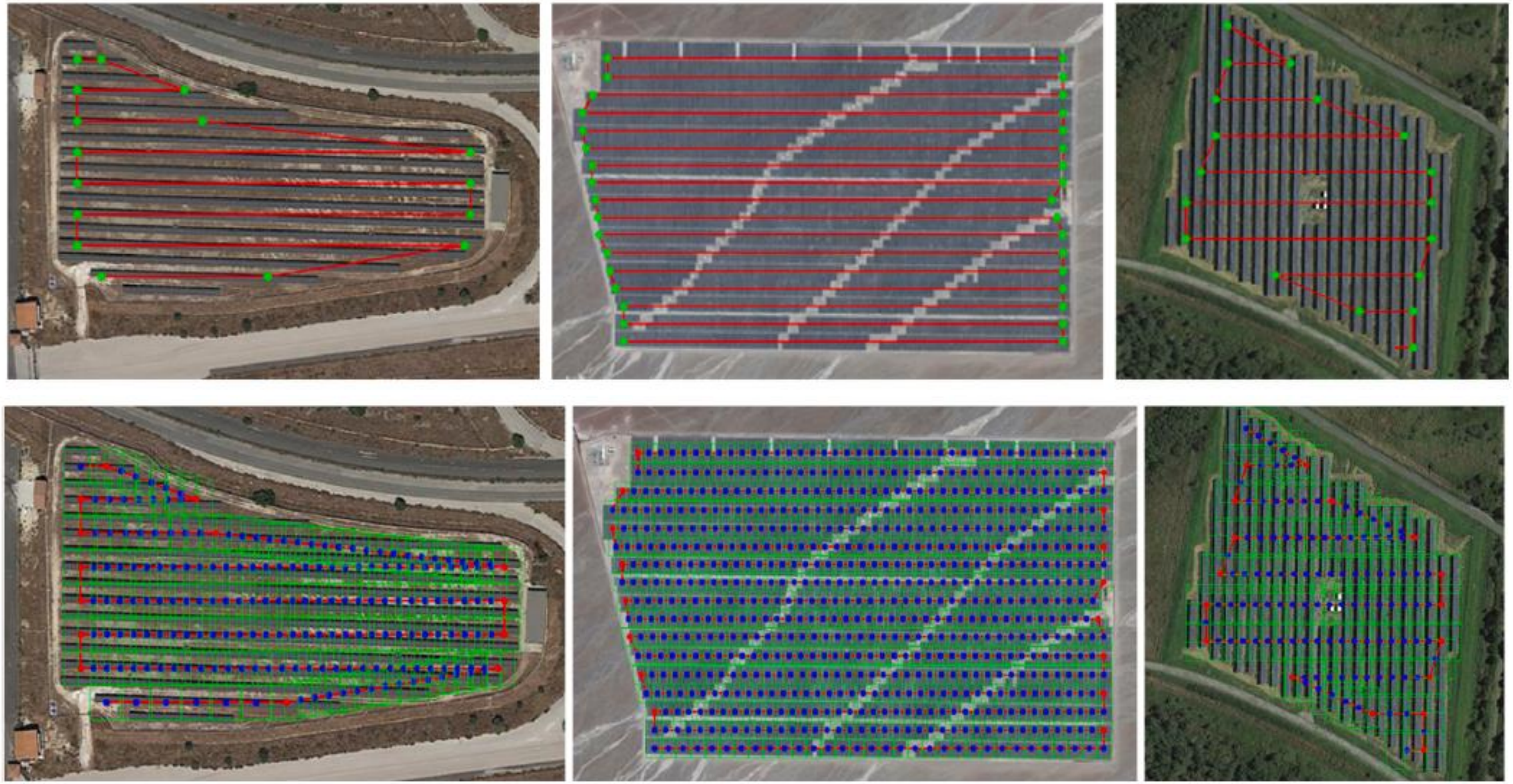
Boundary Detection

- Amir Dataset: 3584 aerial images from various PV plants



- A. M. Moradi Sizkouhi, M. Aghaei, and S. M. Esmailifar, "Aerial Imagery of PV Plants for boundary detection," IEEE Dataport, 2020, doi: 10.21227/g2bb-ms79.
- A. M. Moradi Sizkouhi, M. Aghaei, S. M. Esmailifar, M. R. Mohammadi, and F. Grimaccia, "Automatic Boundary Extraction of Large-Scale Photovoltaic Plants Using a Fully Convolutional Network on Aerial Imagery," IEEE J. Photovoltaics, 2020.

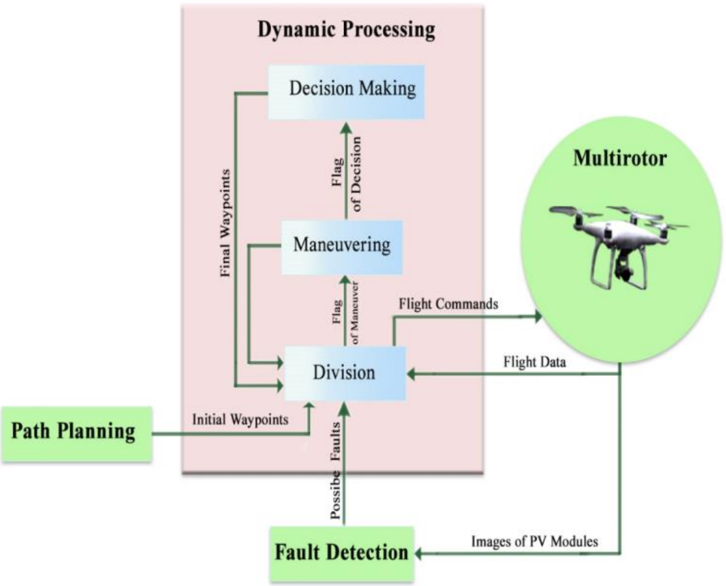
Path Planning

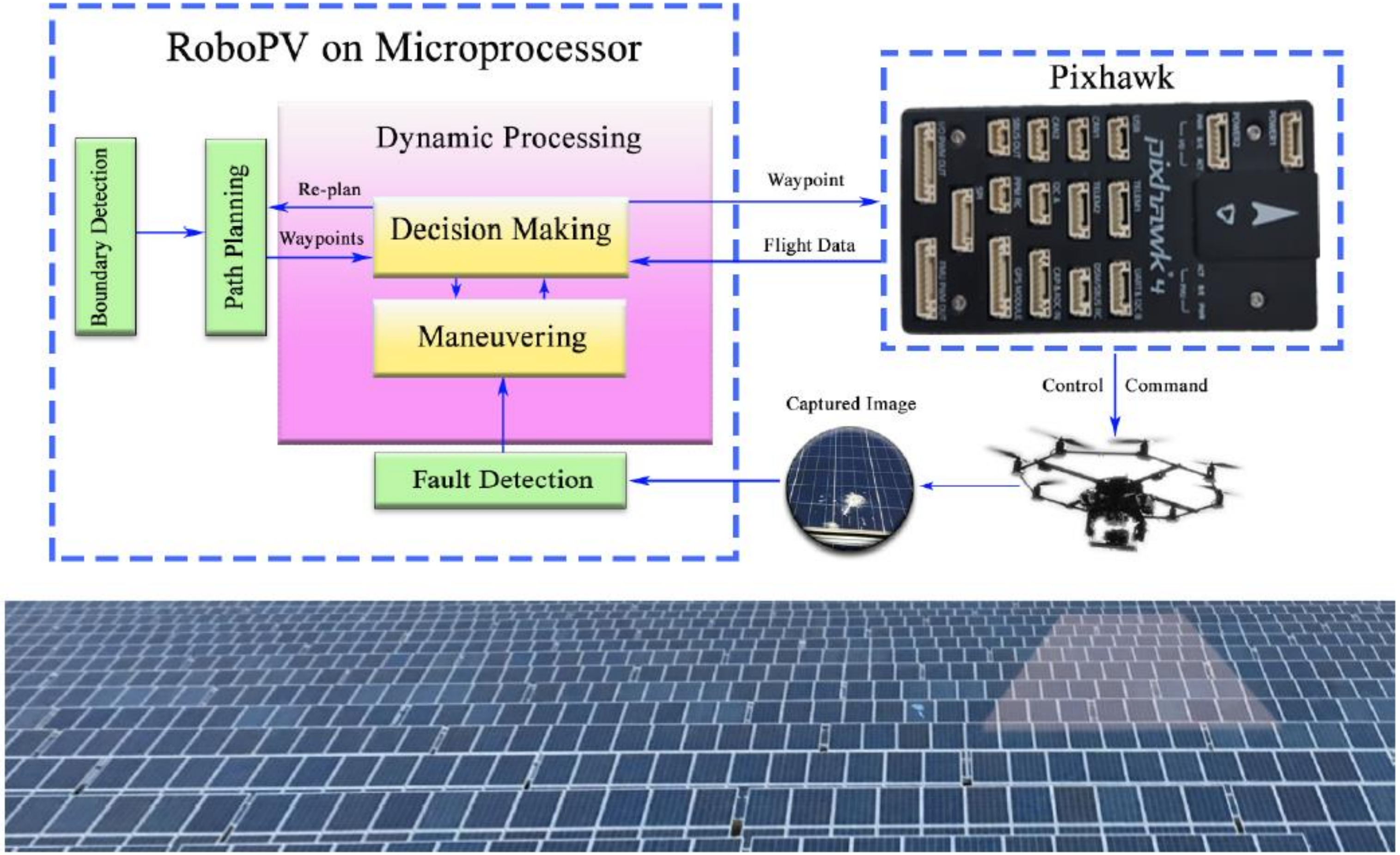


-A. Moradi, S. M. Esmailifar, M. Aghaei, ''RoboPV Monitoring: An Integrated Aerial Robotic Platform for Autonomous Monitoring of Large-Scale PV Plants'', Energy conversion and management, 2022.

Dynamic Processing

- Fast Decision-Making During the Flight
- Connection with PixHawk through MavLink
- Generating Maneuver Commands for Accurate Inspection

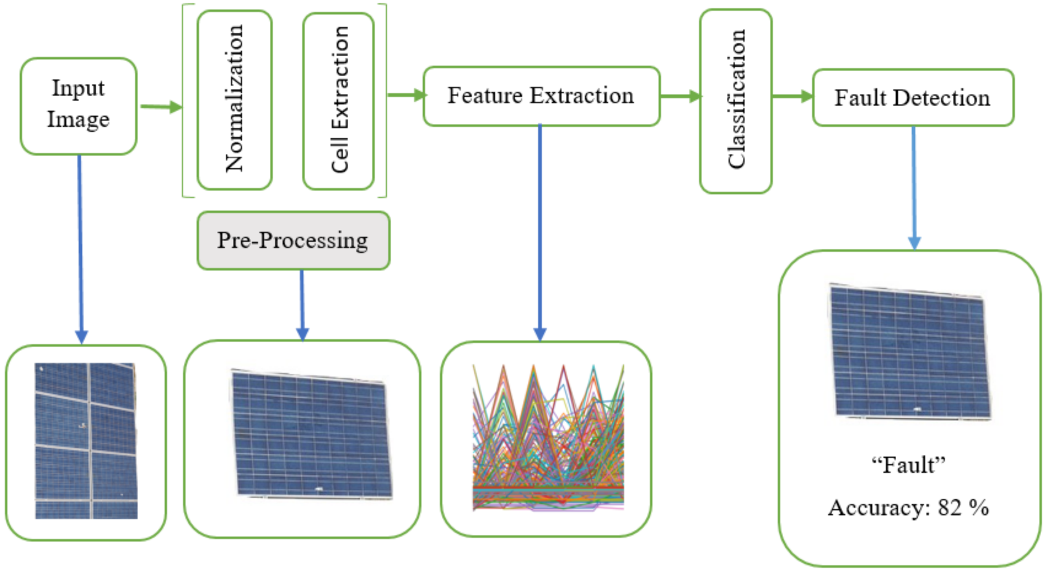


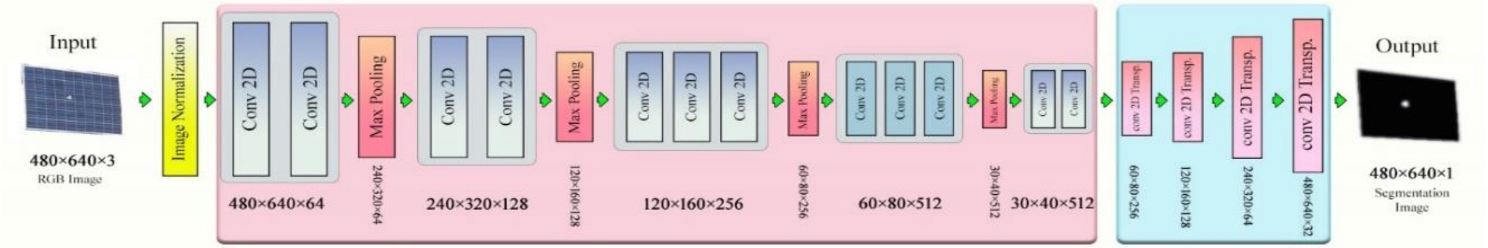


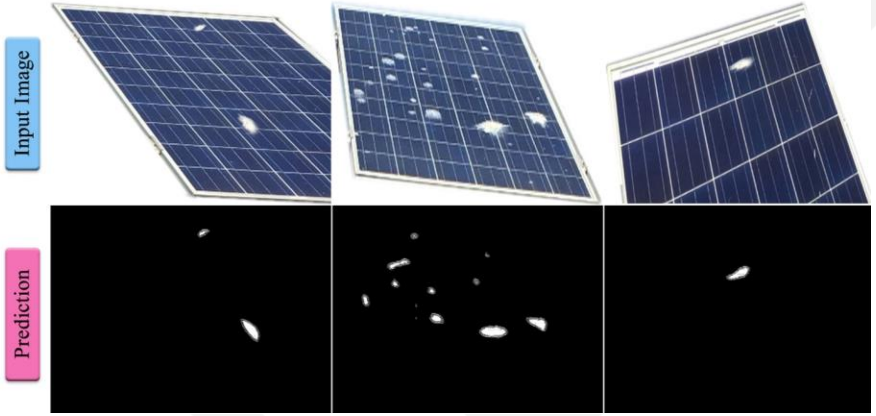
-M.Moradi, M.Esmaeilifar, M. Aghaei, A.K. Oliveira, R.Rüther," Autonomous Path Planning by Unmanned Aerial Vehicle (UAV) for Real-Time Monitoring of Large-Scale PV plants", 46th IEEE PVSC, Chicago, USA, June, 2019.

-A. Moradi, S. M. Esmailifar, M. Aghaei, ''RoboPV Monitoring: An Integrated Aerial Robotic Platform for Autonomous Monitoring of Large-Scale PV Plants'', Energy conversion and management, 2021.

Fault Detection







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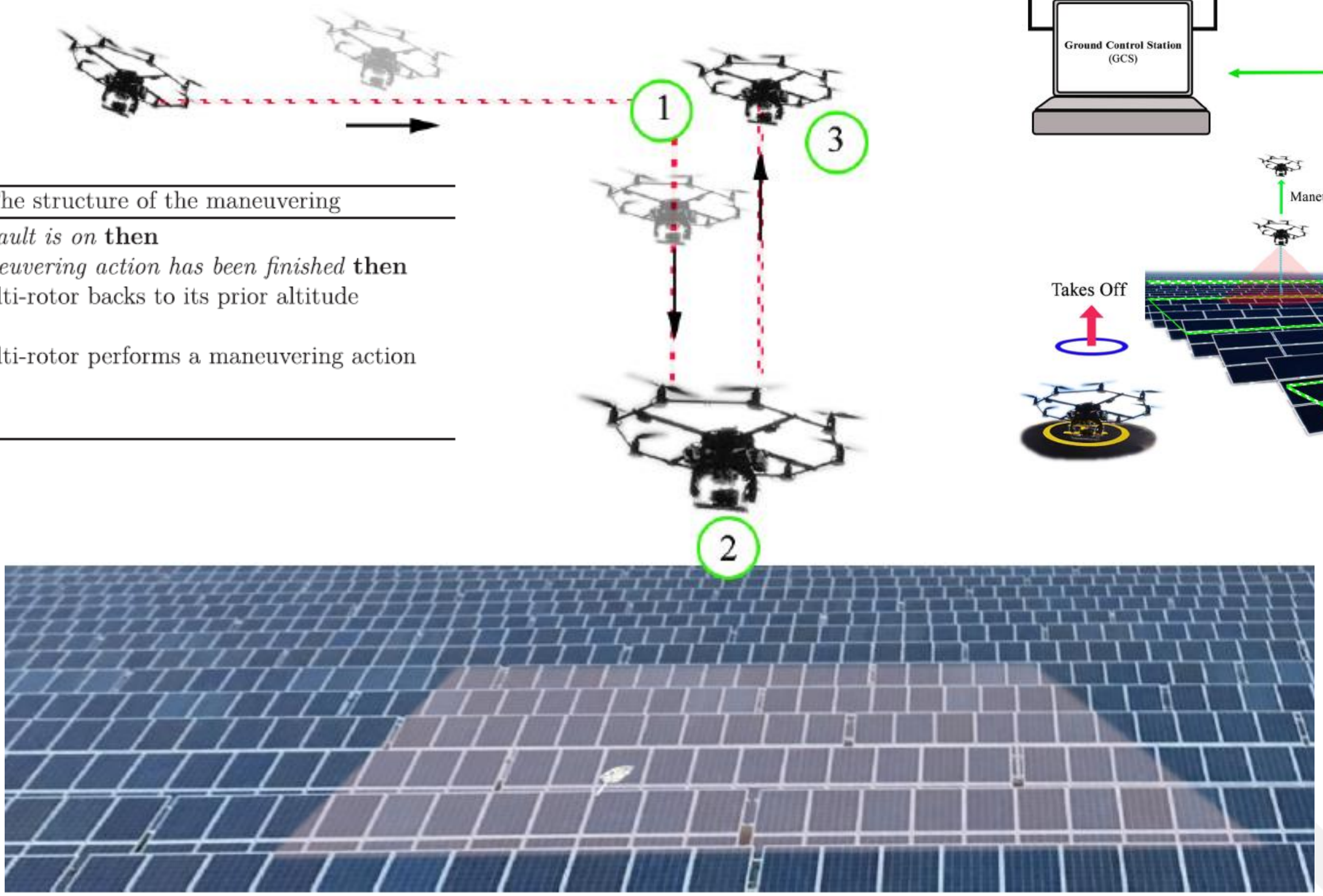
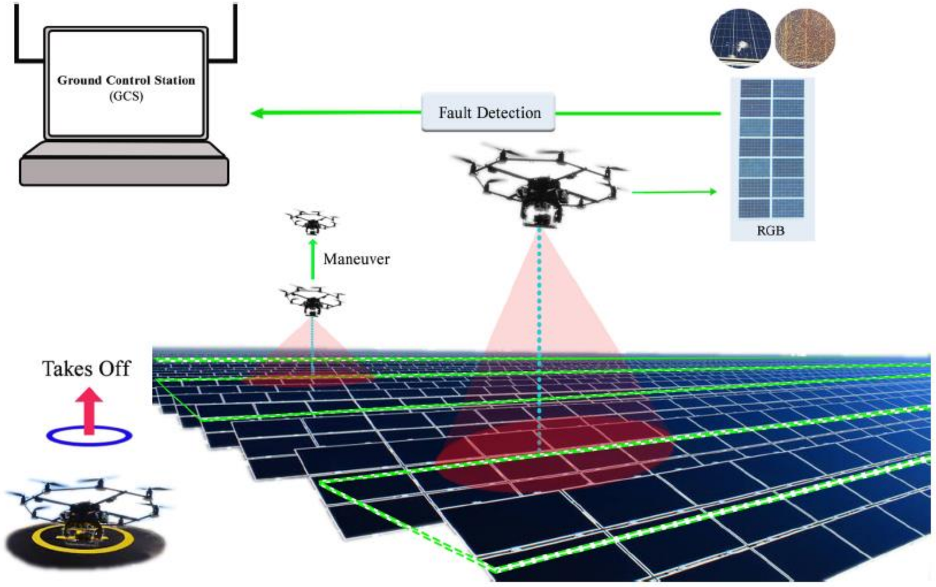
-A.M. Moradi Sizkouhi , M. Aghaei, S.M. Esmailifar, "A Deep Convolutional Encoder-Decoder Architecture for Autonomous Fault Detection of PV Plants by a Multi Copter", Solar Energy, 2021.

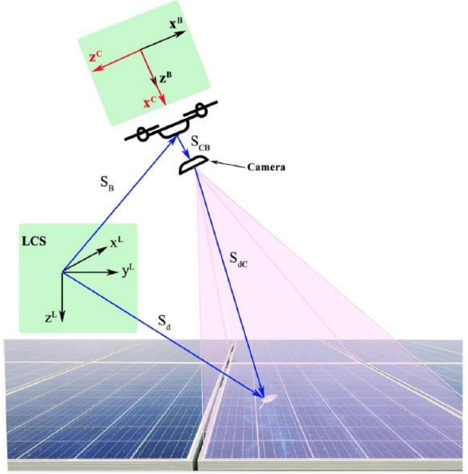
Maneuvering

Algorithm 1: The structure of the maneuvering

```
if The flag of fault is on then
|   if The maneuvering action has been finished then
|   |   The multi-rotor backs to its prior altitude
|   else
|   |   The multi-rotor performs a maneuvering action
|   end
end
```







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Decision-Making

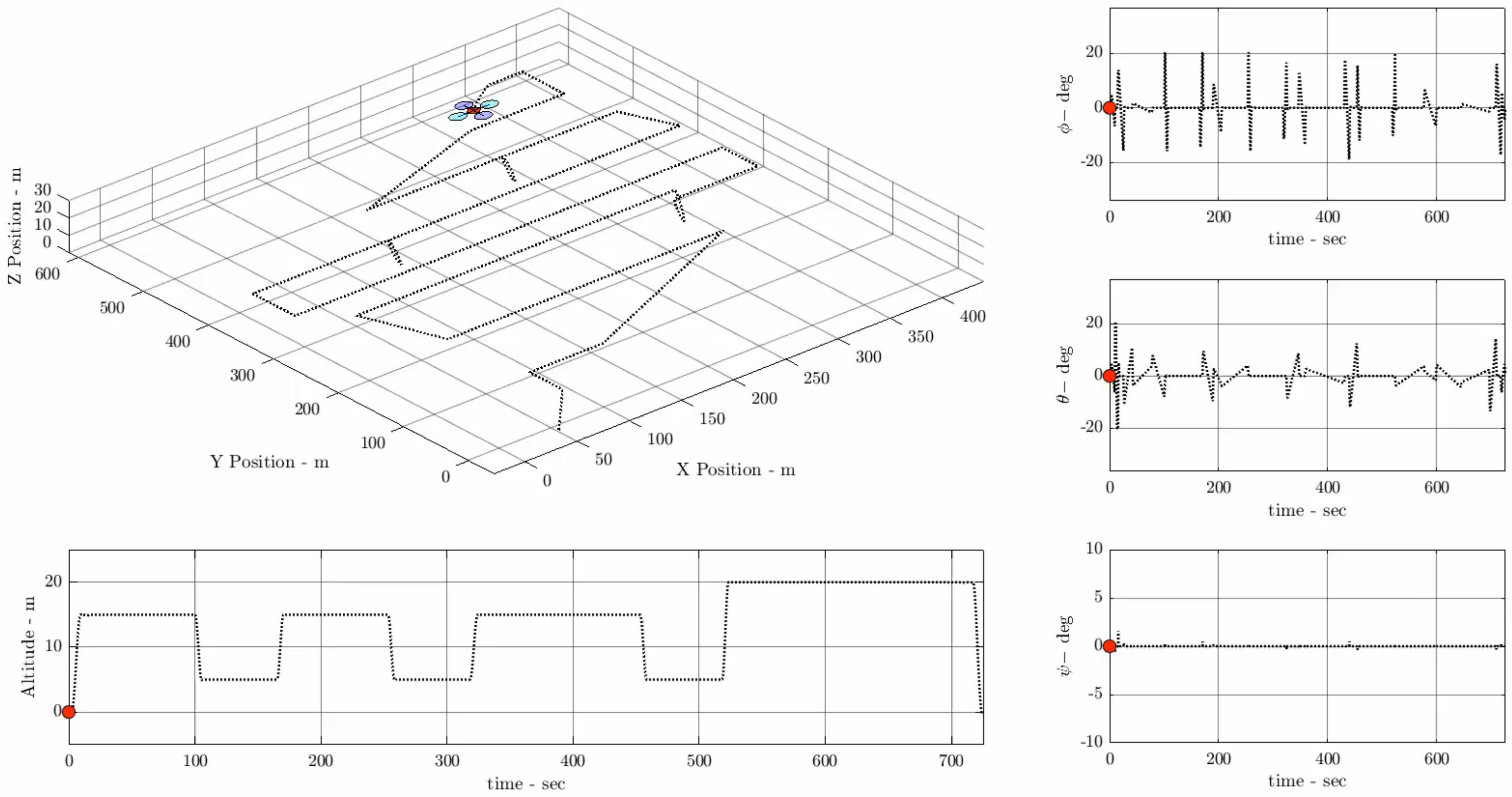
Algorithm 2: The structure of the decision-making

```
if The flag of decision = 1 by maneuvering then
    if RoboPV finds any problem then
        Emergency landing is commanded to the multi-rotor
    else
        The required battery charge of the remained path is calculated.
        if Required battery charge > Available battery charge then
            while The altitude of the multi-rotor < Admissible defined altitude do
                Path planning generates a new trajectory with a new altitude.
                if Required battery charge for the new path > Available battery
                 charge of the multi-rotor then
                    height ← height +1
                else
                    Break the loop
                end
            end
        else
            The mission is continued over the current path.
        end
    end
else
    The mission is continued over the current path.
end
```

-A. Moradi, S. M. Esmailifar, M. Aghaei, ''RoboPV Monitoring: An Integrated Aerial Robotic Platform for Autonomous Monitoring of Large-Scale PV Plants'', Energy conversion and management, 2021.

RoboPV Software Platform Validation

Third PV Plant



-A. Moradi, S. M. Esmailifar, M. Aghaei, ''RoboPV Monitoring: An Integrated Aerial Robotic Platform for Autonomous Monitoring of Large-Scale PV Plants'', Energy conversion and management, 2021.

Summary & Take-Home Messages

- PV systems experience various **unexpected faults** due to human errors, Temperature , Humidity , mechanical load ,UV irradiation, shading, irreversible equipment damage, and environmental impacts and so on.
- The **increasing number of PV installation** as well as related **massive volumes of data** which are collected from energy meters and sensors reveal the importance of **developing new monitoring technologies** and procedures that can handle such large volumes of systems and data.
- Recent advances in software, hardware and also platforms for **large data acquisition, storage and Big Data Analytics (BDA) aim to recognize the failures, faults and malfunctions in PV components efficiently, quickly and precisely** as well as increase the reliability and durability of PV systems.
- The **artificial intelligence techniques** aim to detect and classify any failures in PV systems accurately and authomatically.
- To date, various AI methods like **Probabilistic Neural Network, Random Forest Learning, Conventional Neural network (CNN), decision tree (DT), Kernel-based Extreme Learning Machine (KELM), Graph-Based Semi-Supervised Learning (GBSSL), Support Vector Machine (SVM) etc**. were used for PV monitoring.
- **RoboPV** is a software package for **autonomous aerial monitoring** of PV plants. **RoboPV** has six integrated processing units including boundary detection, path planning, dynamic processing and fault detection, maneuvering and decision-making.

Thank You Very Much for Your Attention!

PEARL PV

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