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Solar Module Condition Monitoring Using Thermal Imagining

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SOLAR MODULE CONDITION MONITORING
USING THERMAL IMAGING

by

Ammar W. Hashim

A thesis submitted to the Graduate College
in partial fulfillment of the requirements
for the degree of Master of Science in Engineering
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Solar energy industry has been exponentially increasing over the past decades with solar panels sales recording significant growth mainly due to the fact that solar energy is a renewable clean source of energy. Similar to other systems, condition monitoring is essential to maintain high efficiency specially that these systems are still not scoring more than 46% efficiency and also to ensure a safe system and prevent electric and fire risks that may occur. In this work, we introduce a system using infrared thermography along with selected image processing techniques to effectively and non-destructively test and detect these defects. Hot spots are easily detected and it doesn’t need to shut-down these solar cell modules or built in sensors to achieve same objectives. Investigation also focused on detecting the panels’ boarders and isolate them from images’ background. Images were taken from real solar systems and results show that a real time system can be an effective automated system for fault detection.
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In the end, I want to say a million thanks to my family back in my country, my father, my mother and my little sister, because of you I’m who I’m now, may god keep you safe, I love you all.

Ammar W. Hashim
# TABLE OF CONTENTS

ACKNOWLEDGMENTS ........................................................................................................... ii

LIST OF TABLES .................................................................................................................. v

LIST OF FIGURES ................................................................................................................. vi

Chapter 1: Introduction ........................................................................................................ 1

1.1 Solar Cells ..................................................................................................................... 1

1.2 Types of solar cells ....................................................................................................... 4
  1.2.1 Crystalline Silicon (c-Si) .......................................................................................... 5
  1.2.2 Thin-Film Solar Cells (TFSC) .................................................................................. 9
  1.2.3 Multi-Junction Solar Cells ...................................................................................... 11

1.3 Growth of PV modules ............................................................................................... 13

1.4 Solar Theory ............................................................................................................... 14

1.5 Statement of Problem ............................................................................................... 18

1.6 Thermal Imaging and its Application ...................................................................... 19
  1.6.1 Infrared Radiation ................................................................................................. 19
  1.6.2 Infrared Camera ...................................................................................................... 20

1.7 Thesis Scope .............................................................................................................. 21

Chapter 2: Background and Literature Review .................................................................. 27

2.1 Fault analysis in solar panels .................................................................................... 27
  2.1.1 Visual Inspection .................................................................................................... 28
  2.1.2 I-V Measurements ............................................................................................... 29
  2.1.3 Infrared Thermography ....................................................................................... 30
  2.1.4 Electroluminescence Imaging .............................................................................. 32

2.2 Thermal imaging applications ................................................................................... 33

2.3 Application of thermal imaging in solar panels ...................................................... 35
  2.3.1 Panel Recognition ................................................................................................. 35
  2.3.2 Defect Detection ................................................................................................... 35

Chapter 3: Proposed System and Methodology .................................................................. 37
# Table of Contents—Continued

Chapter 4 : Experimental Results and Discussion ............................................................. 51  
  4.1 Experimental Results ............................................................................................. 51  
  4.2 Results Summary ................................................................................................. 63  
Chapter 5 : Discussion & Conclusion .............................................................................. 64  
  5.1 Study Limitation ................................................................................................. 64  
  5.2 Future Work ....................................................................................................... 66  
  5.3 Conclusion ......................................................................................................... 67  
Chapter 6 : References .................................................................................................... 69
LIST OF TABLES

2-1. Different types of degradation and its common diagnostic methods ......................................................28

2-2. Typical failures found during IEC 61215, 61646 visual inspection ..........................................................29

2-3. The list of defects in solar panels and how it appears in thermal image ..................................................31

4-1. Shows a comparison between healthy and defective panel in terms of intensity and histogram for figure 4.11. ........................................................................................................................................57

4-2. Shows a comparison between healthy and defective panel in terms of intensity and histogram for figure 4.12 ........................................................................................................................................59

4-3. The results summary of Intensity Thresholding to detect defects ..............................................................63

4-4. The results summary of Canny edge detection to detect defects ..............................................................63

4-5. The results summary of Absolute Thermal Contrast to detect defects along with panel recognition ..63
LIST OF FIGURES

1-1. Layers of Solar Cell .......................................................................................................................... 2

1-2. Illustration of solar cell, string and their connection to form a 33v solar panel .................................... 3

1-3. Reported timeline of solar cell energy conversion efficiencies (from National Renewable Energy Laboratory (USA)).................................................................................................................................. 5

1-4. Monocrystalline solar panels ........................................................................................................... 6

1-5. Polycrystalline silicon solar panels (from Energy Informative).......................................................... 8

1-6. Thin-Film Solar Panels (from Energy Informative)............................................................................. 10

1-7. Different types of solar cells (from Sunday Energy)........................................................................... 11

1-8. The comparison of the light wavelength rang usage in multi-junction solar cells and conventional solar cells (from Compound Semiconductor Epitaxy Laboratory) .................................................................................. 12

1-9. Global growth of PV modules in energy generation ........................................................................ 13

1-10. PV module I-V curve.................................................................................................................... 14

1-11. PV string I-V curve with n modules in parallel ............................................................................. 15

1-12. PV string I-V curve with m modules in series .............................................................................. 15

1-13. The equivalent circuit of a solar cell based on a current source and diode, the series and parallel resistances represents losses in the circuit. .................................................................................. 16

1-14. Complete electromagnetic spectrum .............................................................................................. 19

1-15. Proposed system block diagram with specifications of the solar power system ................................ 22

1-16. Solar power system built for the purpose of this thesis ................................................................... 23

1-17. Thermal image of solar modules, the one on the right represent a normal working module while the one on the left shows an increase in temperature, which means a defective module .......... 24
List of Figures—Continued

1-18. Regular image of solar modules as it seen by naked eyes, as it’s obvious no difference can be detected in the two modules, the defective module can’t be distinguished from the healthy one......24

3-1. Proposed system for detection of panel edges using thermal images.................................................................39

3-2. Line example in 10x5 bitmap ........................................................................................................................................40

3-3. Line representation in (x,y) using (ρ,θ)................................................................................................................................41

3-4. Results of processing three different images (1(a), 2(a) & 3(a)) which represent different composition of horizontal and vertical lines where (a) shows the input image of a line, (b) shows the canny edge detection of the input image and (c) shows the Hough Transform of the image..................................................42

3-5. Results of processing three different images (1, 2 & 3) which represent different composition of horizontal and vertical lines where (a) shows the input image of a line, (b) shows the canny edge detection of the input image and (c) shows the Hough Transform of the image................... .....43

3-6. Representation of a rectangle centered at origin of the coordinate system ..........................................................43

3-7. Hough peaks of H1 ≡ P2P3, H2 ≡ P1P4, H3 ≡ P3P4 and H4 ≡ P1P2..................................................................44

3-8. Hough Transform and hough peaks of a parallelgram ..........................................................................................44

3-9. Detected hough lines of an image .................................................................................................................................45

3-10. The reshaping of the panel images........................................................................................................................47

3-11. Proposed method flow chart ..................................................................................................................................50

4-1. Results of panel recognition using canny edge detection threshold of 0.2 and Gaussian filter standard deviation of 2 while Hough transform fill gab between lines is 20 pixels and minimum length of line 100..........................................................................................................................51

4-2. Results of panel recognition using canny edge detection threshold of 0.2 and Gaussian filter standard deviation of 2 while Hough transform fill gab between lines is 20 pixels and minimum length of line 100..........................................................................................................................52

4-3. Results of panel recognition using canny edge detection threshold of 0.2 and Gaussian filter standard deviation of 2 while Hough transform fill gab between lines is 20 pixels and minimum length of line 100..........................................................................................................................52
List of Figures—Continued

4-4. Results of panel recognition using canny edge detection threshold of 0.2 and Gaussian filter standard deviation of 2 while Hough transform fill gap between lines is 20 pixels and minimum length of line 100.................................................................53

4-5. Results of panel recognition using canny edge detection threshold of default (0.1) and Gaussian filter standard deviation of default (1.4) while Hough transform fill gap between lines is 20 pixels and minimum length of line 100.................................................................53

4-6. Results of panel recognition using canny edge detection threshold of default (0.1) and Gaussian filter standard deviation of default (1.4) while Hough transform fill gap between lines is 20 pixels and minimum length of line 100.................................................................54

4-7. Defect and fault detection using canny edge detection, total defects found is 2..........................55

4-8. Defect and fault detection using canny edge detection, total defects found is 3..........................55

4-9. Defect and fault detection using canny edge detection, total defects found is 4..........................56

4-10. Defect and fault detection using canny edge detection, total defects found is 4.......................56

4-11. Defect and fault detection: (a) original thermal image of a defective panel (b) gray scale image of the original image, (c) intensity thresholding, clustering and labeling on the logical image, (d) defect and fault detection of 4 hot spots as counted.................................................................58

4-12. Results of absolute thermal contrast detecting 2 defects after selecting panel 1 as healthy...........60

4-13. Results of absolute thermal contrast detecting 3 defects after selecting panel 2 as healthy...........60

4-14. Results of absolute thermal contrast detecting 1 defect after selecting panel 1 as healthy.........61

4-15. Results of absolute thermal contrast detecting 2 defects in two different panel (#8 and #9) after selecting panel 5 as healthy.................................................................61

4-16. Results of absolute thermal contrast detecting no defects after selecting panel 6 as healthy.......62

5-1. Algorithm inability to detect panels of two strings ..................................................................64

5-2. Hough Lines can’t be recognized in cold winter.................................................................65

5-3. Not clear lines taken from the thermal camera which led to miss the Hough lines detection.....65
Chapter 1: Introduction

1.1 Solar Cells

Solar cells or Photo-Voltaic (PV) cells because it performs a direct conversion of the sunlight (photons) into electricity (Voltage) using the photovoltaic effect in semiconducting materials. Solar energy is a renewable and clean source of energy that makes photovoltaics a promising technology to mitigate the energy crisis without harming the environment. Alexandre-Edmond Becquerel was the first one who discovered the photovoltaic effect in 1839 [40]; This effect could be described as the excitement of the electrons in the valence band into the conduction band by photons. And then they are driven into a different material by the Galvani potential creating electromotive force [41]. Solar cells can be fabricated from a semiconductor material such as silicon or conducting polymers.

Solar cells usually made of silicon that is a semiconducting material, which means it can transfer electricity under some circumstances but not others, Silicon belongs to group 14 which has 2 electrons belong to the 1st shell, 8 electrons belongs to the 2nd shell but only 4 electrons in the 3rd outer shell which are called valence electrons. This is important because all silicon outer shells consists of 4 valence electrons. However all silicon atoms will form bonds but sharing electrons to form a full outer shell with 8 electrons which make them very stable, in order to disturb the stable state doping atoms or purposely inserted into the silicon. So when Boron (p-type dopant) combined with silicon, a free hole will be created because boron has only 3 electrons in its outer level, but with Phosphorous (n-type dopant) it will create one additional electron because it has 5 electrons in the outer level and that’s where a fascinating phenomenon happens.

The solar cell consist of 2 silicon layer sandwiched together one is doped with n-type dopants which have one extra electron and its located on the top of the solar panel while the other layer with p-type dopants which has one extra hole and its located on the lower level of the solar panel. When the two silicon layer meets electrons can wonder across the p-n junction leaving a positive charge on one side and creating a negative charge on the other.

When photos from the sun hit the silicon layers then hole-electron pairs will be created, then
electrons moved from the n-doped layers, and the holes moved from the p-doped layer, the mobile electrons are collected by a thin metal fingers on the top of the cell from there they flow throw an external circuit doing the electrical work before returning throw a conductive aluminum sheet on the back. The front and the back contacts are installed to the layers for the purpose of creating an electrical flow of electrons. Glasses are installed on top of it to protect the layers and the electrical contacts from damages. Figure 1.1 presents the components of the solar cell.

![Layers of Solar Cell](image)

Figure 1-1. Layers of Solar Cell

Each solar cell generate a voltage of 0.5-0.6 volts DC, which is not enough to power even an electronic watch, in order to generate more power, solar cells are connected to each other in series to form a string of cells, the latter is connected in series as well to form what’s called a solar panel or solar module as it can be seen in Figure 1.2 which illustrate a solar panel consist of 60 solar cells all connected in series to generate about 33 volts DC.
These PV power systems produce energy with proportion to the intensity of sun photons hits the solar cell silicon layer since it’s consisted of light sensitive cells that can generate direct current. And since the electricity that been used on a daily basis is an alternative current, alternating current converters have been introduced to transform the direct current generated by the solar modules into alternating current.

Figure 1-2. Illustration of solar cell, string and their connection to form a 33v solar panel.
1.2 Types of solar cells

There are several variations of solar cells. The two most common types are those made of crystalline silicon and those made with this film technology, their benefits and downsides were listed, and then a look has been taken at a few common scenarios where particular types would be the better than others. Knowing the intensity of light on a surface varies throughout a day, as well as day to day; therefore the output power from the solar cells varies as well.

The fabrication techniques of the solar cells are well developed, and their performance is adequately described. The development of new solar cell materials and structures is the aim of many of the research in order to achieve higher conversion efficiency. Figure 1.3 presents a current report for solar cell efficiency records from National Renewable Energy Laboratory (source: http://cdn.phys.org/newman/gfx/news/hires/2016/1-claimsforsol.jpg). The graph reveals the rapid progress of the solar energy conversion in the recent four decades. Multi-junction solar cells have recorded efficiency as high as 46% conversion rate; on the other hand, mono-crystalline silicon solar cells have recorded a high conversion efficiency of around 27.6%; and the other solar cell technologies are also progressing [42]. Which will lead toward making a possibility of using the solar power for residential demands.
1.2.1 Crystalline Silicon (c-Si)

Around 90% of the World’s photovoltaics now are based on some variety of silicon. In 2011, approximately 95% of all purchases by U.S. manufacturers to the private sector were a crystalline silicon solar panels [37]. The silicon utilized in PV takes many kinds. The main difference is the purity of the silicon.

But what does silicon purity mean? The more ideally aligned the silicon particles are, the better the solar cell will be at transforming solar energy (sunlight) into electricity (the photoelectric effect).

The Crystalline silicon lattice forming the basis of monocrystalline and polycrystalline silicon solar cells:
1.2.1.1 Monocrystalline Silicon Solar Cells

The picture in figure 1.4 shows the monocrystalline solar panels. The solar cells formed by monocrystalline silicon, also called single-crystalline silicon are simply detectable by an external even coloring and uniform look and demonstrates high-purity silicon [38].

Figure 1-4. Monocrystalline solar panels

Monocrystalline solar cells are cylindrical in their shape and evolved by silicon ingots. In order to enhance its performance with minimum cost for single monocrystalline solar cell, the four sides are removed from its cylindrical ingots for creating silicon wafers, which lead to unique appearance for monocrystalline solar panels.

Polycrystalline solar cells appear perfectly in rectangular shape without around edges, and crystal boundaries may be visible. It is a suitable approach to detach mono- and polycrystalline solar panels.
Advantages

- The fact that monocrystalline solar panels are made of highest-grade silicon, efficiency of this solar panels exhibit highest scale. The monocrystalline solar panels efficiency normally ranges between 15% to 20%.
- Monocrystalline silicon solar panels are space-efficient, given they deliver highest power outputs with minimum space requirement in comparison to any other types. Up to four times the amount of electricity as thin-film solar panels are produced by monocrystalline solar panels.
- The life span of monocrystalline solar panels is the longest. 25-year warranty for monocrystalline solar panels is prevalent among solar panel manufacturers.
- The monocrystalline solar panels are inclined to function better than polycrystalline solar panels at low-light conditions, that are rated in the same way.

Disadvantages

- Monocrystalline solar panels are the most expensive. A solar panel that is made of polycrystalline silicon (and in some cases, thin-film) can be better choice for families in terms of cost-effectiveness.
- If the solar panel is partly shielded with shade, dirt or snow, the entire circuit can break down. When foreseen the coverage for the solar panel is a problem, it is recommended to buy micro-inverters instead of central string inverters. Micro-inverters prevent the entire solar array unaffected by shading issues through only one of the solar panels.
- The Czochralski process is employed to produce monocrystalline silicon, which lead to large cylindrical ingots. The silicon wafers are created when its four sides are removed out of the ingots. Thus, considerable amount of the original silicon is wasted.
- Much higher efficiency observed in monocrystalline solar panels in warm weather. As temperature increases, the performance suffers, but less so than polycrystalline solar panels. For most homeowners temperature is not a concern.
1.2.1.2 Polycrystalline Silicon Solar Cells

In 1981, the first solar panels were introduced to the market. These solar panels were based on polycrystalline silicon, which is also known as multi-crystalline silicon (mc-Si) and polysilicon (p-Si). Polycrystalline solar panels don't need the Czochralski method of crystal growth, which is used to obtain single crystals of semiconductors, as monocrystalline-based solar panels do. First, they melt raw silicon, and then pour it into a square mold. Secondly, they cool it and cut it into ideally square wafers.

![Polycrystalline silicon solar panels](from Energy Informative)

**Advantages**

- Polycrystalline silicon is prepared through the simpler and cheaper process. This process wastes less silicon as compared to monocrystalline.
- Heat can affect the functionality of polycrystalline solar panels and decrease their lifespans. Polycrystalline perform poorly at high temperatures as compared to monocrystalline solar panels because polycrystalline solar panels can't tolerate heat as much as monocrystalline solar panels do. However, most homeowners do not take that effect seriously.
Disadvantages

- Polycrystalline are not as pure in silicon as monocrystalline solar panels are, so they are not as efficient as monocrystalline solar panels. They are typically 13-16% efficient. They have lower space-efficiency as well.
- Polycrystalline solar panels cover a larger surface area as compared to monocrystalline solar panels, though produce the same output. Nonetheless, every monocrystalline solar panel doesn't perform better than polycrystalline silicon based panel.
- Monocrystalline solar panels look more smooth than polycrystalline silicon panel that have the speckled blue color panels.

1.2.2 Thin-Film Solar Cells (TFSC)

Thin-film solar cells are fabricated by depositing single or many thin layers of photovoltaic material onto a substrate. Thin-film solar cells are also known as thin-film photovoltaic cells (TFPV).

On the basis of photovoltaic material deposited onto the substrate, thin-film solar cells can be characterized into four different types.

- Copper indium gallium selenide (CIGS)
- Cadmium telluride (CdTe)
- Organic photovoltaic cells (OPC)
- Amorphous silicon (a-Si)

Efficiencies of thin-film solar cells are from 7–13% and the production modules work at 9%. The future module is supposed to reach efficiencies of 10–16%[39]. From 2002 to 2007, the market for thin-film PV grew at annual rate of 60%. In 2011, about 5% of U.S. photovoltaic module shipments to the residential sector were based on thin-film [37].
Advantages

- Mass-production of TFSC is easy. As a result, the manufacture of this type of solar cells has become cheaper than crystalline-based solar cells.
- TFSC have a homogenous look, which makes them aesthetically good. If TFSC can be made flexible; it can help in opening new possible applications.
- High temperatures and shading do not affect on solar panel performance.

Disadvantages

- TFSC are useful for domestic use as they take a lot of space. If enough space is available, the use of TSFC is not the issue.
- TFSC have low space-efficiency. Monocrystalline solar panels producing the same amount of electricity as TFSC, take four times less space than TFSC. Low space efficiency increases the costs of PV-equipment; support structures and cables.
- TFSC has the short warranty as they degrade faster than the monocrystalline solar panel.

Figure 1.7 in the following page, shows the different types of conventional solar cell modules (source: http://www.sundayenergy.com.au/images/sunday/faq/solar_panels.png)
Figure 1-7. Different types of solar cells (from Sunday Energy)

1.2.3 Multi-Junction Solar Cells

The majority of PV cells use a single substance with the addition of specifically selected doping impurities. These solar cells use a particular part of the light spectrum, for example, a specific color or wavelength to do the conversion of light into electricity. The composition of various substances will allow the cells to do more light conversion into electricity, which means different parts of light spectrum will be used at the same time, and that will result in a significantly higher efficiency (up to 46% compared to the conventional solar cell that's around 15-25%). These type of cells are called Multi-Junction solar cells.

The multi-junction cells are manufactured in a similar way to thin-film cells as two or more pn layers of Amorphous Germanium solar cells materials are stacked on top of the other to form what's called a double-junction and triple-junction solar cells and that is why the production of such solar cell is also referred to as “stacking”. However, these cells are more complicated to make and are much more expensive.

Figure 1.8 shows the difference between silicon-based solar cells and compound semiconductor-based solar cells three cells are combined by stacking (source: http://csel.snu.ac.kr/_skin/kor/images/research/sc_03.gif) [54]. The efficiency increment will be achieved when the top cell has a highest energy gap (bandgap) and the bottom cell has lowest bandgap. [53]
Stacking different solar cells with pn junction structure, which is called a subcell, makes the multi-junction cells. The subcell is formed from different semiconductor substance that differs in their energy bandgap. The locations of these subcells are arranged in optical series that the highest bandgap semiconductor material located on top of the solar cell. This way breaks the broad solar spectrum into wavelength subbands so that photons with energy lower than the bandgap will be transmitted to the subcell beneath.

The standard structure of triple junction solar cell consists of a top cell of GaInP with (1.7eV bandgap), a middle cell of GaAs with (1.4 eV bandgap), and a bottom cell of Ge with (0.7 eV bandgap).

Such solar cells have been developed in late 2014 to be majorly used in space application like NASA [1], and because of its extremely high cost, they not have been used for residential or commercial applications.
1.3 Growth of PV modules

Being made from silicon, which over 90% of earth’s outermost layer is composed of silica material, makes the silicon the 2nd most common element on earth and as a result makes it available and very affordable. In addition to the ability to use an energy that existed almost everywhere as long as there is sunlight, the growth of its industry has been rapidly and exponentially increased, the reliability and overall system performance of the PV modules began to have a noticeable attention as well, reaching a global cumulative installed capacity of approximately 229.3 GigaWatt at the end of 2015. “Figure 1.9” shows the global growth of PV modules energy generation from 2000 to 2015 [2,3].

Figure 1-9. Global growth of PV modules in energy generation
1.4 Solar Theory

Solar cell technology can be broadly defined and as mentioned earlier in this study as equipment converting incoming photons (sunlight) to electric energy (voltage). The solar cells of interest in this study are monocrystalline and polycrystalline silicon, technologies that currently have a considerable market share [17].

In a matter of fact, both of these two types of solar cells share the characteristic of being built of one pn-junction, in other words, the bond between two differently doped silicon layers. The silicon consumes the incoming photons in which case an electron-hole pair is created [17], as the electron is accelerated to an outer layer by the consumed energy. Connecting an electric load, such as a heating component, to the terminals of the solar cell will then induce a direct current. In the end, this produces an efficiency of 13 - 18% for single pn-junction silicon layer technology [17].

PV module has a non-linear current vs. voltage (I-V) curve that contains all the possible operation points along with it as shown in figure 1.10. There are three important features of the I-V curve. First one called short-circuit current (Isc) which represent the maximum possible current, second one called open-circuit voltage (Voc) which represent the maximum possible voltage and the last one is the maximum power point (MPP), which represent the maximum possible power that the module can provide under a particular environmental state.

![PV module I-V curve](image)

Figure 1-10. PV module I-V curve
Solar cells is a modular technology that can be made incrementally to fulfill the increasing electricity needs. As the basic building block of PV systems, PV modules can be connected in parallel and/or in series to build a PV array. For example, each PV module has an open-circuit voltage (Voc) and a short-circuit current (Isc). Figure 1.11 shows a connection of n modules in parallel which will create a PV string with a higher short-circuit current (n×Isc) while figure 1.12 shows a connection of m modules in series which creates a PV string with a higher open-circuit voltage (m×Voc).

Figure 1-11. PV string I-V curve with n modules in parallel

Figure 1-12. PV string I-V curve with m modules in series
Moreover, applying the rules illustrated above, a large PV array can be formed. If a string has m identical modules, n identical PV strings can be in parallel to form a PV array containing \((n \times m)\) PV modules. Therefore, the PV array has an open-circuit voltage \(m \times V_{oc}\) and a short-circuit current \(n \times I_{sc}\).

The analyzing of the solar cell can be accomplished utilizing an equivalent electrical circuit model with specified parameters. The one diode model is a broadly used model \([18]\) as shown in figure 1.13. It is based on modeling the solar cell as a current source connected in parallel with a diode. Besides, there are internal losses because of imperfection in manufacturing. These are modeled as a series and a parallel resistance. The resulting current \(I_{load}\) flows across the terminals through a load with a potential difference (voltage) \(U_{load}\). \(I_{photo}\) coincide to the volume of current produced by incoming photons which are proportional to the solar irradiance and the solar cell area.

![Figure 1-13. The equivalent circuit of a solar cell based on a current source and diode, the series and parallel resistances represents losses in the circuit.](image)

Where, \(I_{load}\): load current, \(U_{load}\): load voltage, \(I_{photo}\): photogenerated current, \(I_{diode}\): diode current, \(I_{par}\): parallel loss current, \(R_{par}\): parallel loss resistance and \(R_{serie}\): series loss resistance

In order to resolve the equivalent circuit currents and voltages, a forming of the model initiated using the given the characteristics of a solar cell and summing all the currents in the equivalent circuit which is \(I_{diode} + I_{par} + I_{load} = I_{photo}\). In addition to utilizing Ohm’s law and Shockley’s diode law \([18]\), the equations become as below:
\[ I_{load} = I_{photo} - I_{diode} - I_{par} \]  \hspace{1cm} (1.1)

\[ I_{diode} = I_{sat} \left( e^{\frac{q(R_{ser}I_{load} + U_{load})}{k_B T}} \right) + 1 \]  \hspace{1cm} (1.2)

\[ I_{par} = \frac{R_{ser}I_{load} + U_{load}}{R_{par}} \]  \hspace{1cm} (1.3)

\[ I_{load} = I_{photo} - I_{sat} \left( e^{\frac{q(R_{ser}I_{load} + U_{load})}{k_B T}} \right) - 1 - \frac{R_{ser}I_{load} + U_{load}}{R_{par}} \]  \hspace{1cm} (1.4)

Isat indicates the constant saturation current of the diode, kB \( \approx 1.38 \times 10^{-23} \text{ J/K} \), and q \( \approx 1.60 \times 10^{-19} \text{ C} \). The free variables are I\text{load}, U\text{load} and T, where T is the temperature measured at the pn-junction. All characteristics of the solar equivalent circuit, such as Isat, can be provided in a datasheet or can alternatively be obtained by performing non-linear regression based on samples of the free variables [18].

Furthermore, there are also a range of operating temperatures depending on local weather conditions. The temperature influences the second part of equation 1.1-4 an increased temperature results in a decreased load current. This is essential to take into consideration since otherwise increased temperature might be mistaken for reduced irradiation.

Eventually, it is necessary to recognize that different solar panels have various parameters and that will yield different I-V curves. Aforementioned indicates that inhomogeneous systems offer challenges when comparing generated output power, for example in the case of fault detection.
1.5 Statement of Problem

The world is entering a new era of clean and renewable energy than can fuel the future, solar panels is becoming one of the main sources to harvest that energy using sunlight. As these modules have been manufactured, inspection process should be conveyed for detections of defects like cracks and hot spots and other kind of failures. Also after the installation of these PV modules in a solar plant, periodic inspections should be performed to make sure energy generation is at maximum. Because the output of the generated energy decreases in case of malfunction of some cells or modules, and with the lack of inspection, these defects can be developed into a fire hazard. Specially after the previously mentioned growth of the PV modules during the past few decades, the number of defects and faults in these modules have been increased as well and it became essential to do inspection and maintenance for these solar modules.

Defective cells in the PV module will lead to considerable loss of performance from the system; also a temperature increase of 10 °C above the operating temperature recommended by the manufacturer may result in a 50 % shortening of its lifetime. Not mentioning a defective cells can lead to an enormous heat development, and thus to the danger of fire.

In a matter of fact the efficiency of these regular modules is only 17% which is defined as the electrical power output from the solar module over the total power received from the sun, which means 17% of the energy that comes from the sun is converted to direct current, the rest of the 83% is transferred to heat radiated from the solar cell, which with defects the heat radiation will be increased and the efficiency will suffer from severe drop.

Malfunctioning cell or module generally emits more heat as compared to the normally functioning module (healthy module). Since its efficiency will be dropped, the conversion of energy into electricity will be reduced, and the conversion of energy into heat will be increased. The temperature difference can be detected by infrared (IR) thermography, IR thermography provides images of a specific temperature pattern utilizing the IR radiation, which is emitted by all objects proportionally to their temperatures, and by this difference, the determination of defective module or cell can be detected.
1.6 Thermal Imaging and its Application

1.6.1 Infrared Radiation

Human naked eyes are indicators that are created to detect electromagnetic radiation in the visible light spectrum only. All other types of electromagnetic radiation, like infrared, are invisible to the human eyes. In 1800 an astronomer named Sir Frederick William Herschel discovered the existence of infrared. During his investigation of the thermal difference between the light visible colors, he directed sunlight through a prism of glass to create a spectrum and then measured the temperature of each color. He observed the temperatures of the colors were increasing from the violet to the red part of the spectrum. Following noticing this pattern, He determined to measure the temperature just beyond the red portion of the spectrum in a range where sunlight was invisible. To his astonishment, he discovered that this region had the highest temperature of all.

Infrared radiation extends between the microwave portion and the visible light of the electromagnetic spectrum. Figure 1.14 shows the complete electromagnetic spectrum of different types including the infrared. The primary source of infrared radiation is heat or thermal radiation. Any object that has a temperature above absolute zero (-273.15 degrees Celsius or 0 Kelvin) emits radiation in the infrared region. Even objects such as ice cubes emit infrared radiation. The heat from sunlight, fire or a radiator is all infrared. Although human eyes are not able to see it, the nerves in human skin can feel it as heat. The more temperature the object has, the more infrared radiation it emits.

Figure 1-14. Complete electromagnetic spectrum
1.6.2 Infrared Camera

Normally, our vision is limited to a very small portion of the electromagnetic spectrum. Infrared electromagnetic spectrum has a much longer wavelength than visible light, in fact, that the naked human eye can't even see it, similar to the radio waves. With thermal imaging, the portion of the spectrum human eye perceive is dramatically expanded, helping to "see" heat. Visible light doesn't have an influence on the thermal world, so the ability see is equal in highly lit and totally dark environments. The thermal camera allows us to see things the naked eye could never perceive on its own.

When infrared energy comes from an object is focused by optics onto an infrared detector. The detector transmits the data to an electronic sensor for processing. The electronics interpret the information coming from the detector into an image that can be viewed on LCD screen. Infrared thermography is the technique of converting an infrared image into a radiometric image, which provides temperature measurements to be read from the image. So every pixel in the radiometric image is, in fact, a temperature measurement. In order to do this, algorithms are included in the thermal imaging camera.

Sensitivity describes the ability of an infrared camera to present a good image even if the thermal contrast in a scene is low. in other words, a camera with good sensitivity can recognize objects in a scene that have a small temperature difference. A parameter called Noise Equivalent Temperature Difference or NETD is mostly used to measure sensitivity.

NETD is described as the amount of infrared radiation needed to generate an output signal equal to the system's noise which is an electronic noise that translated to a temperature difference at a receiver temperature of 30 C (86 F), and it's necessary for that noise to be as low as possible. This kind of noise is called Temporal noise. Temporal noise is the time variation in pixel output values under uniform radiation due to device noise.
1.7 Thesis Scope

In the presented research, some types of PV faults and defects were reviewed, and a field inspection is conducted using non-destructive procedures to analyze visible and invisible defects for the PV array, in addition to recognition techniques were applied to detect the solar panel itself and isolate it from the background and by that not only the fault detection will be more reliable and efficient but also the identification and organization of these defects will be more manageable and presentable.

For the purpose of defect diagnosis, a solar power system has been built which include two solar panels manufactured by Suniva-opt 285-60-4-1b0 Monocrystalline type solar cell with power classification of 285W, Open Circuit Voltage (Voc) 39.2 V, Short Circuit Current (Isc) 9.61 A, Voltage at Max. Power Point (Vmp) 32.2 V, Current at Max. Power Point (Imp) 8.84 A, both of these panels are connected in series to give Open Circuit Voltage (Voc) 78.4 V, and Voltage at Max. Power Point (Vmp) 64.4 V. The complete project block diagram of the solar power system can be found in figure 1.15.
Figure 1-15. Proposed system block diagram with specifications of the solar power system.
The solar power system that has been built according to the proposed system block diagram of figure 1.15 for the scope of this thesis can be seen in the below picture of figure 1.16. The solar panel on the left side has some defects on it for the analysis purposes.

Figure 1-16. Solar power system built for the purpose of this thesis
One of these two panels is defect free (healthy panel), but some defects and failure has been introduced to the second panel for diagnosis purposes. Figure 1.17 shows the difference in temperature of normal cells (healthy module) and defective one taken by thermal camera, while figure 1.18 represents an image taken by regular camera for the same two modules, and as its obvious from the image that regular inspection by naked eye won't be efficient to detect these defects as no difference can be seen between them.

Figure 1-17. Thermal image of solar modules, the one on the right represent a normal working module (healthy module) while the one on the left shows an increase in temperature, which means a defective module
Figure 1-18. Regular image of solar modules as it seen by naked eyes, as it’s obvious no difference can be detected in the two modules, the defective module can't be distinguished from the healthy one

In order to do inspection for these solar modules, a person, cart or drone should carry an infrared camera and move from one PV array to another, searching for defects manually by an individual observing the thermal images, and in case of a solar plant or a big solar garden inspection an issue of detecting the anomalies will be raised with all the recording and calculating the defective panels. That will be a problematic task for human to process but it will be easy for a machine with right algorithms to deal with. Consequently, image processing and shape recognition techniques based on infrared thermography are a robust technology to automatically identify irregularities in these large arrays [3].

In this research, a drone that equipped with a regular camera in addition to a thermal camera has been used for inspection purposes, furthermore, a manually holding the camera by person has been used as well. The drone used is Yuneec Typhoon Q500 G Quadcopter, The included GB203 gimbal works with the HERO4 Silver. The gimbal provides three axes of stabilization. It can pitch (tilt) +75 to -120-degree, roll (cant) ±45-degree, and yaw (pan) ±45-degree. The thermal camera used is FLIR Vue Pro 336 with resolution of 336 x 256.

Infrared thermography can be used efficiently to detect common types of anomalies in solar panels that include cracks, hot spots, and hot modules. The defect detection algorithms normally consist of two steps: The pre-processing, and shape recognition. Prior to actually processing the
signal, it's necessary to fix some problems related to the acquisition system and enhance defect contrast of the raw image and reduce the noise by applying image filtering and image enhancement techniques. More analysis centered on shape and size using classification or clustering algorithms are implemented to recognize the defective cells.

This study is majorly divided into two stages. The first stage discusses solar module detection and recognition stage and the second is deals with the defects and faults detection in the modules. In the first stage, which is the recognition of each solar module existed in solar plant, Canny edge detection has been used first to extract the edges of the solar panels thermal image, then Hough Transform (HT) has been applied to detect the lines in the entire image which separate the lines between the panels, the intersection points of these lines has been recorded and represent as the corner of each solar module, and with eliminating the small areas between these lines the solar modules has been recognized and detected.

In the second stage, which is the search for anomalies in each of the solar module. In an individual solar module in solar plant, some small defects like hot spots, cracks is detected by different algorithms, the algorithms that have been used and discussed in this paper are:

1- Absolute Thermal Contrast.
2- Intensity Thresholding.
3- Canny Edge Detection

After the detection of the defect, a counter has been included to facilitate the task of calculating the detected defects and faults in the system. The complete system block diagram is shown in Figure 3.5.

The classification of the defect detection approaches for the PV system can be in a Visual method (discoloration, browning, cell cracks, delamination), Electrical method (I–V analysis, transmittance line diagnosis) and Thermal method (Thermal heating). These different methods will be discussed in the next chapter of this thesis along with the correspondence published studies about the previously mentioned methods.
Chapter 2 : Background and Literature Review

2.1 Fault analysis in solar panels

There are early studies that provided a picture of the past events regarding data and design of the PV system. One report covered a complete failure analysis of a PV system in Austin Texas [29]. From the previously mentioned study data, a determination of the degradation is obtained in addition to exploring other issues that may have played a part in the decline of the system. The study concluded that the early failures of the non-cell conducting ribbons from the modules to the copper busbar took a significant part to system deterioration.

The report was written by John E. Hoffner and have a title of “Module Field Experience with Austin’s PV Plants” [29] discussed a PV-panels project that was installed in 1987 by ARCO which is an American oil company that built a plant contained a total of 6160 modules. During installation, 39 modules were found non-functioning. Then after three months of installation, the total of failed modules were increased to 100. This failure was substantially large to make ARCO appoint a special team to do an investigation of the failure.

The special investigation team was able to physically remove and examine the causes of module failure, and referred the failure of the ribbons to the busbar expansion, a spot welded point on the busbar was where most of the shearing was located.

Then after two years from the installation Hoffner reported [29]:

- Thermo cycling of the busbar caused the ribbon shear.
- The shearing forces tearing the conducting ribbon was because of lack of flexibility since there was a cementing seal the help the ribbons in place
- One of the leading causes of system decline was a failure of the conductive ribbons.
Afterwards, more sophisticated methods for diagnosis and failure investigations have been introduced. Generally there are four different methods for diagnosis of failures in the PV systems, Visual inspection, I-V measurements, Infrared thermography and electroluminescence imaging. Table 2.1 shows the different types of degradation and its common diagnostic methods.

Table 2.1. Different types of degradation and its common diagnostic methods

<table>
<thead>
<tr>
<th>Degradation mode</th>
<th>Common diagnostic methods</th>
</tr>
</thead>
<tbody>
<tr>
<td>Optical losses and degradation</td>
<td>Visual inspection, I-V characteristics</td>
</tr>
<tr>
<td>Degradation of the electrical circuit</td>
<td>IR thermography, I-V characteristics, EL imaging</td>
</tr>
<tr>
<td>Mechanical degradation of the solar cells</td>
<td>EL imaging</td>
</tr>
<tr>
<td>Potential-induced degradation of the solar cells</td>
<td>EL imaging, I-V characteristics</td>
</tr>
</tbody>
</table>

2.1.1 Visual Inspection

Visual inspection is only suitable for detecting the factors causing optical losses and in addition to the degradation in the outer layer of the solar panel. Nevertheless, the visual inspection is inadequate in detecting electrical degradation or failures, but only in case these leaves a visual footprint on the module, for example, corrosion or burn marks.

Prior to the subjection of the PV module to environmental, electrical, and mechanical stress testing in the lab, visual inspection is conducted for these modules. The purpose of these inspections is to evaluate the module designs in the production module quality and its lifetime. Visual inspection is also performed after the installation of these modules.

In order to address the visual inspection of the solar module, it can be split into its parts, and each solar module part is inspected individually with the relevant defects. In IEC 61215 and 61646 standards [19, 20] a requirement of illumination in about more than one kilo-lux during the visual inspection and only defects detectable with the naked eye are considered. The failures conditions are recorded in IEC 61215 and 61646 standards also as shown in Table 2.2.
Table 2-2. Typical failures found during IEC 61215, 61646 visual inspection.

<table>
<thead>
<tr>
<th>PV module component</th>
<th>PV module failures</th>
</tr>
</thead>
<tbody>
<tr>
<td>Front of PV module</td>
<td>Bubbles, delamination, browning,</td>
</tr>
<tr>
<td>PV Cells</td>
<td>Broken cell, cracked cell, discolored anti reflection</td>
</tr>
<tr>
<td>Cell metallization / cell and</td>
<td>Burned, oxidized</td>
</tr>
<tr>
<td>Frame</td>
<td>Bend, broken, scratched, misaligned</td>
</tr>
<tr>
<td>Back of module</td>
<td>Delaminated, bubbles, yellowing, scratches, burn</td>
</tr>
<tr>
<td>Junction box</td>
<td>Loose, oxidation, corrosion</td>
</tr>
<tr>
<td>Wires – connectors</td>
<td>Detachment, brittle, exposed electrical parts</td>
</tr>
</tbody>
</table>

The visual inspections simplicity makes the likelihood of obtaining data very widely. The generation of inspection checklist is used for the evaluation of visual inspection in order to record the observable faults in the PV modules.

2.1.2 I-V Measurements

On the other hand using electrical indications is more helpful and assuring in the monitoring systems [23, 24] This characteristic of electrical methods offer valuable data in diagnosing a PV Cell’s health. Moreover, the analysis of the I-V curve is a primary tool to comprehend the defects in the PV plant. The effect of these defects can be observed in the output characteristics of the I-V measurements, such as Short circuit current (Isc), Open circuit voltage (Voc), Maximum power point current (Impp) and Maximum power point voltage (Vmpp).

A conventional system of the PV module I-V analysis contain a light source that can be natural or artificially simulated, a test bench, monitoring equipment, module temperature controller, and a data acquisition system to measure the current-voltage curve when the voltage across or the current through the module is changed with an external power supply or electric load.

Under simulated light irradiance conditions, a reference cell or reference module with matching or similar spectral response characteristics to the module under test is frequently employed as a reference solar device to measure the irradiance of the light source.

The test parameters (Isc, Voc, Pmax, temperature) can be interpreted into STC more precisely.
because the environment of measurement is much easier to control. The simulated light source (or sun simulator) is a steady state type or pulse type (flash type) simulator and are in line with the requisites and features of different PV technologies.

The pulse simulator can be further split-up into sole pulsed and multi pulsed light source. To modify different PV technologies distinct artificially simulated light sources can be employed. As an example, to conduct rigorous assessment for the module I-V characteristic, the high capacity PV modules need much longer pulse time or a stable state simulator.

Normally, light pulses for solar simulators’ interval range between 1ms to 20 ms with different profiles. But, the given time-period is too short for a proper characterization of some high-efficiency PV modules like heterojunction (HIT) or floating emitter cells (SUNPOWER cells). The cells of these PV modules exhibit a high charge carrier lifespan. Thus, a rather high diffusion capacity is observed which lead to longer test durations of 50 ms or more. The long-pulse or stable-state simulators would be more appropriate for these modules. Mau [25], Virtuani [26], and Herman [27] defined explicit procedures and necessities of high efficiency module I-V characteristics measurement. Besides, thin-film PV modules display number of metastable states, which make it challenging to describe a standardized PV module power for each technique. Some procedures to measure the PV module power of metastable thin-film modules are illustrated by Silverman [28].

2.1.3 Infrared Thermography

Infrared thermography has the ability to recognize electrical degradation which can't be identified by visual inspection. Also, it can recognize failures characterized by increased series resistance, disconnected or shunted cells, or any related issue to variations in temperature distribution of the solar module. IR thermography can be conducted on a single solar module or even a solar plant, which will provide fast inspection of a large number of solar modules at the same time, however, it requires mobile platforms and qualified staff [30, 35]. Although, studies are still ongoing on improving more advanced methods like using a thermal camera attached to a drone to perform a field inspection of PV systems [36].

The IR inspection of PV systems enables a fast identification of defects at the cell and module level in addition to the detection of possible electrical interconnection problems. The inspections are performed under regular operating states that system shut-down is not required. The thermal camera is essentially used for defects determination. The evaluation and classification of the anomalies detected in the solar module require a solid knowledge of the solar technology,
information of the inspected system, and further electrical analyses. In order to achieve correct and adequate thermal imaging measurements, specific requirements and procedures should be implemented, and solar irradiance is needed to be around 500 W/m² – 700 W/m², the angle of view falls between 5° and 60°, with prevention of shadowing and reflections.

Inspections by thermal imaging camera will assist to sustain the solar panels functionality and to increase their lifetime.

In summary the advantages of thermal imaging can be listed in four points:

- Fast (around one second)
- Capability to assess large areas (more than 100 square centimeters)
- Non Distractive Testing (Non Contact)
- Modest cost

Table 2-3. The list of defects in solar panels and how it appears in thermal image

<table>
<thead>
<tr>
<th>Error Type</th>
<th>Example</th>
<th>Appears in thermal images</th>
</tr>
</thead>
<tbody>
<tr>
<td>Manufacturing defect</td>
<td>Impurities and gas pockets</td>
<td>A ‘hot spot’ or ‘cold spot’</td>
</tr>
<tr>
<td></td>
<td>Cracks in cells</td>
<td>Cell heating, form mainly elongated</td>
</tr>
<tr>
<td>Damage</td>
<td>Cracks</td>
<td>Cell heating, form mainly elongated</td>
</tr>
<tr>
<td></td>
<td>Cracks in cells</td>
<td>A portion of a cell appears hotter</td>
</tr>
<tr>
<td>Temporary shadowing</td>
<td>Pollution</td>
<td>Hot spots</td>
</tr>
<tr>
<td></td>
<td>Bird droppings</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Humidity</td>
<td></td>
</tr>
<tr>
<td>Defective bypass diode</td>
<td>N.A.</td>
<td>A ‘patchwork pattern’</td>
</tr>
<tr>
<td>(causes short circuits and reduces circuit protection)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Faulty interconnections</td>
<td>Module or string of modules not connected</td>
<td>A module or a string of modules is consistently hotter</td>
</tr>
</tbody>
</table>
2.1.4 Electroluminescence Imaging

Electroluminescence imaging (EL imaging) is a suitable mean for identifying a large array of modules defects and failures, for example, cracks in the cell, disconnections in cell areas, damage in ribbons and fingers, increment in series resistance regions, Potential induced degradation (PID), shunted cells, corrosion, humidity, or cell malfunction due to manufacturing [9]. Furthermore, adding EL imaging with I-V curve measurements, and visual inspection, can include many important failures and degradation modes influencing PV systems, and can be a very efficient and comprehensive demonstrative method. Such a diagnostic procedure was examined in research [13], for identifying the main failure modes affecting a 15-year-old PV system. Nevertheless, that study's approach does not comply with a wide scale of applications and it can be time-consuming.

Furthermore, in contrast to I-V analysis and IR thermography, EL imaging applications is more limited, demanding a complicated hardware and diagnostic process [31], reducing the application frequency of this technique in the field. Although broad adoption of EL imaging as a PV module diagnostic tool in PV research institutes and laboratories, it's often utilized as a qualitative diagnostic approach, missing failure quantification techniques and standardized measurement procedures. EL imaging of PV modules has been developed and discussed in (IEC TS 60904-13) [32], where some of these problems were described.

Nonetheless, EL imaging has a high potential for machine analysis, in distinguishing and quantifying degradation and defects in solar modules, two published studies [33,34] discussed the automatic detection of manufacturing defects in silicon wafers and cells. In relation to that, further research is required for developing methods of quantifying the extent of degradation and defects distributed inside a solar module, defects like cracks in solar cells, disconnection in cell areas, shunted cell areas, increased series resistance areas, a mismatch in cell voltage, etc. Such approaches would allow to assess and analyze a number of failures within a solar module whether its during module transportation or a field operation, failures like the those previously mentioned that may not have a significant influence on the module performance.
2.2 Thermal imaging applications

As it has been mentioned before, IR thermography is a non-destructive technique for temperature measurement that presents images of a particular temperature pattern using the IR radiation. By this method, the interpretation of these thermal images will provide valuable information in relation to the temperature of the surface, whereas additional image processing techniques can show potential anomalies to the thermal indication of the inspected equipment. These data, along with the understanding of the equipment's physical composition, are adopted to estimate the level of degradation.

The techniques for the thermal imaging processing and its applications in general have recorded an interesting field of research through the related literature.

If thermal images cannot give satisfactory information about the condition of the inspected objects, preprocessing and processing of IR images are proposed. [43–45] Common preprocessing procedures produce noise, so median or Gaussian filtering was recommended to smooth the noise. One research study [43] addressed the non-uniform heating, as well as smoothing operators; produce undesired effects during high-pass filtering and Sobel operators. Simple subtraction techniques, such as spatial and temporal reference techniques can enable the elimination of the unwanted effects. The same study has described many procedures for the improvement of the subtle thermal signatures. Thermal signatures include:

(i) thermal contrast computation,
(ii) Normalization,
(iii) Pulsed phase thermography (PPT),
(iv) Principal component thermography,
(v) First and second derivatives,
(vi) Quantitative processing; defect detection algorithms and thresholding
(vii) Statistical behavior of regions of interest (ROIs).

A research study by Vergura et al. [44] implies that median and Gaussian filters and edge detection can be applied to IR images with insufficient information about the health of PV modules. But another research by Kozikowski et al. [45] suggested methods based on discrete and continuous wavelet transforms improve the ability to determine the health of PV modules. For the detection of thermal non-uniformities in the layered examined objects, space-scale representation of thermal image was used.
In Abdel-Qader et al. [46] study clarified how to automate the findings of subsurface flaws in actual bridge decks using IR thermography. The algorithm, established by the authors in this sphere, was grounded on the region growing method, of which parts were of the image into defective and good regions employing a comprehensive method of adaptive thresholding and fully automated seed selection. Normally, during similar study, the assimilated raw IR images were processed in advance using a 3x3 Gaussian filter, in order to even out remote bright pixels, thus avoiding false seeds. Another interesting method is initiated in [47], where Chou et al. suggested a system known as Infrared Thermography Anomaly Detection Algorithm, the implementation of which was built on the perspective of Otsu's statistical threshold selection algorithm [48] using gray-level histograms.

Thermal image processing is also broadly stated in medical applications. For example, in [50–52], methods such as filtering, data density, false-color contrast enhancement, histograms and ROI analysis are normally employed for advanced processing. Furthermore, feature calculations based on first- and second-order statistical parameters, principal component analysis, linear discriminant analysis, neural networks (NNs), nearest neighbor classification as well as nearest neighbor algorithms and edge detection are effectively used in more advanced approaches for passive thermography. Specifically, for recognizing the edge, Scales et al. [49] recommend a method of a sequence of Canny edge detectors, given the robustness to noise and their equal treatment of both false positives and negatives. For active dynamic thermography, transform methods are extensively used, i.e. fast Fourier or wavelet ones. Last but not least, in line with Wiecek [51], multispectral analysis is being attracted for further scientific study on processing sequences of thermal images.
2.3 Application of thermal imaging in solar panels

2.3.1 Panel Recognition

Thermal image processing techniques have a remarkable field of study worldwide, its application to solar panels is very expedient, but even though only one study has been established very recently in relation to the recognition of solar panels. Xiang Gao et al. (2015) in [4] developed an algorithm for solar panel recognition, based on Hough Transform (HT) to detect the lines, and filtering the horizontal and vertical lines, with identifying the point of lines intersection, a representation of one corner of a panel is determined, and with four corners connection, the borders of a panel are defined. The results showed some recognition missing in the top row of the solar string; also the first column couldn’t be recognized. Furthermore, the panel recognition will be missed as well if the installation of these panels didn’t from a straight line and with good alignment.

2.3.2 Defect Detection

On the other hand, there are a lot of written works reflecting the growing interest in IR thermography applications and their potential to detect and diagnose the faults of PV module. The mainstream of the reported techniques has a common, and well-established approaches and algorithms, the efficiency of these studies have been shown through the last decades.

In the early stage of these studies, Buerhop et al. (2007) first discussed the feasibility of applying IR thermography imaging to PV modules for outdoor settings [5].

Regarding the measurement precision of PV modules using IR thermography, Krenzinger et al. [6] (2007) and Makrides et al. [7] (2009) were two early-published studies that dealt with the errors of infrared reflection of the glass surface. Furthermore, Buerhop et al. [10] (2011) introduced a procedure for correcting the measurement of IR emissivity of the glass cover, in the spectral range of the used thermal cameras, suggesting a needed offset of the temperatures to correct the reflection effects.

The prominence of additional analysis of the thermal images with focusing on more specific approach of heat development and abnormalities in PV modules was introduced by Acciani et al. and Botsaris et al. (2010) in [8,9], the IR thermography addressing of hot spots and other early challenges for fault detection was conducted, showing an effective detection of hot spots associated with singular faulty cells or group of cells that is known as Regions Of Interest (ROI) was implemented by IR thermography computations and image interpretation assigned to hot spot areas. The resultant rise of the operating temperatures was calculated at a good speed and adequate
accuracy.

Florin Ancuta et al. (2011) demonstrated the solar panels failure analysis and hot spot detection by thermal imaging. This study has shown the efficiency of the thermal analysis to detect the anomalies in the PV plants manually through observation of the thermal image, some of the observations indicated that the increase in temperature might occur when shunts are created by dust and other kinds of structural / materials defects. [11].

John A. Tsanakas et al. (2013) presented a methodology that combines image segmentation and Canny edge detection maps, that approach successfully detected 40 hot spots out of 43 during an inspection of two PV strings in a solar plant using IR thermography. Nonetheless, it also presents limited defect ability of classification and false alarms, in some occasions of unrelated background information [12].

E. Suresh Kumar et al. (2014) focused on identification of cell parameters for a comprehensive specification of the electrical and thermal operational performance and provided a table of error/defects based upon its appearance in the thermal image, in addition to suggesting a simple method to identify the worst hot spot within solar module for safety testing [13].

Anwar et al. (2014) projected an algorithm for the detection of micro-crack defects in the multicrystalline solar cells that merged an improved anisotropic diffusion filter and an advanced image segmentation technique [15]. Researchers have also borrowed concepts from texture analysis to investigate the defect detection problem. Independent component analysis (ICA) with learning and detection stages has been used to detect defects in electroluminescence images [14]. In this technique, basic images are first chosen from normal solar cells, and the test image is reconstructed by the linear combination of the basis images. The reconstruction error between the test image and its reconstructed image is then used as a discrimination measurement. It can achieve a mean recognition rate of 93.4% for a set of 80 test samples.

Xiang Gao et al. [4], (2015) proposed a system based on DBSCAN clustering which depends on the mean temperature readings of all panels within the same row. If more than one cluster is created, the panels belonging to the cluster(s) with the higher temperature are classified as hot modules. The results showed 28 hot spots were detected out of 38, in addition to 7 miss and 21 false alarms, giving a detection rate of 80%.
Chapter 3 : Proposed System and Methodology

The IR thermal image contains the solar panels and other background information and since the detection of defects and faults mostly based on the heat radiated from the solar cells, other hot objects might be detected in the background as well such as electrical cables, switches, humans and animals, or any other object that emit heat and the algorithm will classify them hot objects, therefore, it is very essential to the success of this proposed system is to separate the solar panel information from background information.

We selected Canny method since it is optimal edge detector, however, noise reduction and smoothing are also needed as pre-processing steps. This can be achieved by using the Kernel of Gaussian filter, which is given by:

\[
G_{\sigma} = \frac{1}{\sqrt{2\pi \sigma^2}} \cdot \exp \left[ -\frac{x^2 + y^2}{2\sigma^2} \right].
\]  

(3.1)

Where \( x \) is the distance from the origin in the horizontal axis, \( y \) is the distance from the origin in the vertical axis and \( \sigma \) is the Gaussian distribution standard deviation.

While the second step is to compute the two-dimensional image gradient in order to estimate the strength of the edges (Absolute Gradient Magnitude) at every pixel. The gradient approximation in the \( x \)- and \( y \)- directions is found by 3 x 3 Sobel convolution masks, by using the two kernels as shown in next page in equation (3.2):
The phase and magnitude (edge strength) of the gradient have been calculated by the following two equations respectively:

\[
\Theta (x, y) = \tan^{-1} \left[ \frac{g_y (x, y)}{g_x (x, y)} \right] 
\] (3.3)

\[
M (x, y) = \sqrt{g_x^2 (x, y) + g_y^2 (x, y)} 
\] (3.4)

Where \( g_x \) and \( g_y \) represent the gradient in the x- and y- directions respectively.

Next is the suppression of low-frequency information and detect the peak data only, which will transform the blurred edges into a sharper one, a process called non-maximum suppression process has been used for this purpose that will set the pixel to zero if they are not part of the local maxima after a comparison of each pixel with its neighbours in edge strength.
The main steps of Canny edge detection can be seen in figure 3.1 block diagram.

Figure 3-1. Proposed system for detection of panel edges using thermal images

Hough Transform (HT) was implemented in the second stage of the proposed method to detect the lines in the image to allow for recognition of the lines separating between the panels. The lines can be represented by two parameters, a and b as in equation (3.5), which represent the linear transform for detecting straight lines in its simplest demonstration.

\[ y = m \cdot x + b \]  

(3.5)

In the image space, the linear transform for detecting stright lines can be graphically plotted for each pair of image points (x,y). In the Hough transform, a main idea is to consider the characteristics of the straight line not as image points x or y, but in terms of its parameters, here the slope parameter m and the intercept parameter b. For example, Figure 3.2 shows 5 points on a 10x5 bitmap. Given this bitmap, we can define points A(1,1), B(3,2), C(5,3), D(7,4) and E(9,5). Point A can have a family of lines passing through it, and this can be expressed by equation (3.5), when we apply the values of A(1,1) to x and y, then a and b become parameters for the family of lines passing through A. Given this characterization of a line, we can then iterate through any number of lines that pass through a given point.
We incorporate the results in an Accumulator Array. At the beginning, the Accumulator Array is initialized to zero for all cells. After that, for every value of \( a \) with a corresponding value of \( b \), the value of that cell is incremented by one. If you draw all possible lines that pass through point A, some of these will also pass through points B, C, D and E. Similarly, some of the lines that pass through point B will also pass through points A, C, D and E. Cells are incremented in the accumulator array when lines pass through multiple points. At the end of the accumulation process, the cell that has the highest value represents the line that passes through the most number of points in the source image array. However, this method has its drawbacks. If the line is horizontal, then \( a \) is 0, and if the line is vertical, then \( a \) is infinite. So, a more general representation of a line will be represented by polar form in equation (6).

\[
\rho = xi \cos (\theta) + yi \sin(\theta) \tag{3.6}
\]

Where \( \rho \) is the distance from the origin to the nearest point on the straight line, and \( \theta \) (\textit{theta}) is the angle between the x-axis and the line connecting the origin with that nearest point. \( \theta \in [-90, 90] \), \( \rho \in \pm n\sqrt{2} \) if the image is of size \( n \times n \).

So for Hough Transforms, we will express lines in the Polar system. Hence, a line equation can be written in (3.7).
Some images which have different lines combinations (horizontal and vertical lines) have been processed through Canny edge detecting and Hough transform to analyze the output, which can be seen in figure 3.4.
Figure 3-4. Results of processing three different images (1(a), 2(a) & 3(a)) which represent different composition of horizontal and vertical lines where (a) shows the input image of a line, (b) shows the canny edge detection of the input image and (c) shows the Hough Transform of the image.

The next stage is finding the local maxima of HT, $C(\rho, \theta)$ i.e. accumulator array, is the number of edge points satisfying the equation $\rho = x \cos \theta + y \sin \theta$, peaks of the HT we extract all points satisfying $C(\rho, \theta) \geq TC$.

TC is set to 0.3 of the maximam Hough transform found in the accumulator array for optimum results. Check figure 3.5 for the detected hough peaks (1,2 & 3) which corresponds to figure 3.4 (1(c), 2(c) & 3(c)).
Figure 3-5. Results of processing three different images (1, 2 & 3) which represent different composition of horizontal and vertical lines where (a) shows the input image of a line, (b) shows the canny edge detection of the input image and (c) shows the Hough Transform of the image.

In order to recognize a panel in a solar garden, first we need to identify its lines and intersection points of a shape like rectangle. The representation of a rectangle centered at the origin of the coordinate system with vertices of: P1=(x1,y1), P2=(x2,y2), P3=(x3,y3), P4=(x4,y4), P1P2 // P3P4 = length a, P1P4 // P2P3 = length b can be seen in figure 3.6. The corresponding Hough peaks can be found at H1 at (ρ1,θ1) ≡ P2P3, H2 at (ρ2,θ2) ≡ P1P4, H3 (ρ3,θ3) ≡ P3P4 and H4 at (ρ4,θ4) ≡ P1P2, as it seen in figure 3.7.

Figure 3-6. Representation of a rectangle centered at origin of the coordinate system
Figure 3-7. Hough peaks of $H_1 \triangleq P_2P_3$, $H_2 \triangleq P_1P_4$, $H_3 \triangleq P_3P_4$ and $H_4 \triangleq P_1P_2$

For the analysis purposes, an image sample of a parallelogram shape has been used to check the output of the hough transform since the shape of the solar panel is similar to the sample shape. The results can be seen in figure 3.8.

Hough lines has been used with Converts hough lines to hough finite lines. In this study, the
minimum length of a line was set to 40 pixels, and the algorithm was allowed to connect lines through holes of up to 100 pixels. Illustration image can be seen in figure 3.9.

![Illustration image](image)

Figure 3-9. Detected hough lines of an image

Next we use the general line equation $y = m.x + b$ to find the slope, y-intercept ($b$) and x-intercept($x$) of each horizontal and vertical line by:

$$m = \frac{y_2-y_1}{x_2-x_1} \quad (3.8)$$

$$b = y - m \cdot x \quad (3.9)$$

$$x = \frac{-b}{m} \quad (3.10)$$

where $m$ is the slope of the line, $b$ is the y-intercept of the line and $x$ is the x-intercept of the line.

The next step is calculating the intersection point of two lines (vertical to horizontal), this can be achieved when the two lines intercept in a point where $P(x,y)$ is the same in the vertical line and horizontal line, which is going to where:

$$b_{(\text{horizontal})} = y - m_{(\text{horizontal})} \cdot x = b_{(\text{vertical})} = y - m_{(\text{vertical})} \cdot x \quad (3.11)$$

$$x = \frac{b_{(\text{horizontal})} - b_{(\text{vertical})}}{m_{(\text{vertical})} - m_{(\text{horizontal})}} \quad (3.12)$$
\[ y = m_{\text{horizontal}} \cdot x + b_{\text{horizontal}} = m_{\text{vertical}} \cdot x + b_{\text{vertical}} \] (3.13)

After finding the intersection points of the panels, we will get the maximum and minimum coordinates of 4 intersections which will detect the panel, but first we find the distance of each panel line, in order to calculate the area of the panel as in equation (3.14) and (3.15), and as a result the panels which has an area not big enough to be detected as a panel will be rejected.

\[ \text{Dist} = \sqrt{(x_2-x_1)^2 + (y_2-y_1)^2} \] (3.14)

\[ \text{Area} = \text{Dist}_{\text{horizontal}} \cdot \text{Dist}_{\text{vertical}} \] (3.15)

Rotation matrix has been used in order to rotate the panel back to zero degree, theta can be calculate by equation (3.16), the rotation matrix equation can be seen in (3.17) and the rotation points can be calculated by equation (3.18)

\[ \Theta = -\tan(m_{\text{horizontal}}) \] (3.16)

\[ R = \begin{bmatrix} \cos(\Theta) & -\sin(\Theta) \\ \sin(\Theta) & \cos(\Theta) \end{bmatrix} \] (3.17)

\[ \begin{bmatrix} X_r \\ Y_r \end{bmatrix} = \begin{bmatrix} \cos(\Theta) & -\sin(\Theta) \\ \sin(\Theta) & \cos(\Theta) \end{bmatrix} \begin{bmatrix} x \\ y \end{bmatrix} \] (3.18)

\[ X_r = x \cos(\Theta) - y \sin(\Theta) \] (3.19)

\[ Y_r = x \sin(\Theta) + y \cos(\Theta) \] (3.20)
After the detection of the panels, pixel shifting techniques were used to re-shape that panel into a rectangular shape. Figure 3.10 illustrates the different panel shapes input and output.

<table>
<thead>
<tr>
<th>Input panel shape</th>
<th>Output panel shape</th>
</tr>
</thead>
</table>

Figure 3-10. The reshaping of the panel images

We follow as shown in figure 3.11 the two approaches that were implemented for the purpose of defect and fault detection. First one Absolute thermal contract has been applied, where each detected solar panel temperature would be subtracted from a reference image temperature (healthy module) that was previously taken or even taken at the same time. Thermal contrast-based techniques are probably the most common way of processing thermo graphic data. Various thermal
contrast definitions exist [16]; most of them share the need of a sound area $S_a$, i.e. a non-defective region within the field of view.

The absolute thermal contrast can be defined below in equation (3.21):

$$\Delta T(t) = T_{d}(t) - T_{S_a}(t)$$

(3.21)

Where: $T(t)$: temperature at time $t$.

$T_d(t)$: temperature of a pixel $p$ (defective or not).

$T_{S_a}(t)$: temperature at time $t$ for the $S_a$.

$S_a$: Sound area (reference image).

No defect can be detected at particular $t$ if the absolute thermal contrast = 0.

But in order to use the absolute thermal contrast techniques, both images of the panels (the reference panel image and the inspected panel image) should be matched in dimensions, therefore image resize techniques were implemented to change the dimensions of the recognized inspected panels to match the size of the reference panel dimensions. Knowing the selection of the reference panel is accomplished manually by the user after loading the reference solar panels string. Then a comparison of temperature between the reference solar panel and the inspected solar panel will be commenced, and if there was no difference between both images of the panels then no defect will be detected, on the other hand, in case a difference was found between the previously mentioned images then defects will be detected. Furthermore, the resultant image of subtraction will go through thresholding techniques and conversion to binary for defect detection, also will go through labeling and clustering techniques has been used to emphasize the defect contrast for the purpose of visualizing the labeled regions and then counting the number of the detected defects found in each panel.

The second approach process the detected solar module directly without the need of the reference image or resizing the image, but instead it will be processed by intensity thresholding algorithm since the defect would emit more heat that the other cells which mean higher intensity. In this thresholding technique, a greyscale image is turned into a binary image (black and white or zero and one) by first choosing a grey level (threshold) $G_{L_{th}}$ in the original image, and then turning every pixel black or white according to whether its grey value is greater or less than $G_{L_{th}}$. In single thresholding, a pixel becomes:
- White “logical 1”, if its grey level is \( > \) GLth.
- Black “logical 0”, if its grey level is \( \leq \) GLth.

In this approach, thresholding was selected for a primary segmentation of the obtained thermal images, due to its intuitive and simple implementation. The output images from a single thresholding process that was provided in Matlab R2015a environment, with a threshold \( GLth = 225 \). The latter was selected, after several trials, as the optimum threshold value that accomplishes a fair separation of unwanted regions in the majority of the tested thermal images, without cutting out any ROI. The resultant images from this stage provide a valuable sum of binary data, overly clear from possible erroneous variations. These data, in the form of images with hot-spot-related ROI.

Other thresholding measurement was applied and discussed, by using a reference healthy image of the panel, we measure the maximum intensity level of the gray scale which can be used a thresholding for the inspected panel.

\[
TH = \text{Max intensity of healthy panel} \quad (22)
\]

Finally, shape recognition techniques were used to help to identify the defects, such as hot spots, cracks, dents, bird drops, and others based on the shape of the defect. The complete proposed method block diagram is illustrated below:
Figure 3-11. Proposed method flow chart
Chapter 4: Experimental Results and Discussion

4.1 Experimental Results

After applying the proposed method algorithms to thermal images taken from different solar power plants in a string, the algorithm has proven to efficiently detect the solar module and extract it from the thermal image, figure 4.1. Figure 4.2 shows the results of the panel detection.

Figure 4-1. Results of panel recognition using canny edge detection threshold of 0.2 and Gaussian filter standard deviation of 2. While Hough transform fill gap between lines is 20 pixels and minimum length of line 100.
Figure 4-2. Results of panel recognition using canny edge detection threshold of 0.2 and Gaussian filter standard deviation of 2. While Hough transform fill gap between lines is 20 pixels and minimum length of line 100.

Figure 4-3. Results of panel recognition using canny edge detection threshold of 0.2 and Gaussian filter standard deviation of 2. While Hough transform fill gap between lines is 20 pixels and minimum length of line 100.
Figure 4-4. Results of panel recognition using canny edge detection threshold of 0.2 and Gaussian filter standard deviation of 2 While Hough transform fill gab between lines is 20 pixels and minimum length of line 100.

Figure 4-5. Results of panel recognition using canny edge detection threshold of default (0.1) and Gaussian filter standard deviation of default (1.4) While Hough transform fill gab between lines is 20 pixels and minimum length of line 100.
Figure 4-6. Results of panel recognition using canny edge detection threshold of default (0.1) and Gaussian filter standard deviation of default (1.4) While Hough transform fill gab between lines is 20 pixels and minimum length of line 100.

The user using Matlab software, in this example, will enter reference panel selection manually; panel number one was selected to be the reference panel

Now, for the purpose of detecting the defect and faults in the PV module, three different algorithms were used (Absolute Thermal Contrast, Intensity Thresholding and Canny edge detection) on different panels. The thermal image has been taken as in figure 4.7, 4.8, 4.9, 4.10, which shows the detected defects of hot spots in the solar panels using canny edge detection and morphological operations (dilate, clear border and majority/bridge morphological).
Figure 4-7. Defect and fault detection using canny edge detection, total defects found is 2

Figure 4-8. Defect and fault detection using canny edge detection, total defects found is 3
Figure 4-9. Defect and fault detection using canny edge detection, total defects found is 4

Figure 4-10. Defect and fault detection using canny edge detection, total defects found is 4

A comparison between the healthy panel and the defective one has been made, with showing the histogram of each panel as it shown in table 4.1. The histogram indicates and shows the
defective panel has a higher gray scale values than the healthy one, the maximum recorded value in the healthy histogram is 225 while the maximum recorded value for the defective histogram is about 240 for the solar panel in figure 4.11, while table 4.2 shows the histogram for figure 4.12.

Table 4-1. Shows a comparison between healthy and defective panel in terms of intensity and histogram for figure 4.11. The defective panel histogram shows higher value in the gray scale than the healthy panel.
Figure 4-11. Defect and Fault detection: (a) original thermal image of a defective panel  (b) gray scale image of the original image, (c) intensity thresholding, clustering and labeling on the logical image, (d) defect and fault detection of 4 hot spots as counted.
Table 4-2. Shows a comparison between healthy and defective panel in terms of intensity and histogram for figure 4.12. The defective panel histogram shows higher value in the gray scale than the healthy panel.

<table>
<thead>
<tr>
<th></th>
<th>Defective Panel</th>
<th>Healthy Panel</th>
</tr>
</thead>
<tbody>
<tr>
<td>RGB Image</td>
<td><img src="image1" alt="Defective Panel Image" /></td>
<td><img src="image2" alt="Healthy Panel Image" /></td>
</tr>
<tr>
<td>Histogram</td>
<td><img src="image3" alt="Defective Panel Histogram" /></td>
<td><img src="image4" alt="Healthy Panel Histogram" /></td>
</tr>
</tbody>
</table>
The last fault defect detection technique used was the absolute thermal contrast combined with the panel recognition and reshaping, the results can be seen in figures 4.13, 4.14, 4.15, 4.16 and 4.17.

Figure 4-12. Results of absolute thermal contrast detecting 2 defects after selecting panel 1 as healthy

Figure 4-13. Results of absolute thermal contrast detecting 3 defects after selecting panel 2 as healthy
Figure 4-14. Results of absolute thermal contrast detecting 1 defect after selecting panel 1 as healthy

Figure 4-15. Results of absolute thermal contrast detecting 2 defects in two different panel (#8 and #9) after selecting panel 5 as healthy
Figure 4-16. Results of absolute thermal contrast detecting no defects after selecting panel 6 as healthy
Results summary of the three different algorithms can be found in table 4.3, 4.4 and 4.5

Table 4.3. The results summary of Intensity Thresholding to detect defects

<table>
<thead>
<tr>
<th>Image</th>
<th># of Defects</th>
<th>Defects Found</th>
<th>Defects Missed</th>
<th>False Alarm</th>
</tr>
</thead>
<tbody>
<tr>
<td>Image #1</td>
<td>2</td>
<td>2</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>Image #2</td>
<td>3</td>
<td>3</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>Image #3</td>
<td>3</td>
<td>2</td>
<td>1</td>
<td>0</td>
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<td>Image #4</td>
<td>4</td>
<td>3</td>
<td>1</td>
<td>0</td>
</tr>
<tr>
<td>Image #5</td>
<td>1</td>
<td>1</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>Total</td>
<td>13</td>
<td>11</td>
<td>2</td>
<td>0</td>
</tr>
</tbody>
</table>

Table 4.4. The results summary of Canny edge detection to detect defects

<table>
<thead>
<tr>
<th>Image</th>
<th># of Defects</th>
<th>Defects Found</th>
<th>Defects Missed</th>
<th>False Alarm</th>
</tr>
</thead>
<tbody>
<tr>
<td>Image #1</td>
<td>2</td>
<td>2</td>
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<td>0</td>
</tr>
<tr>
<td>Image #2</td>
<td>3</td>
<td>3</td>
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<td>0</td>
</tr>
<tr>
<td>Image #3</td>
<td>3</td>
<td>4</td>
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</tr>
<tr>
<td>Image #4</td>
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<tr>
<td>Image #5</td>
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<td>0</td>
<td>0</td>
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<tr>
<td>Total</td>
<td>13</td>
<td>14</td>
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</tbody>
</table>

Table 4.5. The results summary of Absolute Thermal Contrast to detect defects along with panel recognition

<table>
<thead>
<tr>
<th>Image</th>
<th># of Panels</th>
<th>Panels Detected</th>
<th># of Defects</th>
<th>Defects Found</th>
<th>Defects Missed</th>
<th>False Alarm</th>
</tr>
</thead>
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<td>0</td>
<td>0</td>
<td>0</td>
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<tr>
<td>Garden #2</td>
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<td>6</td>
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<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>Garden #3</td>
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<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>Garden #4</td>
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<td>1</td>
<td>1</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>Garden #5</td>
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<td>9</td>
<td>3</td>
<td>2</td>
<td>1</td>
<td>0</td>
</tr>
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<td>2</td>
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<td>2</td>
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<tr>
<td>Project #2</td>
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<td>0</td>
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<tr>
<td>Total</td>
<td>33</td>
<td>33</td>
<td>9</td>
<td>8</td>
<td>1</td>
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</tbody>
</table>
Chapter 5 : Discussion & Conclusion

5.1 Study Limitation

Even though the proposed algorithm results have shown good ability to detect the panels and defects in the solar panels but its still can’t detect solar panels of two different strings. Also if the thermal contrast is not high like in dark night or in winter or even if the thermal camera couldn’t take a clear image of the lines the separate the panels then lines of the panels can’t be recognized. Check figure 5.1, figure 5.2 and figure 5.3.

![Figure 5-1. Algorithm inability to detect panels of two strings](Image)
Figure 5-2. Hough Lines can’t be recognized in cold winter

Figure 5-3. Not clear lines taken from the thermal camera which led to miss the Hough lines detection
5.2 Future Work

This study has been conducted after the images have been taken from thermal camera and then read it and process it in an offline processing/batch processing, more work can be done to make this approach process the information on real time.

In addition to add the ability to process a video instead of single images.
5.3 Conclusion

The growth of solar power systems has recorded an exponential increase during the past years, which indicates the world is starting to depend on solar energy even more. But with that growth, the number of defects and faults in these modules have been increased as well, and as a results, the reliability and overall system performance of the PV modules began to have a noticeable attention in order to maintain the efficiency as maximum as achievable.

In this study, an IR thermography-based system is proposed to recognize the PV panels and detect any potential faults and was experimentally evaluated and tested. For the purpose of PV panel recognition, field IR images were taken from PV strings of a solar garden which were installed in Parkview Engineering campus of Western Michigan University. In particular, the main goal was to investigate the applicability and appropriateness of standard thermal image processing, edge detection, and Hough Transform to recognize the PV modules.

Panel recognition based on Canny and HT is useful to eliminate the background information, which will help in detecting the defects in addition to counting the panels.

Panels in low resolution camera (336x256) were detected in high speed but it needed to use specific thresholding and sigma in canny edge detection (generally 0.2,2), but in other hand in high resolution camera (640 × 512) the panels were detected easily with the default threshold but compromising the speed.

The use of Absolute thermal contrast along with panel recognition solved the problem of panel reflection, connection socket which appears as hot spot in the thermal image while its not a defect.
Intensity thresholding technique misses some defects i.e less sensitivity, more precision while canny edge detection tend to give false alarm, i.e more sensitivity, less precision.

For defect detection, thermal images were taken from two PV arrays installed on the mobile cart. IR thermography has proven to be a convenient way to detect faults and defect even the ones in their early stage of development, fault localization in real time and issue and alert to take necessary precautions to prevent additional damage. Not mentioning it’s an appropriate technique to measure temperature difference, performance factor and solar parameters.

More improvement can be implemented to this study in relation to the defect detection, shape recognition can be used to detect the defect, and then identify the type of the defect. Also the software can be developed to recognize the panel and detect the defects on real time. In addition to adding the ability or processing videos instead of images.
Chapter 6 : References

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