DESIGN AND DEVELOPMENT OF AUTONOMOUS MANIPULATOR FOR SOLAR PHOTOVOLTAIC CLEANING

By

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THESIS COMPLETION CERTIFICATE

This is to certify that the thesis on **"Design and Development of Autonomous Manipulator for Solar Photovoltaic Cleaning"** by **Amit Kumar Mondal** in Partial completion of the requirements for the award of the Degree of Doctor of Philosophy (Engineering) is an original work carried out by him under our joint supervision and guidance.

It is certified that the work has not been submitted anywhere else for the award of any other diploma or degree of this or any other University.

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Amit Kumar Mondal
University of Petroleum and Energy Studies
July 2015

DEDICATED
TO

MY PARENTS
&
ALMIGHTY

DECLARATION

I do hereby declare that this submission is my own work and that, to the best of my knowledge and belief, it contains no material previously published or written by another person nor material which has been accepted for the award of any other degree or diploma of the university or other institute of higher learning, except where due acknowledgment has been made in the text.

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EXECUTIVE SUMMARY

The global energy needs have increased significantly in the past several decades and are predicted to rise more than 50% by 2030. At present the energy needs are met mostly from the conventional sources of energy like coal, gas and oil, which are exploited in an unsuitable manner resulting in exhausting global reserves of fossil fuels in the near future. With growing cost of electricity and concern for the environmental impact of fossil fuels, implementation of eco-friendly energy sources like solar power are rising. Electricity generation using PV technology is increasing rapidly throughout the world during the past decade. The prime method for harnessing solar energy is with arrays made up of photovoltaic (PV) panels. Accumulation of dust and debris on a single panel in an array diminishes their efficiency in energy generation considerably and give emphasis to the need to keep the panels surface as clean as possible. Current labor-based cleaning procedures for photovoltaic arrays are expensive in energy usage, water, time and lack automation capabilities. Existing efficiency of Mono crystalline module is 14-16%. After moderate amount of dust deposition, efficiency decreases by 69-97%.

The chief limiting factors which reduce extensive use of PV applications includes the relatively low conversion efficiency of PV cells due to heating of PV panels and the high initial investment cost. Module temperature is always higher than the ambient temperature. Higher temperature of the module is because of the glass cover over it, which traps the infrared radiation. Overall, power output and efficiency of the PV cells decrease with the increase in its operating temperature. Dust collection on PV panel surface also reduces its efficiency, and the output power of the PV module strongly depends upon the solar irradiation falling on it. The power output of a module increases linearly with the increase in the incident solar radiation. Accumulation of dust and debris on even one panel in an array reduces their efficiency in energy generation considerably and emphasizes the need to keep the panel surface as clean as possible. Due to humidity, when light hits water droplets, it may be refracted, reflected or diffracted, which affects the reception levels. High content of water vapour in the air causes encapsulation. Because of the water content of the humidity, failure at cell interconnections or cracked cells happens in crystalline silicon cells, and failure at scribe lines is the dominant cause of cell thin film modules degradation. The impact of sedimentation (i.e. dust and dirt particles) on exposed surfaces of SPV panels. Dust prevents the incident light in reaching to the SPV, causing reduced

power output and efficiency. Dust accumulation occurs at different rates in different parts of the world; also, it depends upon the panel orientation, direction of wind, and nature of dust: dust composition, size distribution, deposition density. Apart from the above natural factors, even the manufacturing technology also plays a role, as different type of PV technologies having different amount of efficiencies. Orientation and tilt angle of the PV module plays an important role for the efficiency of SPV as performance of SPV module depends on the amount of solar radiation received by a PV module which in turn depends on the orientation and tilt angle. Orientation of modules is generally north in southern hemisphere and south in northern hemisphere. Tilt angle is site dependent and has to be optimized to maximize the incident solar radiation on the PV module surface.

There are several existing methods available in industrial grade and is been used in real time. Existing solutions are also dependent on: Geographical terrain and area of application. Depending on the above factors, existing solutions can be further compared on the basis of cost, ease of use, performance rate, etc. The existing solutions are not universally applicable for all situations. In this research solar panel cleaning robotic arm that can clean SPV panels has been developed. It is an ergonomically designed system with traits like anti-interloped design, automated grid cleaning mechanism, efficient algorithm, all weather cleaning support, plug-n-play strategy and economical establishment costs.

CHAPTER- 1
INTRODUCTION

The global energy needs have increased significantly in the past several decades and are predicted to rise more than 50% by 2030 [1]. At present the energy needs are met mostly from the conventional sources of energy like coal, gas and oil, which are exploited in an unsuitable manner resulting in exhausting global reserves of fossil fuels in the near future. With growing cost of electricity and concern for the environmental impact of fossil fuels, implementation of eco-friendly energy sources like solar power are rising. Electricity generation using PV technology is increasing rapidly throughout the world during the past decade. The prime method for harnessing solar energy is with arrays made up of photovoltaic (PV) panels. Accumulation of dust and debris on a single panel in an array diminishes their efficiency in energy generation considerably and give emphasis to the need to keep the panels surface as clean as possible. Current labor-based cleaning procedures for photovoltaic arrays are expensive in energy usage, water, time and lack automation capabilities. Existing efficiency of Mono crystalline module is 14-16%. After moderate amount of dust deposition, efficiency decreases by 69-97% [2].

Robotics is a modern technology which has become a vital technology in automation industry of the present world. Robots perform flexible but restricted number of actions. These systems generally contain a programmable chip (micro controller or microprocessor) that controls the actions of the robot. Robotics is an interdisciplinary field that combine various subjects like control system, electronics and electrical, mechanical, computer science engineering. Mechanical engineering contributes for the study of kinematics and dynamics of the robot, Control theory deals with the control flow of the system, electronics and electrical technology plays a vital role in system voltage and sensor related issues and programming of the robot is taken care by computer science engineering for desired task.

1.1 DEFINITION OF A ROBOT

"A re-programmable, multifunctional mechanical manipulator designed to move material, parts, tools, or specialized devices through various programmed motions for the performance of a variety of tasks." (*Robot Institute of America, 1979).*

1.2 ROBOT NOMENCLATURE

1.2.1 Link

The individual rigid bodies that are joined together to form a robot.

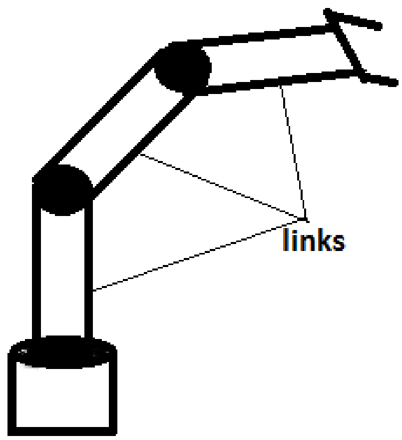


Fig. 1.1: Rigid bodies joints to form a link

1.2.2 Workspace

The surrounding space upto which the robot can reach.

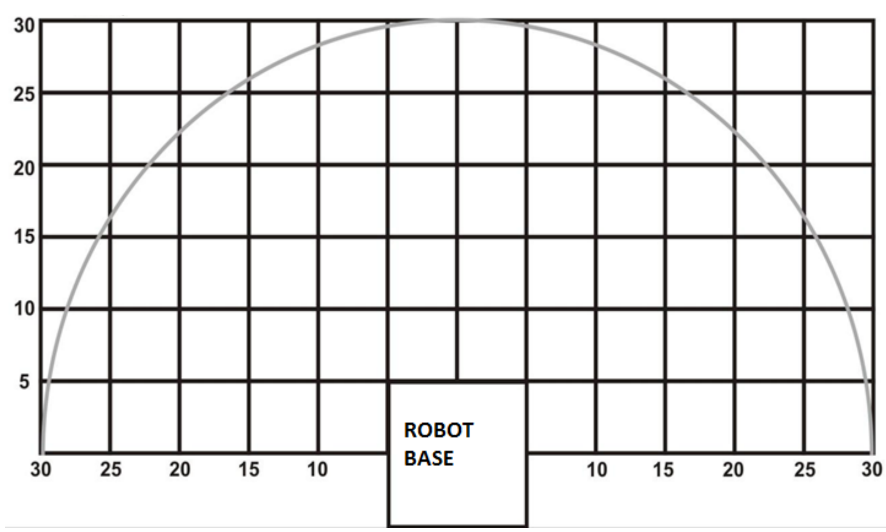


Fig. 1.2: Workspace of a robot

1.2.3 End effectors

It is the end of the robot which handles the applications. All the links are linked up in a chain to the end effectors. This part is attached to the last joint of a manipulator that in general handles objects makes connections to other machines, or executes the required tasks.

1.2.4 Joint

Joint is a point that attaches two links or parts that revolve, flex, translate or rotate. Joint plays a very vital role that helps the robot to move in different directions. There are different types of joints used in robotics providing better degree of freedom.

1.2.5 Prismatic joints

This joint provides a sliding or a linear motion to the link

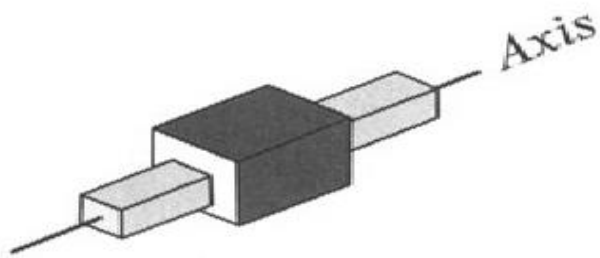


Fig. 1.3: Prismatic joint

1.2.6 Revolute joint

This joint provides an angular motion to the link

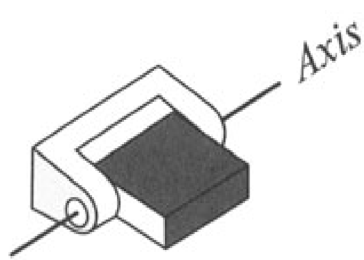


Fig. 1.4: Revolute joint

1.2.7 Cylindrical joint

These joints are not commonly used. They are used in flying objects

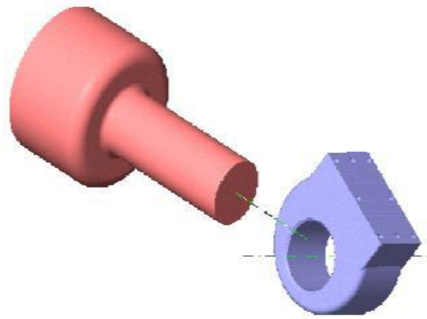


Fig. 1.5: Cylindrical joint

1.2.8 Spherical joint

These joints slide causing a revolute movement

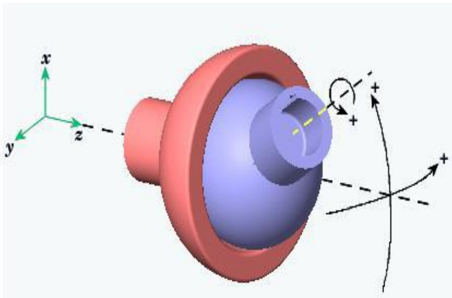


Fig. 1.6: Spherical joint

1.2.9 Screw joint

These joints are used to move along the axis using thread

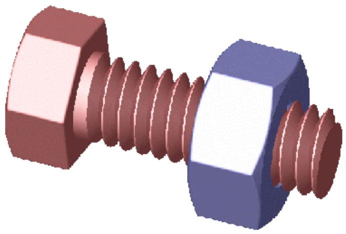


Fig. 1.7: Screw joint

1.2.10 Degree of freedom

Degree of freedom (DOF) is used to denote the direction in which the robot moves. Each joint denote one degree of freedom. Robots generally have 5 or 6 DOF depending upon the application.

1.2.11 Robot manipulators

This is the main body of the robot which consists of the links, joints and other structural elements of the robot.

Over years different types of robots have been developed have different mechanical and configurations depending upon the application. Six types of configurations have been evolved.

Cartesian robot (3P)

This robot is formed by three prismatic joints whose axes are coincident with the Cartesian coordinate system. It has three translator motions at right angles to each other.

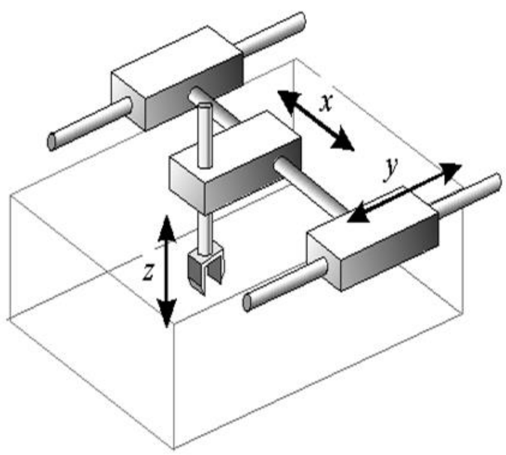


Fig. 1.8: Cartesian Robot

Cylindrical robot (PRP)

This robot rotates along the main axis i.e. the original axis forming a cylindrical shape. It has one revolute and two prismatic joints for orientating the part plus positioning the part..

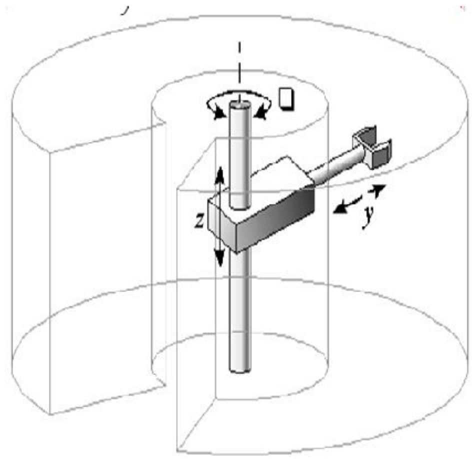


Fig. 1.9: Cylindrical Robot

Spherical robot (P2R)

This robot has two revolute and one prismatic joint for orientation plus positioning of the part.. These joints move along to form a hemisphere or a polar coordinate system.

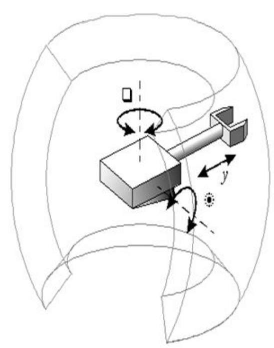


Fig. 1.10: Spherical Robot

SCARA Robot

Selective compliance assemble robot arm has two revolute joints that are parallel and let the robot to move in a horizontal plane and one prismatic joint that travels vertically.

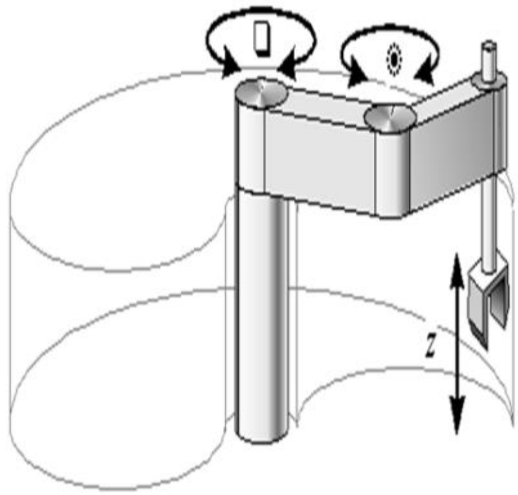


Fig. 1.11: SCARA Robot

Articulated robot (3R)

An articulated robot's joints are all revolute, similar to a human's arm.

1.3 ROBOT SPECIFICATIONS

The specifications generally include number of axes, tool orientation, reach and stroke, repeatability, accuracy, precision and load bearing capacity.

1.3.1 Axes

All the manipulators have three types of axes MAJOR axes which gives the position of the wrist, MINOR axes for the orientation of the tool.

1.3.2 Tool orientation

A coordinate system is attached to describe the position and orientation of the body in space. Transformation is used to calculate the position of the object from one frame to another.

1.3.3 Position

A 3x1 position vector of a point can be located once the coordinate system is established. The vectors are written with an upper subscript. This indicates the coordinate system to which they are referred. Example, ${}^{A}P$ that is the value of ${}^{A}P$ has the distance (vector) between the coordinate point and the new point.

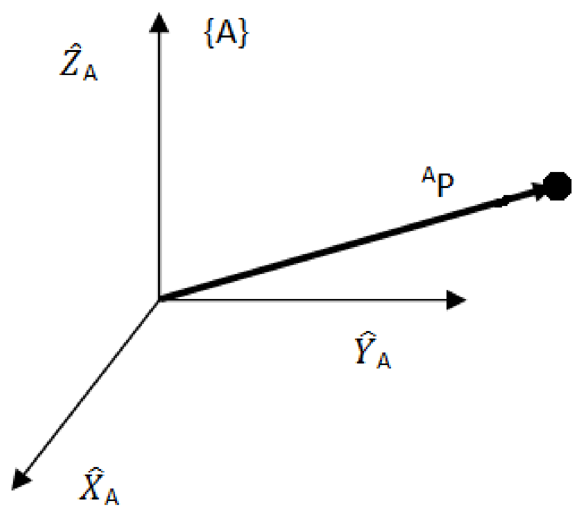


Fig. 1.12: Position vector of a point

{A} is the coordinate system and ${}^{A}P$ is the position of a point. ${}^{A}P$ is represented as a vector and can be assumed as a point represented in the space. The individual elements of the vector are:

$$ {}^{A}P = \begin{bmatrix} Px \\ Py \\ Pz \end{bmatrix} $$

Therefore, the position of the point in the space is represented as a vector.

1.3.4 Orientation

For an object not only position but also the orientation in the space is important. In orientation a coordinate system is attached to the body and is described using a reference frame. A coordinate frame {B} is attached to the {A} and {B} is described with respect to frame {A}.

Thus, position of the point is described with vector and orientation is described by attaching a coordinate frame.

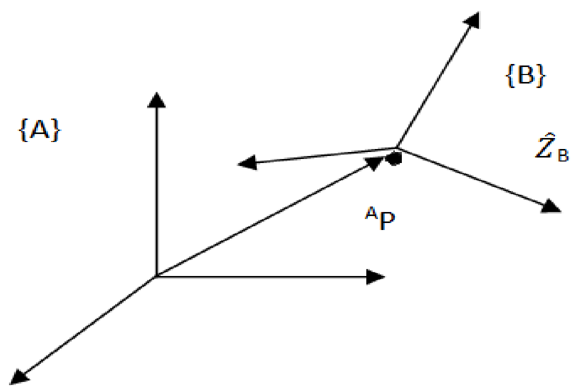


Fig. 1.13: Position vector of a point

To describe the orientation of the point attached to frame, {B}, is to write the unit vectors of the three principle axes in terms of frame {A}. The axes of the unit vectors of the point can be written as $\hat{X}_B$, $\hat{Y}_B$, and $\hat{Z}_B$, in terms of {A} they can be written as $^A\hat{X}_B$, $^A\hat{Y}_B$, and $^A\hat{Z}_B$. These three vectors are represented as 3X3 matrix and is called rotation matrix.

1.3.5 Reach and Stroke

Reach is the extreme distance a robot can reach within its work envelope. It is a function of the robot's joints and lengths and its configuration. This is an important specification for industrial robots and must be considered before a robot is selected and installed.

There are two types of reach and two types of strokes. They are horizontal reach, horizontal stroke and vertical reach, vertical stroke.

1.3.6 Accuracy

The ability of the robot to place the tool tip at the desired location

1.3.7 Repeatability

The ability of the robot to place the tool tip again and again repeatedly at the same location. Since many features may affect the accuracy of the position, the robot may not reach the same point every time but will be within a certain radius from the desired point. The radius of a circle formed by the repeated motions is called repeatability. Repeatability defines the extent of the random error, it cannot be predicted and consequently cannot be eliminated.

1.3.8 Precision

Precision is well-defined as how accurately a specified point can be reached. This is a function of the resolution of the actuators as well as the robot's feedback devices.

1.3.9 Load bearing capacity/ Payload

The maximum weight that be barred by the robot and still remain within its other specifications. The payload of robots compared to their own weight is usually very small.

1.4 SENSOR TECHNOLOGY

Autonomous robots are robots that can complete tasks without any human interference. Different robots are autonomous in different ways. For a robot to be autonomous sensors play a vital role. There are different types of sensors used in robotics for different purposes.

Sensors are used to sense the data. There are two types of sensors proprioceptors and exteroceptors.

1.4.1 Proprioceptors

Proprioceptors are sensors used to sense robot's internal parameters like kinematic and dynamic parameters. Based on these sensors the control system of the robot activates. The most common sensors used for measuring these parameters are potentiometers, encoders, RVDT, etc.

1.4.2 Exeroceptors

Exteroceptors are sensors used for measuring position or force type interaction of the robot with the external environment. Examples are, proximity sensors, touch sensors, far away sensor, etc.

1.5 OVERVIEW OF SOLAR PV TECHNOLOGY

1.5.1 Brief history of Solar PV Technology:

The history of solar PV technology can be traced back to 1839 when French physicist Edmund Becquerel discovered the photovoltaic effect while observing certain materials producing an electric current when exposed to light. Then, in 1883, American inventor Charles Fritts constructed the first solar cell prepared of selenium which had an efficiency of nearly 1% [3]. Another notable event was in 1905 when Albert Einstein published his findings which provided a theoretical explanation of the photovoltaic effect based on the photon/wave properties of light. In 1922, he was presented the 1921 Nobel Prize in physics for his discovery of the photoelectric effect law. It wasn't until 1954 when the first practical solar cell, which had an efficiency of 6% and a cost of $286 per watt, was invented in 1954 by scientists from Bell Labs. The extremely high cost and small energy output of solar cells in the 1950's and 60's have limited their application to space exploration missions where light weight and reliable operation under harsh environment are critical. Price of solar cells continued to decline while efficiency improved that by the 1970s solar cells have found its place in the navigation aids market and by the 1980's, after a further cost decline, solar energy became an attractive option for remote power applications where a small amount of energy is required in the absence of a grid .

The cost and efficiency of solar cells continued the downward and upward trend respectively through the 1990s and the new millennium. Solar energy is now a mature technology used everywhere around the world to power, homes, offices, street lights, etc. Yet, despite the increasing efficiency and the lower cost, it is still considered a secondary energy option and a relatively expensive one compared to other conventional energy sources. However, in the last decade, the solar PV market has experienced a huge growth in many countries around the world especially in Germany, Japan, and the United States all thanks to pilot programs and government subsidies aimed at stimulating the solar energy industry and promoting the use of renewable energy [4].

1.5.2 How PV works:

The sun constantly emits radiation energy that travels a long distance in space until it reaches the earth's atmosphere. As the distance between the earth and sun varies throughout the year, the amount of radiation that reaches the earth increases as the distance decreases and decreases as the distance increases. On average, that solar radiation energy just outside the earth's atmosphere equals 1367 W/m^2 and is referred to as the solar constant. However, this amount of radiation doesn't fully reach the earth's surface and is further reduced as it enters the atmosphere due to absorption by oxygen, ozone, greenhouse gases, and due to scattering by air molecules, aerosols, clouds, and suspended dust. The sunlight that falls on the earth's surface has direct and diffused components. On clear sunny days, the direct radiation is the dominant component. During very cloudy days on the other hand, the diffused (indirect) component which is caused by light reflection off clouds and scattering through the atmosphere accounts for the bigger portion. When a PV module is exposed to light, photons with enough energy cause the valence bonds in the semi-conductor to break and create free positive and negative charges (hole-electron pairs). In order to control the flow of charges and create an electric field, positive and negative regions known as a p-n junction must be created. In crystalline silicone, this is accomplished by doping the silicone with small amounts of phosphorous which has 5 valance electrons thus creating an n-type region. On the other hand, doping the silicone with a small amount of a trivalent element such as boron creates the p-type material. When the two regions are brought together to form a p-n junction and the PV module is exposed to light, voltage builds across the cells and by connecting a load to the PV module, electrons will flow from one electrode to the other creating an electric field that powers the load [5].

However, not all the energy from the photons will be utilized by the PV module. This is because of the spectral sensitivity of the PV material and the spectral distribution of the incoming light. In other words, sun light has different wavelengths and thus the photons falling on the PV module have different energy levels. In order to break the bonds in the semiconductor and create free electrons, the energy in the photons must be within the band-gap energy (energy needed to free electrons) of the PV material. Photons with less energy than the band-gap energy will not contribute to electricity generation. Photons with excess energy than needed will also be wasted and dissipate as heat. Therefore more than 50% of the light energy falling on the PV module is lost[5]. Other PV efficiency limiting factors include:

- Shading and optical losses where part of the incoming light is reflected off the top surface of the module or blocked by the electrical contacts on wafers.

- Internal resistance within the cell caused by interconnections and the bulk resistance of the semiconductor material.

- Recombination losses which are caused by electrons and holes recombining instead of separating in the p-n junction [5].

1.5.3 Solar Cell Characteristic I-V Curve:

The performance of a solar cell can be characterized using solar cell characteristic I-V curve. The main parameters of this curve are as follows:

- The open circuit voltage (V_{oc}) is the maximum cell voltage at zero current. That is, if light falls on an unloaded PV cell and the voltage that builds up as a result is measured across the terminals of that cell, then this voltage is called the open circuit voltage.

- The short circuit current (I_{sc}) is the maximum current generated at zero voltage. In other words, if the illuminated cell is short circuited and the current is measured using an ammeter then this current is defined as the short circuit current. Using a variable resistor and measuring the corresponding cell current and voltage values for different resistance values, the cell I-V curve can be plotted and the cell power curve can be determined by the product of all V and I values.

- The maximum power point power (Pmpp) is the point on the I-V curve where the cell generates maximum power. That is, it is the maximum product of I and V values and these values are known as I_{mpp} and V_{mpp} respectively. The I_{sc} is directly proportional to the irradiance and therefore its value goes up with increasing irradiance and goes down when it decreases. However, the V_{oc} remains constant with irradiance and only falls once irradiance falls below around 100 W/m^2

For standardization and comparison purposes, I-V characteristic curves for different cells and modules are determined under what is known in the PV industry as standard test conditions (STC):

- Direct Irradiance = 1000 W/m^2

- Cell temperature = 25 °C

- Air mass (AM) = 1.5

At a given location when the Sun is directly overhead and the sun light has the shortest path length to the module, the AM has a value of one. If the sun is instead at an incline from such a path by an angle φ, then the AM equals 1/cos φ. An AM of 1.5 corresponds to a sun inclination of 48.20° from overhead.

1.5.4 PV System performance:

In addition to ambient temperature and available irradiance, the energy yield of a PV system depends on the performance and reliability of key components that make up the overall system. The following describes de-rate factors that contribute to loss in energy yield:

❖ Nameplate DC Rating:

The nameplate DC rating or the sticker DC power rating that PV module manufacturers provide on their modules is for maximum power output under STC. Actual field performance might differ from the nameplate rating due to inaccuracy by the manufacturer or due to light-induced degradation that some modules suffer from when they are exposed to sunlight for the first time before stabilizing during the first few hours of operation [6].

❖ Diode and Connection losses:

Some power loss will occur due to by-pass diodes used in PV modules and resistive losses in connections between modules and other electrical components.

❖ Mismatch losses:

Modules with different current and voltage characteristics that are connected together yield a total power output less than that achieved by summing the power output of individual modules. The difference in this power output is known as mismatch loss and the output for individual modules is limited to that of the module with the lowest output.

❖ DC and AC Wiring:

DC and AC wiring de-rates account for cable and wire resistive losses that occur throughout the PV plant starting from the modules until connection to the main power grid.

- ❖ Sun Tracking:

Sun tracking losses might occur if single or dual axis tracking systems are not at the optimum orientation or are misaligned due to a mechanical malfunction.

- ❖ Shading

Shading losses occur if a shadow is cast on the PV modules from other PV arrays that are in close proximity or from other structures blocking the sun's rays.

- ❖ Inverter losses

The inverter de-rate factor accounts for inverter related losses that arise from different power conditioning tasks. An inverter (power conditioning unit) is an essential component of a PV system that mainly converts the DC current produced by the SPV modules to AC current suitable for main grid transmission and use by devices requiring AC current. It also performs the following:

- o Optimization of AC power output by tracking the maximum power point (MPP) which constantly changes during the day due to changes in temperature and irradiance levels.
- o Monitoring and storing of operating data.
- o Sometimes includes a transformer to match voltage levels to that of the grid.
- o Provides voltage overload protection.

- ❖ Transformer losses:

Some power loss will occur in the transformers which are common components in electrical devices and power grids used to step up or step down the voltage between electrical circuits.

- ❖ Soiling losses:

These losses account for power drop from dirt, snow, dust, and other objects that might cover the module surface.

The preceding factors represent the major parameters affecting system performance but they are by no means inclusive of all parameters affecting the energy yield. The PV system quality can be measured regardless of size and irradiance levels using the performance ratio (K) which is defined as “the ratio between the actual energy output of a system and nominal energy generation potential of a system”. PV system performance ratio values are assumed to fall between 0.70 and 0.85 while systems achieving higher values are considered very good designs. It can be evaluated using the following formula:

$$K = EP / \{PAS\ (HA / GS)\}$$

Where,

EP = actual system generated electricity (kWh)

PAS = nominal array output at STC (kW)

HA = actual in-plane irradiation (kWh/m2)

GS = reference irradiance (=1 kW/m2)

Trajectory and position control of robots are very essential tasks, also positioning must be precise, fast, stable and reliable in order to guarantee high standards, but often robotic arms, due to instability starts oscillating around the desired position [7]. Most of the robotic systems are designed to work in stable and controlled conditions, it is essential to study the effects of instabilities and damage, danger caused due to it. Design has been proposed to implement a robotic arm that can clean solar panel; such a design would be ideally suited for situations where human interference is less. The project will be based on guide rails that will be installed parallel to the pre-installed solar panels. This helps to remove the weight of the cleaning arm to be directly over the panels and hence preventing the panels in case of any adverse happening which may lead to falling down of the cleaning arm on the panel and damaging it.

The guide rails will upkeep the base of the cleaning arm, which will be driven by motor and controlled by ultrasonic/proximity sensors. The arm will move towards the panel to be parallel to the cleaning surface. The leaning of the arm will be controlled by the ultrasonic/proximity sensors installed at the specific pre-defined angle (depending on individual panels).The motion of the cleaning head is also controlled by the ultrasonic/proximity sensors which are installed at the upper and lower end of the arm. The piping is done in the cavity of the arm so as to properly utilize the space of the robotic arm and to provide a dynamic balance to the arm. The motors used for the inclination of arm as well as motion of the cleaning head are Worm geared dc servo motor and side shaft DC motor with modifications in the gear arrangements to suit the needs of the application and ease of control.

1.6 PROBLEM STATEMENT

Solar PV energy plays a major role in reducing emissions from fossil fuels and checks depletion of non-renewable energy resources. However, soiling of SPV modules drastically reduces the energy yield and even decreases the lifetime of SPV modules and other components associated with it. Soiling can be in the form of dust, dirt, bird droppings, leafs and pollen, which accumulates on the surface of SPV modules.

The SPV modules must be periodically cleaned to ensure clean, clear and dirt free surface. This task might not pose a big problem in terms of financial and environmental costs associated with SPV cleaning as its cost comes from the enhanced efficiency. Furthermore, there are several methods of cleaning SPV's are available with its advantages and disadvantages. Choosing the ideal method, will optimize the energy yield of SPV modules in light of economic and environmental factors.

1.7 THESIS OUTLINE

Chapter 2 discusses in detail about the literature survey done on two aspects:

i. About the effect of dust on SPV and upto what extent it is reducing the efficiency of SPV's. Also it covers the effect of different type, composition, size etc. of dust on SPV efficiency;
ii. About the Industrial Automatic and robotic solutions used for cleaning SPV modules and their gaps.

Chapter 3 discusses in detail about the soiling of SPV panels and why it is an area of concerned. As per the cleaning techniques available what will be the optimum solution and the technique and methodology followed for it.

Chapter 4 discusses in detail about the Cleaning mechanism and approach for cleaning. A 2 DOF nonlinear model has developed and explained in detail. Few control strategy is also discussed which helps in moving in the guide rail and do the cleaning operation smoothly. Trajectory planning has been done for the manipulator to calculate the torque required for it. Considering other factors solid works modeling has been done to choose the material to fabricate the manipulator. This helps in designing an optimal robotic manipulator.

Chapter 5 includes the overall results and discussions. It consists of the real time data of the test rig, data collection, performance analysis and reporting. Data was collected for a period of four weeks from morning 1000 hrs to evening 1700 hrs over an interval of 30 minutes. Data was been monitored for the both the SPV modules (cleaned and uncleaned). Further performance comparison has been done with market available products.

Chapter 6 deals with the conclusion and future scope. The later chapter deals with references used.

CHAPTER- 2

LITERATURE REVIEW

2.1 INTRODUCTION

In this chapter the first half discusses in detail about the effect of dust on SPV and upto what extent it is reducing the efficiency of SPV's. Also it covers the effect of different type, composition, size etc. of dust on SPV efficiency. The later section discusses about the Industrial Automatic and robotic solutions used for cleaning SPV modules and their gaps. Objectives, research focus and the methodology followed is also discussed in detail.

The global energy requirements have increased considerably in the past several decades and are projected to rise more than 50% by 2030 [1]. Present world energy requirements are met mostly from the conventional sources of energy like coal, gas and oil, which are being exploited in an unregulated manner resulting in exhausting world reserves of fossil fuels in the near future. With increasing cost of electricity and concern for the environmental impact of fossil fuels, implementation of renewable energy sources like solar power are rising. The main method for harnessing solar power is with arrays made up of photovoltaic (PV) cells. Electricity generated using solar photovoltaic (SPV) technology can only be economical if the PV modules operates reliably for 25–30 years under field conditions [8].The key limiting factors which reduce widespread use of PV applications comprise the high initial investment cost [9] and the comparatively low conversion efficiency of PV cells due to heating of PV panels [10-12]. Module temperature is always higher than the ambient temperature [13]. Higher temperature of the module is because of the glass cover over it, which traps the infrared radiation. Overall, power output and efficiency of the PV cells decrease with the increase in its operating temperature as shown in Figure 1. Dust collection on PV panel surface also reduces its efficiency [13, 14], and the output power of the PV module mainly depends upon the solar irradiation falling on it [13]. The power output of a module increases linearly with the increase in the incident solar radiation shown in Figure 2. Accumulation of dust and debris on even one panel in an array reduces their efficiency in energy generation considerably and emphasizes the need to keep the panel surface as clean as possible [15, 16]. Due to humidity, when light hits water droplets, it may be refracted, reflected or diffracted, which affects the reception levels. High content of water vapour in the air causes encapsulation [17]. Because of the water content of the humidity, failure at cell interconnections or cracked cells happens in crystalline silicon cells, and failure at scribe lines is the dominant cause of cell thin film modules degradation. The impact of sedimentation (i.e. dust and dirt particles) on exposed surfaces of SPV panels. Dust prevents the incident light in reaching to the SPV, causing reduced power output and efficiency. Dust accumulation occurs at different rates in different parts of the world; also, it depends upon the panel orientation [18], direction of wind [19], and nature of dust [20]: dust composition, size distribution, deposition density as shown in Figure 3–6. Apart from the above natural factors, even the manufacturing technology also plays a role, as different type of PV technologies having different amount of efficiencies as listed in the Table 1. Orientation and tilt angle of the PV module plays an important role for the efficiency of SPV as performance of SPV module depends on the amount of solar radiation received by a PV module which in turn depends on the orientation and tilt angle [21, 22]. Orientation of modules is generally north in southern hemisphere and south in northern hemisphere. Tilt angle is site dependent and has to be optimized to maximize the incident solar radiation on the PV module surface.

The review includes the detailed description on different automated solar panel cleaning systems, a brief overview about electrical, mechanical, chemical and electrostatic methods. The paper also reviews various successful electrical, mechanical, chemical and electrostatic methods developed in the recent years for various applications.

2.2 LITERATURE REVIEW ON INDUSTRIAL SOLAR PV CLEANING PRODUCTS:

- **Heliotex: Automatic Solar Panel Cleaning Systems. http://www.solarpanelcleaningsystems.com/solar-panel-cleaning-services.php; August 2013 [23].**

  It automatically washes and rinses the solar panels. It attaches nozzles to the solar panels as shown in fig. 2.1. It comprises of a five gallon reservoir for soap concentrate. There is also a sediment filter that contains water softener media. It is also having an anti siphon valve to prevent backwashing into the system. System consists of a controller which automatically provides wash and rinse cycles, the controller programming can be changed as per seasonal requirements. It requires treated water and the filter needs to be replaced periodically.

Fig.2.1: Heliotex Automatic Solar Panel Cleaning System.

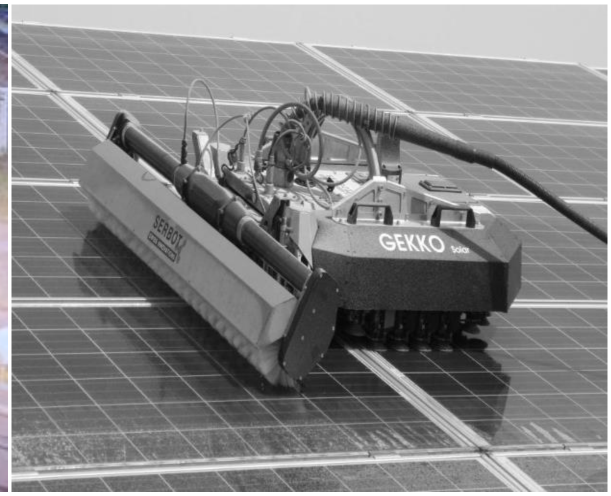


Fig.2.2: Cleaning of Solar PV module using Gekko Solar

- **Serbot Swiss Innovations; Gekko Solar** **http://serbot.ch/images/documents/TD_GEKKO%20Solar_En_2013_06_06.pdf; August 2013 [24].**

  Gekko Solar is developed for mobile deployment onto Solar PV panels as shown in fig. 2.2. It is having a cleaning capacity of 400 m^2/hr. Thorough cleaning using rotating brush and demineralized water. Its movement is based on feet, with vacuum technology, which are rotating on two trapezoid-shaped geared belt drives, enabling the robot to astonishing flexible movement in every chosen direction. It can be radio controlled with a joystick from a distance of 300m. Vacuum based feet movement which requires air pressure of 8 bar. It is able to clean inclined panels upto 45 deg.

- **Serbot Innovations; Gekko Solar Farm** **http://serbot.ch/images/documents/TD_GEKKO%20Solar%20Farm_En_2013_06_26.pdf ; August 2013 [25] .**

  Gekko Solar Farm is developed for the cleaning of large field solar farms. It is having a cleaning capacity of 2900 m^2/hr. Thorough cleaning using multiple rotating brushes and demineralized water. Its movement is based on feet, with vacuum technology, which are rotating on two trapezoid-shaped geared belt drives, enabling the robot to astonishing flexible movement in every chosen direction. It can be radio controlled with a joystick from a distance of 300m. Vacuum based feet movement which requires air pressure of 8 bar. It is able to clean inclined panels upto 30 deg.

- **National Instruments(Prototype Design); Design and prototype of an Autonomous Robot to automatically clean solar panels [26].**

In this using NI's LAB View real time software to manage the behavior of a robotic arm. The robotic arm was mounted over a moving vehicle as shown in fig. 3.3. By using the NI Lab View tool, controlling for Engine platform, continuous contact and controlled pressure between cleaning tool and SPV panel, sample time, vibrations resistance. The major constraint is channelizing the vehicle motion parallel to the Solar PV panels.

Fig 2.3: NI's Prototype cleaning demonstration

- **Tuff fab; Nano Clear: SPV Panel Glass Coating Solution**
http://www.tufffab.com/solar-panel-glass-coating-solution.html; August 2013 [27].

It is available as a solution which is easy to apply. Once applied it makes the glass surface Non-stick, easy to clean and look new for years. User no longer needs to use harsh chemicals and scrub clean your glass any more. Just a wash with clean water or mild detergent and a wipe with a soft towel will clean the panels. In this method cleaning has to be done, only advantage is cleaning process would be easy.

- **Wash Panel: SPV panel array cleaning Robot;**
http://www.washpanel.com/en/documenti.php; August 2013 [28].

This system is fully autonomous; it has a double programmable functioning through a rain sensor and by use of water jets. It provides a constant and uniform cleaning. Ths system is modular, with possible supervision and management from remote site. It doesn't require any extra frame, support and additional guides. It can be installed on ground systems, buildings, peaked roof or shed roof. For continuous monitoring it sends text messages to mobiles, allowing command control from remote sites.

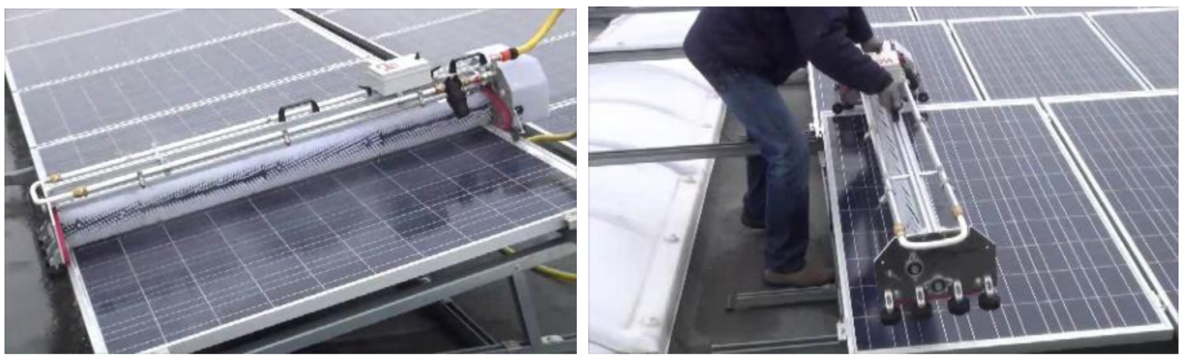


Fig. 2.4: Wash Panel cleaning and placing over Solar PV panel

From fig. 2.4, it is clear that the Wash Panel robot is kept over the Solar PV panel, which requires additional attachments on edges of PV panels. Also, it requires continuous outside supply.

- **Mark Anderson, Ashton Grandy, Jeremy Hastie, Andrew Sweezey, Richard Ranky, Constantinos Mavroidis, Yiannis P. Markopoulos. "Robotic device for cleaning photovoltaic panel arrays" [29].**

In this paper authors have made a solar panel cleaning robot, its design comprises of two motorized trolleys at the edges of panels which provide horizontal motion and a cleaning head driven by a belt and pulley system for vertical motion. Cleaning head comprises of rotating cylindrical brushes to scrub the PV panel and a scraper to remove the dirt solution. As per the design and working of the cleaning robot shown in fig. 2.5, horizontal shifting of the robot is a problem as the wheels skid over the Solar PV, also the weight of the cleaning robot is over the solar PV panel.

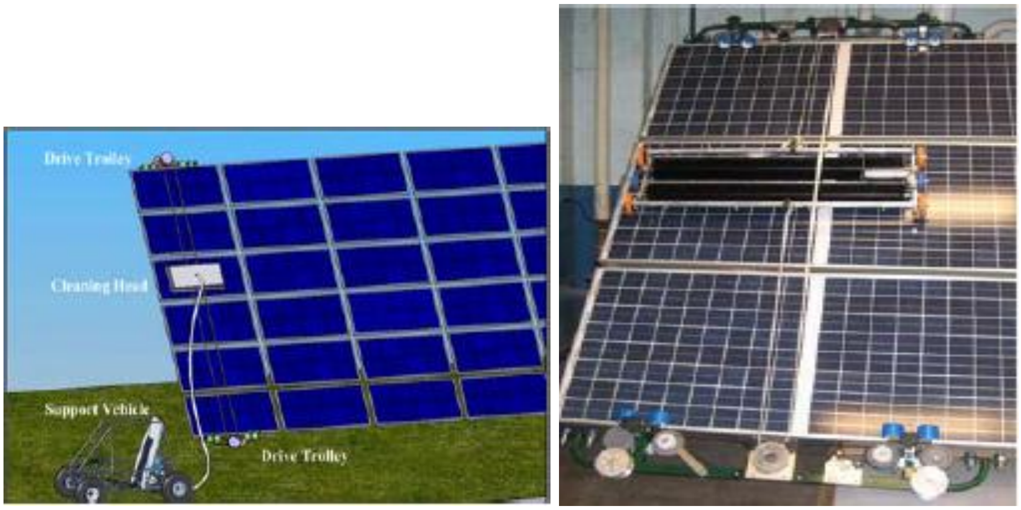


Fig. 2.5: Simulated and real time operation of PV cleaner

- **Solar Brush: Solar Brush cleans and inspects solar power plants http://www.solarbrush.de/about; August 2013 [30].**

It is a robotic cleaning system for Solar PV panels. The robot "SolarBrush" walks over the solar PV panel. It can function upto an inclination of 35 degrees. It is wireless and rechargeable. It is having a cleaning brush which swipes the dust. SolarBrush is light weight of 2.5 kg. As the cleaning method is swiping which may results in stains in the glass of Solar PV panel. Performance is very slow of 1m^2/min.

Fig. 2.6: Solar Brush Cleaning SPV module

Fig.2.7:HECTOR Robot cleaning SPV module

- **HECTOR- Cleaning robot system for Heliostats ; http://www.sener-aerospace.com/AEROESPACIAL/ProjectsD/hector-cleaning-robot-system-for-heliostats/en; August 2013. [31]**

  It is a robotic cleaning system for Heliostat's, which can be used for Solar PV panel cleaning also, as shown in fig. 2.7. It is wireless, Rechargeable and carries water solution tank with itself. It is fused with various sensors which permit it to navigate autonomously without any human supervision. It requires no external power or water supply for its operation; it carries its own batteries and water tank. HECTOR is designed for night and day operation.
  Its performance is very slow and the weight of HECTOR is over the panel.

- **Greenbotics's: GB1; http://www.greenbotics.com/; August 2013 [32].**
  It is a robotic cleaning system for Solar PV panels. It is wireless and rechargeable. It comprises of rotating cleaning brushes perpendicular to the axis of panel and a wiper system, so that not only it cleans the panel but also clear the dirty water. Hence, effective for all types dust and bird droppings. Also, effective for one axis tracking solar PV panels. As per the design, robot is moving at the edges of the frame of solar PV panel as shown in fig. 2.8.

Fig. 2.8: Greenbotics Solar PV cleaning robot in action

2.2.1 SUMMARY OF THE INDUSTRIAL AVAILABLE SOLAR PV CLEANING SYSTEMS:

Table 1.1: Summary of available industrial Solar PV module cleaning system

S. No.	Cleaning System	Advantage	Disadvantage
1.	Manual	1. Cleaning only when required	1. Cost varies subjected to location and manpower. 2. Time consuming and ineffective
2.	Transparent Shield	1. No mechanical movement on the surface of SPV panel to scratch the protective surface	1. Requires high voltage for good performance. 2. Causes shading when used on a PV panel. 3. Cannot be directly powered from the SPV panel.
3.	Electrodynamic Screen (EDS)	1. Efficient and can be used to take away dust from a variety of surfaces 2. No mechanical movement on the surface of SPV panel to scratch the protective surface. 3. Efficient with and without use of external power supply.	1. Needs Digital Signal Controller (DSC) which is costly. 2. Requires switching devices for converters hence more maintenance is required.
4.	Standing wave Electric curtain	1. Highly efficient at high gas pressure. 2. No mechanical movement to scratch the protective surface.	1. Removal is difficult when gas (atmospheric) pressure is below a certain limit. 2. Dust removal capability depends on the size of the particles deposited.
5.	Solar Brush PV Robot	1. Automated Robot 2. Works up to an inclination	1. Heavy weight 2. Initial cost is high.

		of 35 deg. 3. Wireless controlled 4. Rechargeable	3. Requires human intervention 4. Performance speed is very slow
6.	Gekko Solar	1. Self regulating and flexible uninterrupted cleaning operations.	1. Limitation of inclination upto 45 deg. 2. Complex gear, belt system.
7.	Gekko Solar Farm	1. Self regulating and flexible uninterrupted cleaning operations.	1. Limitation of inclination upto 30 deg. 2. Complex gear, belt system.
8.	Heliotex Automatic Solar Panel Cleaning Systems	1. Water reaches to every part of Solar PV modules. 2. Helps in cooling of Solar PV modules, which increases the efficiency.	1. Treated water required. 2. Filter has to be change periodically. 3. Huge wastage of water.
9.	Tuff Fab's Nano Clear	1. Long lasting	1. Cleaning is still required, but with less effort.
10.	Hector	1. Compatible, intergrated with all supplies. 2. Operational day and night	1. Performance is slow 2. Feeding has to be done regularly
11.	Greenbotics: GB1	1. Able to clean dust and Bird droppings	1. Requires continuous outside feed
12.	Wash Panel	1. Able to clean dust and Bird droppings	1. Requires continuous outside feed

2.3 LITERATURE REVIEW ON EFFECT OF DUST ON SOLAR PV PANEL

- **United States Patent; Transparent Self- Cleaning Dust Shield; Inventors: Malay K. Mazumder, Robert A. Sims, James D. Wilson; Assignee: Board of Trustees of the University of Arkansas, Little Rock, AR (US); Appl. No.: 10/253,625; Patent No.: US 6,911,593 B2; Date of Patent: Jun. 28, 2005.[33]**

In this patent paper, inventor has invented a transparent technique for solar PV panel's dust cleaning on self. The shield is a panel of clear non-conducting (dielectric) material with embedded parallel electrodes. The SPV panel is coated with a semiconducting film [34]. Electrodes are attached to a single-phase AC signal or to a multi-phase AC signal that produces a travelling electromagnetic wave [35]. If the electrodes are connected in a three-phase current source to produce a travelling wave by which particles are propelled lengthwise along the panel. If a single electrode is connected to a single phase AC signal, and the panel is vertical or substantially vertical so that the dust particles repelled from the surface of the panel fall by gravity without the need for the travelling electromagnetic wave to sweep the particles away.

- **D. Sera, Y. Baghzouz, "On the Impact of Partial Shading on PV Output Power", RES'08, Corfu, Greece. Papers from Conference Proceedings, 2008 [16]**

In this paper author has shown that partial shading of a SPV array diminishes its output power capability. The amount of degradation in energy production is often not proportionate to the shaded area. In this paper author has done an experiment to verify the results by partial PV shading on a number of PV cells connected in series and/ or parallel with and without bypass diodes [36].

Partial shadowing only two cells (series connected sub modules) can cause a considerable reduction in output power generated and the amount of loss greatly depends upon which two cells are shadowed.

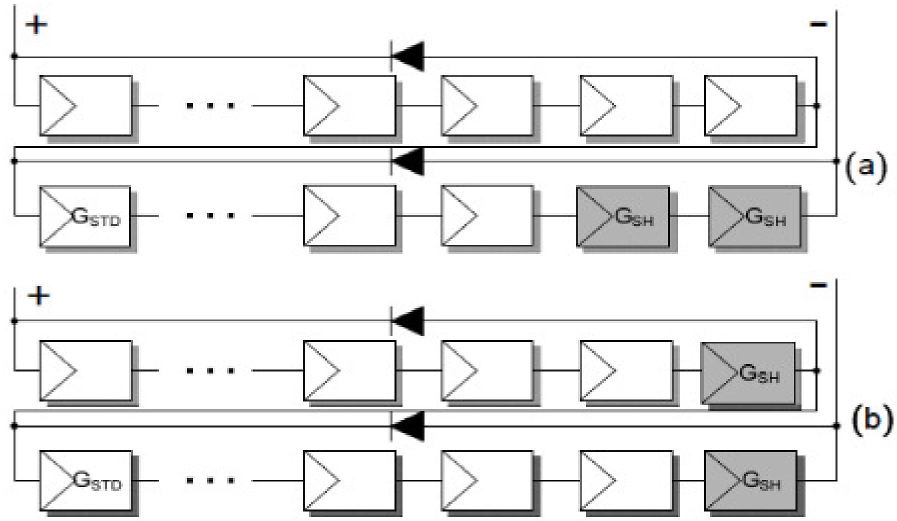


Fig. 2.9: Series connection of two sub modules (a) Two cells shaded in one sub module, (b) one cell shaded in each module

The maximum power reduction from fig.2.9 (a) and (b) are 50% and 70%, which clearly illustrates that the maximum power production is also proportionate to the non-shaded area of a PV module.

Partial shadowing of two parallel- connected sub modules, the maximum power reduction as shown in fig. 2.10 (b) is same as that of fig. 2.9 (b), that is the power reduced by 70%. On the other hand power reduced from fig.10 (a) by 35% only.

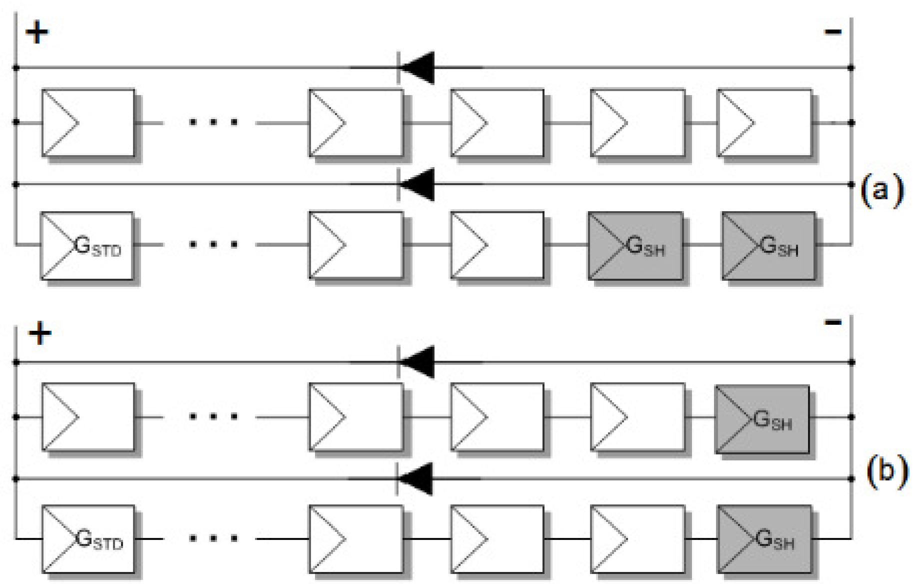


Fig. 2.10: Parallel connection of two sub modules (a) Two cells shaded in one sub module, (b) one cell shaded in each module

- **Jacob P. Bock, Jason R. Robison, Rajesh Sharma, Jing Zhang, Malay K. Mazumder. "An efficirnt power management approach for self cleaning solar panels with integrated electrodynamic screens". Proc. ESA Annual Meeting on Electrostatics 2008, Paper O2. [37]**

In this paper author has worked on a particular downfall of Electrodynamic Screen (EDS) [38] and tried to resolve it by providing an integrated approach. An EDS based system requires a high-voltage external power source for its operation, but the EDS can be made self-sustainable with the power output from the PV cell itself. Author incorporates a transparent EDS with a PV array as its power source to make itself sustainable. The block diagram of the system is shown below in fig. 2.11. The three phase high voltages create a travelling wave with a strong translational energy that can move the triboelectrically charged dust particles from one end of the substrate to another. Uncharged particles that may become deposited on the screen soon become charged by polarization of a charge or through induction, allowing it to also be cleared from the surface.

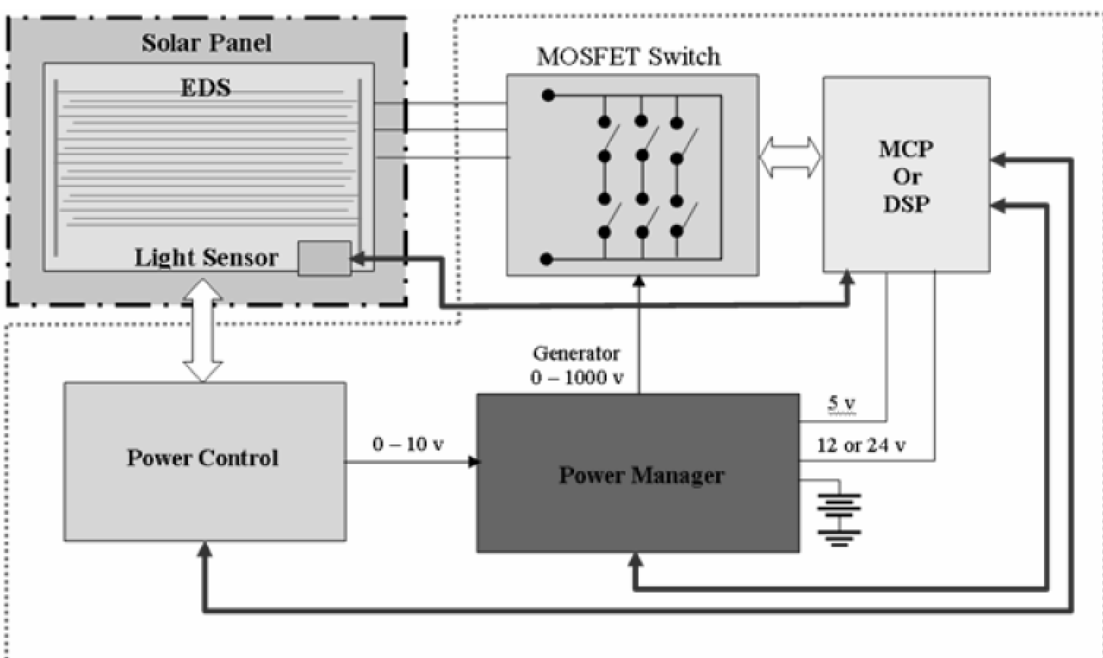


Fig. 2.11. Block diagram of EDS/PV array system

- **Atten, P., H.L. Pang, and J.-L. Reboud,** ***Study of dust removal by standing-wave electric curtain for application to solar cells on mars.*** **Industry Applications, IEEE Transactions on, 2009. 45(1): p. 75-86.[39]**

In this paper author has described about a type of wave generation in Electrodynamic Screens (EDS) [38], also the proposed method had been suggested for Solar Cells on Mars. Author has used the electrostatic charge concept for lifting and transporting charged particles of insulating materials [40]. There are two types of curtains: (a) Multiphase Electric curtains, and (b) Standing wave type electric curtain. Author has spoken for type (b) Standing wave type electric curtain and that to in different climatic pressures keeping in mind the climatic conditions of Mars. As shown in fig. 2.12, two comb type electrodes, one being ground and the other being supplied with ac voltage. In this case, we have a standing wave, and at any point, the electric field has a definite direction and amplitude oscillating at the imposed frequency. A single charged particle oscillates along the field line. For a horizontal setup, it experiences an uprising vertical resulting force which can lift it, and part of it escapes the stressed zone. The main constraint of this technique is, it requires dry state of the surface and for this reason it has been suggested for Mars climatic conditions [41].

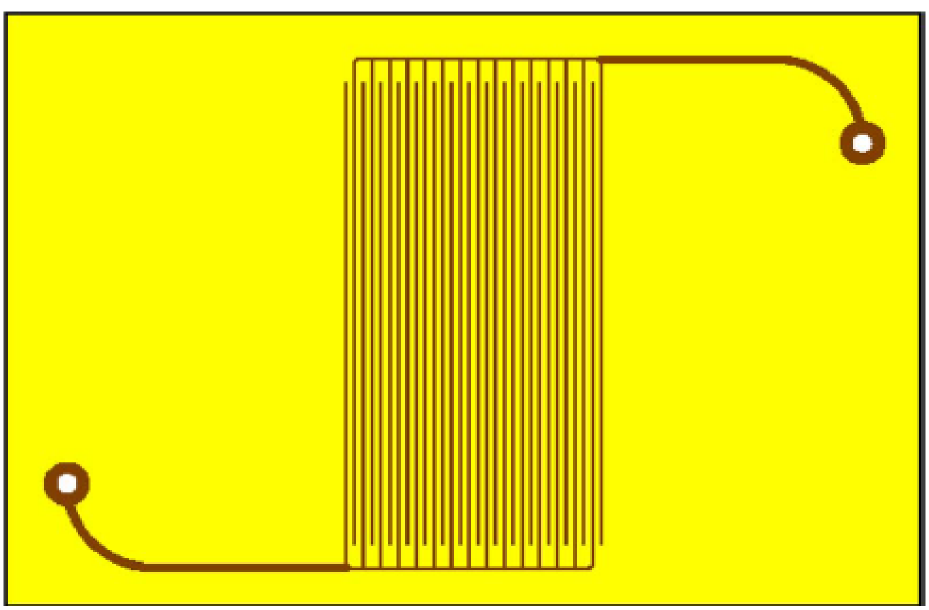


Fig. 2.12. Single phase electric curtain with the two “combs” of parallel electrode.

- **Dr. Ali Ibrahim. "Effect of Shadow and Dust on the Performance of Silicon Solar Cell" Journal of Basic and Applied Scientific Research, 2010. [2]**

  In this paper author has created a simulated environment for V-I characteristics effect due to dust. Author has chosen a halogen lamp 100W and solar PV of 10 cm X 6 cm for this experiment. Due to gathering of dust on SPV module, short circuit current I_{SC} and open circuit voltage V_{OC} of silicon solar cell were decreased up to 2.78% and 0.863% respectively. On the other hand, effect of shadowing selected location over the solar PV module shows I_{SC} is more decreased in a high percent than V_{OC}.

- **K. Watanabe, A. Higo, M Sugiyama, Y. Nakano."Self-assembled SiO2 particle coating on 2 layer anti-reflection films for efficiency enhancement of GaAs PV cells ".Photovoltaic Specialists Conference (PVSC), 2010 35th IEEE, 20-25 June, 2010. Page No. 205-208 [42].**

  In this paper author suggests for a special type of anti reflection coating (ARC) over the solar PV panels. Owing to the diffraction and light trapping effect [43] caused by a sub-wavelength size of structure, the reduced reflectance covering a wide-wavelength can be expected at a surface of the photovoltaic (PV) cell [44]. Author in his experiment tried a nano-scale structure fabrication by small-size particles combined with conventional 2 layers ARC on GaAs PV cells. The small-size spherical particles show well aligned self-assembly on the substrate when the solution containing micro-spheres were dried with a proper sheer force. Using the pure water solution of colloidal SiO_2 spheres and an ordinal spin-coating technique, a well aligned mono-particle layer has been fabricated on the 2 layer ARC (TiO_2 and SiO_2) on a GaAs PV cell. In the range of tested particle size, the smaller particle was preferable to avoid scattering loss and provides a larger efficiency enhancement to GaAs PV cells.
- **Ji Liming, V.V. Varadan. "Fishnet metastructure for efficiency enhancement of a thin film solar cell". Journal of Applied Physics, Volume:110, Issue: 4, Aug 2010, Page No. 43114- 43118** [45]

In this paper author proposed embedment of fishnet meta structure in the back passivation layer of thin film SPV cells. Incident light excites a plasmon resonance [46] that results in frequency dependent effective impedance for the embedding layer so that the input impedance fulfills impedance matching condition. Reflection is very little under this condition. Author did detailed experimentation on electromagnetic modeling of the absorption in different layers of the solar cell. 64% of the total absorbed energy at resonance is in the silicon layer and this absorption is evenly disseminated inside the silicon. Based on the enhancement of photocurrent density near the bandgap of a-Si:H, author obtained 14.8% enhancement in total short circuit current at ordinary incidence and the estimated PV efficiency of the solar cell with the fishnet is 7.43% at normal incidence compared to 6.36% without fishnet. The fishnet can be tuned to provide absorption enhancement at any desired frequency where the intrinsic absorption of the semiconductor is low.

- **L. Dorobantu, M.O. Popescu, Cl. Popescu, A. Craciunescu. "The effect of surface impurities on photovoltaic panels" International Conference on Renewable Energies and Power Quality, Las Palmas de Gran Canaria (Spain), 13th to 15th April, 2011. [47]**

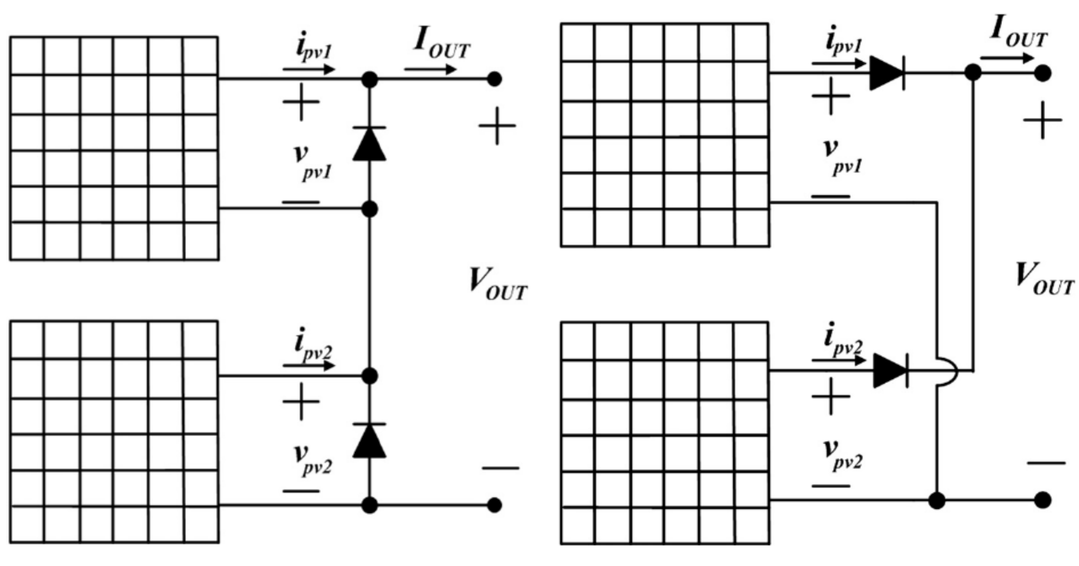
In this paper author has simulated when a cell is covered by deposition, its internal temperature rises and thus it leads to occurrence of losses in Comsol Multiphysics. Thus, the studies on the behavior of photovoltaic cells covered by impurities show that these situations should be evaded as much as possible as inevitable losses occur in the system.

- **Cheng –Chuan Chen, Hong –Chan Chang, Cheng –Chien Kuo, Chien –Chin Lin. "Programmable energy source emulator for photovoltaic panels considering partial shadow effect". Energy; Volume 54; Page No. 174-183. [15]**

In this paper author has produced a programmable emulator for photovoltaic panels. A even solar illumination model, a partial shaded model with two photovoltaic modules in series and a partially shaded model with two photovoltaic modules in parallel are used [16, 36]. The specification of any kind of photovoltaic panels can be presented by the open circuit voltage, the short current and the current and voltage respectively, when it is at maximum output power condition, as well as the temperature coefficient of open circuit voltage and the temperature coefficient of short circuit current, even when the photovoltaic panels are made of different materials.

Author has selected two photovoltaic modules in series connection fig. 2.13(a), 25 °C was the setting value of the ambient temperature for both the modules. The maximum percentage error in power amid the theory values and the emulator [36, 48, 49] output is about 5% under a load resistance condition when compared with a non shaded, fully illuminated model.

When the emulator was set up as two photovoltaic modules in parallel connection fig. 2.13(b), keeping other conditions same, the maximum percentage error in power between the theory values and the emulator [36, 48, 49] output is about 2% under a load resistance condition.



(20) (b)

Fig. 2.13. (a). Two photovoltaic modules are connected in series (b) Two photovoltaic modules connected in parallel

- **Prudhvi P, Chaitanya Sai P."Efficiency improvement of solar PV panels using active cooling" [Environment and Electrical Engineering (EEEIC), 2012 11th International Conference on], 18-25 May 2012, Pages 1093-1097 [50].**

Reflection of the sun’s irradiance usually diminishes the electrical yield of PV modules by 8-15% [10]. The accumulated reflection loss over one day for a fixed tilt-angle of the module depends on the latitude, clearness index (diffuse-direct ratio), surface treatment and the match of refractive indices within the layers of module encapsulation. A glass encapsulated or laminated PV module at a perpendicular incidence angle yields a reflection loss in the range of 4-5% [10]. Water with a refractive index of 1.3, is a viable intermediary between glass (n_{glass} = 1.5) and air (n_{air} =1.0), it helps in keeping surface clean and reduces reflection by 2-3.6%.

As Efficiency and electrical yield decrease with increased operating temperatures, it is preferred to maintain low module temperatures. To achieve so several techniques have been suggested like mounting water filled tank beneath PV module and due to its high thermal capacity of water in the tank, the PV module temperatures would be low [51-53], Flowing film of water on PV module front: Due to rapid flow of water there would be only a nominal increase in water temperature, the evaporating water further declines PV module’s operating temperature [10, 54] water trickling on the front surface of PV module [11], Placing under water solar PV panels [55, 56].

- **Malay Mazumder, Mark Horenstein, Jeremy Stark, Peter Girouard, Robert Sumner, Brooks Henderson, Omar Sadder, Ishihara Hidetaka, Alex Biris, and Rajesh Sharma.” Characterization of Electrodynamic Screen Performance for Dust Removal from Solar Panels and Solar Hydrogen Generators”. IEEE transactions on Industry Applications, Volume 49, Issue 4, July/August 2013. [57]**

In this paper author suggested for Electrodynamic Screens (EDS) [38] process for cleaning of solar PV panels. Transparent Electrodynamic screens (EDS), consisting of rows of transparent parallel electrodes embedded within transparent dielectric film can be used for dust removal. When the electrodes are triggered by phased voltage, the dust particles on the SPV surface of the film become electrostatically charged and are removed by the traveling wave

generated by applied electric field. Over 90% of deposited dust is removed within two minutes, using a very small fraction of the energy produced by the panels.
Technique suggested in this paper is good for dry climatic conditions, but it has constraints in humid conditions. Dust is not the only factor, other factors like bird dropping, water stains etc. comes into picture which reduces the efficiency of the Solar PV panels, where the above mentioned technique would not be successful.

- **Mark N. Horenstein, Malay K Mazumdar , Robert C Summer, Jeremy Stark, Tareq Abuhamed, Raymond Boxman. "Modeling of trajectories in an Electrodynamic Screen for Obtaining Maximum Particle Removal Effieciency". IEEE Transactions on Industry Applications; Volume 49, Issue 2; March/ April, 2013. [58]**

In this paper author has suggested for efficiency improvement of Electrodynamic Screens (EDS)[46]. One unpredicted result is the chaotic behavior of larger particles which jump sporadically back and forth and gradually migrate in the direction of the imposed electrostatic surface wave, shown in fig. 2.14. There are various factors which come into play like electrode width, electrode spacing, electrode voltage and excitation frequency. To assess the effects of these changing parameters, so as to determine the optimal values for a given particle size and charge, author has suggested a discrete-time-step simulation, to compute the motion of a single particle due to various forces exerted on it.

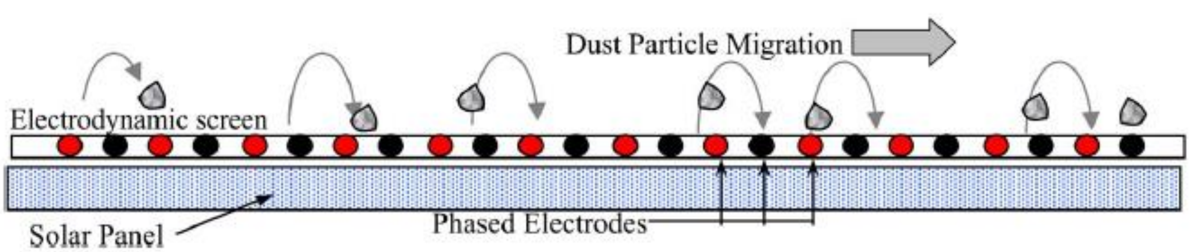


Fig. 2.14: Surface Electrodes energized by phased voltages produce an electrostatic travelling wave for lifting and transporting dust particles

Author simulated the particle charge-to-mass ratio q/m, and as per the mean value provided a baseline for use in the trajectory simulations. Fig. 2.15 shows a computed particle trajectory obtained by simulating.

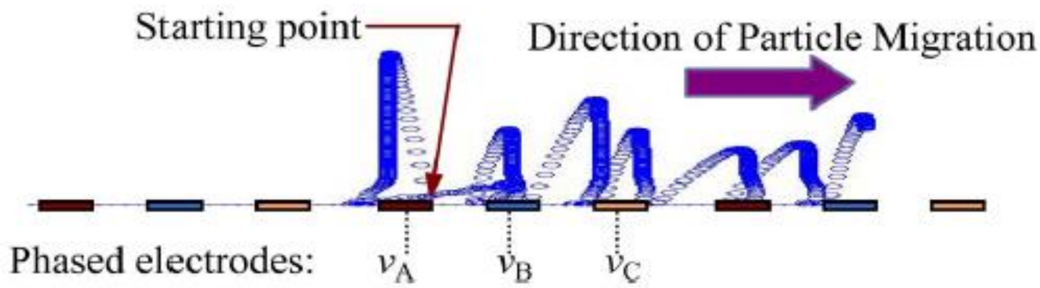


Fig. 2.15. Simulation model for calculated particle trajectory.

2.3.1 SUMMARY OF DUST EFFECT ON SOLAR PV PERFORMANCE FOR THE PERIOD OF 1942 TO 2012.

Table 2.2: Summary of Dust effect on Solar PV performance for the period of 1942 to 2012.

Reference	Location	Type of solar device	Period of study	Key findings	Comments and conditions
Hottel and Woertz [59]	Boston, MA, USA	Solar–thermal collectors	3 months	Maximum degradation during the test period was 4.7%	A correction factor of 0.99 (for a 45’’ tilt angle)
Dietz [60]	NY, USA	Glass samples	3 months	At tilt angles between 0’’ and 50’’, the reduction in solar radiation due to dirt was 5%	
Garg [61]	India	Solar collectors (glass and plastic covers)	30 days	For glass, 30% transmittance reduction for horizontal and 2% for vertical positions. Greater reduction was found for plastic	A correlation factor of 0.92 was deduced from the study (45’’ tilt angle); higher correlation factor for plastic than for glass
Sayigh[62]	Saudi Arabia	Solar collectors	25 days	Heat-collection reduction of 30% after 3 days without wiping	
Anagnostou and Forrestieri [63]	Cleveland, OH, USA	PV modules	1 year -	Degradation is site dependent. Washing does not eliminate all degradation. Permanent loss in maximum power reaches a steady value after several hundred days	Local condition is most damaging

Hoffman and Ross [64]	Pasadena, CA, USA	PV module (glass)	Laboratory testing	Test procedure for two field-related problems: surface soiling and encapsulate delaminating	
Pettit, Freese, and Arvizu [65]	New Mexico, USA	Solar mirror	1 month	The portable directional reflectometer used to measure the specular reflector loss due to dust accumulation can be limited to a single wavelength	Method to determine solar-averaged reflectance loss from a single measurement at 500 nm
Blackmon and Curcija [66]	California & New Mexico, USA	Heliostat	6 months	Washing heliostat by spray is feasible, and rain and snow could effectively clean it	
Berg [67]	New Mexico, USA	Heliostat	5–6 weeks	High-pressure water spray can recover 95% of the reflectance loss	Mobile system (automated)
Freese [68]	New Mexico, USA	Mirrors	7 months	Wind can cause a slight decrease in the reflectance. Melting snow and rain are effective in cleaning dust	Useful correlations with wind, rain; cleaning cycle experiments
Murphy and Forman [69];Forman [70]	Lexington, MA, USA	PV module (glass)	18 months	Measurement of soil accumulation and model cleaning using gloss meter	
Nimmo, Saed [71]	Saudi Arabia	Solar collectors& PV	6 months	26% and 40% reduction of efficiency from solar collector and PV panels,	Dry conditions

		modules (glass)		respectively	
Hoffman and Maag [72]	California, USA	PV module (glass)	17 months	To identify key environmental factors that govern soiling levels	Outdoor exposure testing for long durations is the most effective means of evaluating soiling
Roth and Pettit[73]	New Mexico, USA	Mirrors		Reflectance as function of particle size/scattering effects. Small particles are most significant scattering source (less than 1 micro meter)	Reported effectiveness of surface coatings and electrostatic biasing for mitigation. Wind tunnel studies
Cuddihy [74]	Pasadena, CA, USA	PV module	Theoretical study	Describe known and postulated mechanism of soil retention on surfaces	Dust morphology/size data
Pettit and Freese [75]	New Mexico, USA	Mirrors	10 months	Deposited particles are much more effective in reflecting particles than absorbing it	Force mechanisms proposed and investigated for dust adhesion
Zakhidov and Ismanzhanov [76]	USSR	Mirrors	Experiment	Strong wind with driven dust causes damage to the surface of the mirror	
Wakim [77]	Kuwait	PV modules (glass)	6 days	17% reduction in efficiency of module	
Roth [73]	New Mexico, USA	Mirrors	Up to 10 months	Reflectance losses as function of wavelengths of incident light and of particle size/distribution	Differences in particle distributions between day and night due to soluble

					nature of the particles. Morphology data. Adhesion forces.
Bethea et al. [78]	Texas, USA	Solar concentrator	Laboratory experiment	Reflectivity expected to decrease by 2.4% per year due to dust storm conditions	Simulated studies; Accelerated lifetime test development.
Sayigh et al. [79]	Kuwait	Glass, plexiglass, stainless steel, mirrors	38 days	64%, 48%, 38%, 30%, and 17% transmittance reduction for 0’’,15’’,30’’,45’’, and 60’’ tilt angles, respectively	Dust particle topography, dust size evaluations
El-Shobokshy et al.[80];Zakzouk [81]	Saudi Arabia	CPV	1 month	Open-circuit voltage did not change, and short-circuit current and cell efficiency showed a large change with dust deposition	Concentrating PV study; effect on dust accumulation on cell temperature investigated; Modeling of series resistance effects
Berganov et al. [82]	USSR	PV cells	6 months	Effect of soiling on solar cell power production is High	
Bajpai and Gupta [83]	Nigeria	Silicon solar cell	4 months	Poor efficiency due to scattering of incoming radiation by dust particles	
Michalsky [84]	New York, USA	Pyranometers	2 months	1% reduction for the exposed, not-cleaned Pyranometer	

Ryan et al. [85]	Oregon, USA	Solar module array (glass)	6 years	Unwashed solar cell array has degraded at a rate about 1.4% per year	Fluctuations in degradation (rates) do exist and long-term testing of degradation is needed
Said [86]	Saudi Arabia	Solar collectors& PV modules (glass)	1 year	7% reduction per month for PV panels and 2.8% to 7% for solar collectors	
Deffenbaugh et al. [87]	6-sites, USA	Parabolic solar collectors		Long-terms exposure testing for reflective and transmissive loss evaluation. Developed prediction method based upon modeling of results. Wash frequency and optical degradation rates are used as primary inputs to model long term observations.	Used various sites to establish independence of methodology to any specific location. (Oregon, Georgia, Texas (2), Ohio, California, New Mexico)
Al-Alawy [88]	Baghdad, Iraq	Horizontal surface (glass)	9 years	Higher percentage of cumulative dust leads to an energy reduction of 50% or more	Good correlations with wind speed and dust accumulations; good base of daily and hourly solar radiation used for models

Nahar and Gupta [89]	India	Solar collector	18 months	Annual drop in transmittance for daily cleaning cycle was 4.26%, 2.94%, 1.36% and for weekly cleaning cycle was 15.06%, 9.88%, 3.28% for glass at tilt angles of 01,451, and 901	Examined glass, vinyl, acrylics—glass is superior under dust conditions. The data raise concerns about locating large solar power plants without including strict cleaning plans
Hassan and Sayigh [90]	Kuwait	Glass	38 days	64%, 48%, 38%, 30%, and 17% transmittance Reduction for 0°, 15°, 30°, 45° and 60° tilt angles, respectively	Spectral report that all wavelengths are affected
Pande [91]	India	PV module (glass)	1 year	Reduction in current value due to dust was up to 30%	
Goossens et al. [19]	Israel	PV module (glass) and mirror	Laboratory work	Wind direction and panel orientation have a severe effect on dust deposition and distribution. A wind velocity of greater than 2 m/s has only a minor effect on dust distribution	Wind tunnel experiments. Correlated these with real conditions
El-Shobokshy and Hussein [20]	Saudi Arabia	PV modules (glass)	Laboratory work	Dust material, size and deposition density has a strong effect on loss of output power	PV surface prepared under zero wind velocity and no natural desert dust was used

Alamoud [92]	Riyadh, Saudi Arabia	PV module (glass)	1 year	Efficiency decreased by 5.73% to 19.8% depending on the type of the module when exposed to outside environment	Compared module specifications to manufacturer's claims (differences). Hot, arid conditions
El-Nashar [93]	United Arab Emirates	Evacuated-tube collector	1 year	Monthly percentage in glass transmittance decline is seasonal: 10% in summer and 6% in winter. Reduction of 70% of collector performance when left without cleaning for one year	Hourly and monthly data acquired
Bowden et al. [94]	Sydney, Australia	PV roof tiles and concentrators	Laboratory work	Dust affects the energy conversion to a small degree. Examined effect of dust on the loss in internal reflectance of the CSP roof units. Total losses less than 1.3%	Part of a larger study on performance of PV products for rooftops. Data for coastal and in-land locations/ residential/commercial
Adanu [95]	Ghana	PV system (glass)	4 years	Effect of dust particles in atmosphere generally lessens the solar irradiance and the energy output from the PV array	Time of day data reported. Cleaning by wiping of module surface
Kattakayam et al. [96]	India	PV module (glass)	Laboratory work	The loss of power due to accumulation of dust and the increase in temperature of the panel can be	Careful analysis of IV characteristic from operating PV field. Provides

				significant	information on instrumentation for monitoring
Becker et al. [97]	Cologne, Germany	PV cells	Laboratory work	The pollution leads to a partial shadowing of the cells reducing the output	This pollution has minor effects on PV operation (Less than 4%)
Hammond et al. [98]	Arizona, USA	PV module (glass) and radiometer	16 months to 5 years	Soiling effect on PV module increase as the angle of incident increases. Losses increased from 2.3% at normal incident to 4.7% at 241and 8% at 581. For radiometer, lost more than 2% due to soiling, and up to 8% due to bird droppings.	Extensive soiling data on PV modules and radiometer outputs
Offer and Zangvil [99]	Israel	Mirrors	1 week in May, 1990	Airborne particle accumulation on solar mirrors decreases the reflectivity and the mirror efficiency. Reflectivity reductions greater than 90%	Desert testing, including dust storm data
Goossens, Van Kerschaever [100]	Israel	PV modules (glass)	Laboratory work	Fine dust deposition on the cell has significant effect on power output. Considered effects of due to air borne dust concentration and wind velocity.	Reported I–V characteristics as a function of the dust density

				Reported losses in solar intensity on cells, open-circuit voltage, fill factor, short-circuit current and power as function of accumulation time. Power losses greater than 95%	
Mastecbayeva and Kumar [101]	India	Glass	30 days	Transmittance dropped from 87.9% to 75.8% over the 30-day period	
Biryukov[102, 103]	Israel	Mirror	Laboratory experiments	For measurement of dust influence on reflector, the experiment showed the intensity of concentrated light; confirmed result of measurement with specular reflectometer	Used three different techniques to determine dust effects on specular properties of parabolic concentrator
Asl-Soleimani et al. [104]	Tehran, Iran	PV system	10 months	Air pollution can diminish the energy output of solar module by more than 60% in a city like Tehran	PV module output monitored as function of time of day under ‘‘pollution’’ conditions
Hegazy [105]	Egypt	Glass plates	1 year	Solar transmittance as function of tilt angles. Vertical plates had dust with diameterso1mm only. Compared a calculated ‘‘dust factor’’ (correction factor) to the	Plates purposely not cleaned over 1-month periods. Compares data to reports from India and Kuwait

				observed one. Loss in transmittance typically 75–80% over a month's exposure	
El-Nashar [106]	Abu Dhabi, United Arab Emirates	Evacuated-tube collectors (glass)	1 year	Drop in transmittance (0.98 under ''clean'' condition to 0.70), causing as much as 40% drop in distillate production. (Need to supply 38% more power from conventional electricity generation)	Application is a solar desalination plant (1864 m^2 collector field); Seawater distillation with 120 m^3/day capacity
Badran [107]	Arizona, USA	Mirrors of telescope	3 years	Coating for 3 years exhibited 5%–7% drop in reflectivity at 310 nm and no decease in other wavelengths. Water washing is the best cleaning method	Cleaning methods developed for Cherenkov telescope at Mt. Hopkins.
Hassan et al. [108]	Saudi Arabia	PV modules (glass)	6 months	33.5% and 65.8% reductions in efficiency after 1 month and 6 months.	
Kobayashi et al. [109]	Tokyo, Japan	PV module (glass)	Laboratory experiments	Changing the aspect ratio of PV cell used for PV module results in degradation output of 80% or less with 3% of spot dirt on the module area.	Primarily ''dirt spot'' analysis; Some correspondence to the shape of the solar cell in the module. Also, studied cell circuit-configuration

					effects.
Elminir et al. [110]	Helwan, Cairo, Egypt	PV cells and glass	7 months	Decreases in PV output of about 17.4%/month	Provides information as a function of tilt angle. Includes a chemical analysis of the dust.
Kimber et al. [111]	California and South-western USA	PV system (grid-connected)	1 year	''Soiling'' study for utility-connected PV system. Efficiency and energy losses (typical 0.2% per day without rainfall)	Restorative nature of rainfall well documented. Various locations provided in these portions of USA.
El-Nashar [112]	Abu Dhabi, United Arab Emirates	Evacuated-tube solar–thermal collectors (glass)	1 year	Seasonal losses due to dust at 14%–18%	Updated and seasonal data following El-Nashar (2008); solar desalination plant; automated data Acquisition.
Al-Helal and Alhamdan [113]	Saudi Arabia	Polyethylene covers	13 months	Reduction in global solar radiation was 9% after 1 month, then reduced to 5% after 11 months due to rainfall in the area	GSR and PAR transmittance evaluations; application to greenhouse enclosures.
Clark et al. [114]	MD, USA	Lunar dust control	Laboratory experime	Design a compact device less than 5 kg mass and using less than 5	

			nts	W to harness the dust for sampling as part of the extended exploration of Mercury, Mars, or other regions of the solar system	
Vivar et al. [115]	Madrid, Spain; and Canberra, Australia	CPV system (various lenses)	4 months	CPV system more sensitive than flat-plate PV to dust accumulation. Up to 26% loss after 4 months exposure	Dust is critical factor for CPV performance
Yerli et al. [116]	Istanbul, Turkey	PV modules (glass)		Derating parameters reported for temperature and dirt; dust has most significant effect	750 Wp system
Mani and Pillai [117]	Bangalore, India	PV module and system	Review article	The paper includes two phases of research appraisal. Phase I from 1960 to 1990, phase II for post 1990. Table has been developed to guide in the identifying appropriate cleaning/ maintenance cycle for PV systems in response to the prevalent climatic and environmental conditions	Detailed review provides excellent guidance for cleaning and mitigation cycles.

Miller and Kurtz [118]		CPV Fresnel lenses	Review article	Primary look at PMMA lenses (some silicone-on-glass). Detailed examination of the loss mechanisms and durability. Soiling review included definitions, variation of reflectance with time, inclination (tilt), wavelength, the mechanisms of adhesion and accumulation, moisture, particle size and distribution, and prevention/soiling	Comprehensive examination of soiling of Fresnel lenses for CPV. Paper has much wider examination of the durability and degradation issues with the Fresnel lenses beyond the dust issues.
Ju and Fu [119]	Chongqing, China	PV modules (glass)	1 year	PV ‘‘fouling coefficient’’ proposed (0.985 during rainy season and 0.958 during dry season)	For PV project, proposed important considerations for dust in 3 stages of development: (1) Planning; (2) Design, and (3) Operation
Ibrahim [2]	Laboratory Tests and Kuwait	Solar cells (large-area 10 cm*6cm)	10 days	Current losses of greater than 13% and voltage losses of greater 0.86% (5%–15% loss in peak power)	Also studied shadowing of cells
Cabanillas and Mungui´a	Hermosillo, Sonoro,	Crystalline and amorphous	90 days (August through	4%–7% reduction in power for crystalline Si modules and 8%–13% for	Particle-size analysis as part of study. Careful analysis of

[120]	Mexico	Si PV modules	Decembe r)	amorphous-Si modules. Demonstrated sensitivity to module technology type	relationships between particle size and volume percent of that size occurring.
Sulaiman et al. [121]	Malaysi a	PV modules	Laborator y experime nt	18% or reduction in peak power when depositing dust on PV module. 6% power reduction difference between mud and talcum deposition	
Zorrilla-Casanova et al. [122]	Spain	PV module (glass)	1 year	In dry seasons, energy losses exceed 20% over 3-month periods. Annual average losses in PV output were 4.4% (with natural cleaning by rain). Proposed regular, periodic cleaning scheduled for modules	Provided simple model, simulated with ray-tracing methods to explain the behavior of dust-induced loses in solar PV modules. Looked at both fixed and tracking systems of PV panels; Evaluated time-of-day losses.
Pravan et al. [123]	**Italy**	PV system (1 MW)		Investigated two 1-MW PV systems; Soil type and washing technique control the losses. 6.9% loss with sandy soil and 1.1% with more compact soil	All measurement under STC. Regression model used (superior to performance ration which is influenced by

					seasonal variations in temperature and plant availability)
Jiang et al. [124]	**China**	PV module (glass)		Dust deposition layer 0 to 22 g/cm 2 , PV efficiency decreased by 26% (linear relationship). No difference between cell types	Note that modules encapsulated with epoxy (organic) degrade more.
Kaldellis and Kapsali [14]		PV generators	Modeling	Examined micro grids. Distributed systems are shown to have as much as a 12% better performance under dust conditions than a central station.	Modeling study for grid
Qasem et al. [125]	Kuwait	CdTe thin-film PV modules	Outdoor tests and modeling	Examined effect of dust densities o performance (in vertical and horizontal module configurations), with latter having increase risk of hot spots with dust deposition	Showed effects of moisture/dust in photos. Provided modeling of IV characteristics with dust deposition (using PSPICE)
Al Busairi, Moller ;Al-Busairi and Al-Kandari	Kuwait	Glass surfaces on various PV modules	Outdoor tests	Demonstrated that the decrease in power from PV module depends on the angle between the incident sun (photons) and the	Loading depends on the tilt angle and is non-uniform over module surface (time of day

[126]				normal to the panel	dependences)
Mekhilef et al.[127]	Malaysia	Solar cells and modules	Laboratory and modeling (2-month periods)	Examined the literature for dust effects on Performance as function of tilt. Reported average drop in performance (power): US 1–4.7%; Saudi Arabia 40%; Kuwait 65%, Egypt 33.5–65.8%, Thailand 11% (1 month)	Dust containing minute pollens, bacteria, fungi, microfibers (carpets and fabrics), vehicular and volcanic activity (specific to this region) Effects of moisture.
Mohamed and Hasan [128]	Libya	PV Modules	Outdoor Testing	PV modules exposed for a period from February through May in Sahara environment. Reported significant though gradual reduction in power. Cleaning procedures.	Object of study is to evaluate the cleaning needed to keep the PV output at a sufficient level. Weekly washing (water) kept power loses in the 2%–5% Range.
Qassem et al. [129]	Kuwait	PV Modules	Outdoor Testing	Investigated effect of dust on PV modules with respect to concentration and spectral transmittance. Examined a-Si:H, CIGS, and crystalline Si technologies	Provided interesting information on the spectral effects of the dust. Showed that because of this, wide-band gap technologies are affected more than lower band gap technologies.

2.3.2 SUMMARY OF STUDIES USING FORCED AIR (BLOWING) WITH WATER MIST AND ULTRASONIC TRANSDUCER ASSISTS [130].

Table 2.3: Summary of Forced air blowing technique

Technique	Medium	Effectiveness	Observations and constraints
Vortex nozzle	Air	Good	Requires close proximity to surface (0.30'' or less for a typical 0.10'' nozzle); lifecycle costs of cleaning about the same as using solution (water plus detergents)
Converging nozzle	Air with water mist Injection	Good to very good	Recovery of reflectance to 99% of original for mirrors. 10-cm separation from the surface for cleaning nozzle with 10 psig air. Water usage 2.14 mL/min (minimal water use)
Ultrasonic transducer with nozzle	Air with ultrasonic energy assist	Very good	Appreciably enhances the cleaning process of a mirror than with air blast alone (about 2% improvement). Transducer separation from mirror ~41 mm. Concluded to be best approach with improvement of transducer technology

2.3.3 SUMMARY OF MITIGATION APPROACHES TO REMOVE OR PREVENT DUST ACCUMULATIONS [67, 131-133]

Table 2.4: Summary of Mitigation Approaches

Strategy	Description	Focus
Deterrence: Keep dirt from settling and adhering to the surfaces(*preventative*)	Uses noncontact, continuous techniques. Material and design intensive. Durability and lifetime concerns. No labor. Timescale: Mid- to long-term	New materials development; design and materials
Washing: Wash off the dirt with water or low surface energy detergent-type solutions before strong	Involves frequent washing with detergent solutions, labor intensive, environmental impacts such as water usage, quality and disposal of waste water. Labor intensive	Primarily based on existing commercial products; operation and maintenance

chemical or mechanical bonding can develop (*restorative*)	(possible automation). Time scale: Short-term and immediate	
Cleaning: Use chemical or mechanically active cleaning techniques capable of breaking the chemical and mechanical bonds (*restorative*)	Mechanical or chemical supplements to washings. Design intensive (i.e., automated high-pressure washers). Concerns about damage. Labor intensive (possible automation). Timescale: Short-term and immediate	Chemistry understanding and design; operation and maintenance
Surface modification: Modify the surface (treatments, coatings, films) so that strong bonding cannot develop(*preventative*)	Surface modifications or a substitute surface. Substitute surfaces can be permanent or temporary coatings such as surfactants that can be periodically restored. Materials transmission and interfaces important; durability and service lifetime. No labor. Timescale: Long-term	Physics and chemistry understanding; design and materials

2.3.4 GENERAL RECOMMENDATION OF MITIGATION MEASURES AGAINST IMPACT OF DUST ACCUMULATION ON SPV PERFORMANCE.

Table 2.5: General recommendation of mitigation measures against impact of dust accumulation on SPV performance.

Climatic zone and Characteristics	**Conditions influencing SPV performance and dust deposition**	**Recommended cleaning cycle to mitigate impact of dust**
Group-I: Low Latitudes- Comprises mainly the wet, wet tropical. Average temperature: 20-34 °C	Wet- dry and the dry tropical climate. Low latitudes require low tilt in PV systems for maximum solar gain, but lower tilts will tend to accumulate higher dust deposition.	High annual precipitation could reduce dust accumulation (by periodic washing). Weekly cleaning recommended during dry spells and may be altered

Annual precipitation: > 250 cm Latitude Range: 10°S to 25°N	Tilts higher than latitude recommended to reduce dust accumulation. High annual precipitation could minimize dust accumulation.	based on intensity of dust accumulation.
Wet dry tropical Temperature range: 20 – 30 °C Annual Precipitation: > 150 cm Latitude Range: 15° to 25° N and S	Trade winds dominate during the dry season; blow from the north – east in the northern hemisphere and vice versa. PV systems with higher tilt recommended. PV panels to be oriented to benefit	Weekly cleaning recommended for moderate dust accumulation; daily cleaning recommended in case of intense dust accumulation.
Dry Tropical Temperature range: 20 – 49 °C Annual Precipitation: 15 cm Latitude Range: 15° to 25° N and S		

2.3.5 SUMMARY OF TECHNIQUES INVESTIGATED FOR PREVENTING DUST ACCUMULATION ON SOLAR SURFACES (REFLECTIVE AND TRANSMISSIVE).

Table 2.6: Summary of techniques investigated for preventing dust accumulation (reflective and transmissive)

Technique	Comment
Stowing (inverting) for	May be ineffective because of time constants for stowing arrays; not

Protection	applicable for fixed-axis arrays.
Aerodynamic streamlining	Prevention of turbulent eddies and dead spots; special engineering required
Electrostatic biasing	Several hundreds to thousands of volts with normal electric field rejects particles; less effective with moisture (cementation)
Vibrating the surface	Accelerates the surface motion until particles can no longer move due to inertia; damage potential with long-term use of techniques (e.g., contacts)
Thermally induced air currents	Boundary type of phenomenon used on astronomical telescopes; reliability and cost are issues; potential for damage (‘‘sand blasting’’)

2.4 RESEARCH GAP

Current labor-based cleaning methods for photovoltaic arrays are costly in time, water and energy usage and lack automation capabilities. Existing solutions are also dependent on geographical terrain, area of application. Depending on the above mentioned factors, existing solutions can be further compared on the basis of cost, ease of use and performance rate etc.
The existing solutions are not universally applicable for all environmental conditions.

Table 2.7: Comparison between different techniques used for Solar PV Cleaning/ protection

Technology	Method	Merits/Demerits
Water Sprinkler	Water is only been sprinkled to Solar PV panels. Sprinklers are fixed at a definite position on the side of Solar PV.	Excessive loss of water Spreading of water/ Reach is not uniform Economically not viable for Solar PV plants Unless demineralized water is used, it will leave traces.
Human Effort	With the help of wiping and cleaning material, Solar PV panels are cleaned.	Costly as person has to be a technical one Reach is not uniform
Existing Cleaning modules available (like Gekko Solar,	Rolling cleaning heads are rolled over the Solar PV panel with the help of robots kept over the	Cleaning robot weight is directly put over the Solar PV panels. Power consumption is more.

Gekko Solar Farm etc.)	panels.	Performance area is less.
Strowing (inverting) for protection	To avoid dust accumulation during night or dust storm, movable type arrays are inverted.	Ineffective because of time constants for stowing arrays Not applicable for fixed array type
Vibrating the surface	Vibrations are provided by special mechanical-electrical instrumentation for the device and activating it during dust storms	Damage potential with long term use of techniques (e.q. contacts)
Electrostatic Biasing	Several thousands of volts is applied which repel the charged particles.	Less effective with moisture concentration.
Proposed Robotic arm	Separate sprinkling and wiping units on cleaning head.	Minimum consumption of water Power consumption is less Performance area is more

The above table comprises of the comparison between present technology and the proposed technology. The table discusses the methods used, merits and demerits of both the technologies. The existing technologies are specified to a particular climatic condition but are not suitable for generalized climatic conditions.

2.5 OBJECTIVES

The research aims at making an Autonomous Solar PV panel cleaning system:

- ❖ To optimally design a solar panel cleaning robotic arm which will clean the SPV's using optimum resources.
- ❖ To develop and validate the mathematical model of Solar Panel cleaning robotic arm.
- ❖ Installation and performance analysis of the designed Solar panel cleaning robotic arm for cleaning SPV Modules and gathering real time data.

CHAPTER 3

EXPERIMENT DESIGN

3.1 PROBLEM DEFINITION AND RESEARCH QUESTIONS

The literature review discusses that there has been considerable research focused on the study of soiling effects on SPV modules and partial cleaning methods have been developed to counteract the situation. As the world is begin to prepare for a transition from fossil fuel (non- renewable) based energy sources to renewable sources, where solar energy is likely to be used in large scale. Despite low energy density of SPV Panels, it is the easiest way to collect and use the Solar energy. However SPV installation sites are wide open and easily susceptible to dust, sand etc, which deteriorate the expected performance of SPV modules. Furthermore, there are a variety of cleaning methods and technologies available for SPV plant operators to choose from, each with its advantages and disadvantages. Choosing the optimal method to clean PV panels over the lifetime of the power plant could be challenging due to the presence of several uncertainties such as operating cost variations, PV plant performance variation, soiling unpredictability, and lack of comparative field data regarding the different cleaning methods. This brings up the following questions:

i. Is it worth investing in cleaning of PV plants in arid regions?
ii. If worth, how often is it economically feasible to clean PV modules?
iii. What overarching factors should we consider when choosing the most appropriate cleaning method?

3.2 OVERVIEW OF TEST BED

i. Analysis Period: 1 Month (4 weeks/ 6 days per week)
ii. SPV Plant/ Test Bed Capacity:
iii. Module Type (with surface area):
iv. Mounting type (and Latitude angle): Fixed- Tilt; 29.8°.
v. Test Bed Layout: Two Rows each with one module.

vi. Access to Water and Runoff Measures: Access to Fresh water is available on site while full measures were taken to handle water runoff, such that concerns about soil and ground water pollution in the vicinity of the PV plant are minimal.

3.3 DETAILS OF SOLUTION PROCEDURE

The steps of the solution procedure are discussed in more detail as follows:

3.3.1 ESTIMATION OF SOILING EFFECTS

Estimating the consequence of soiling on the SPV modules is an important component of this research as it determines the necessity and cost of using robot from the enhanced performance of SPV modules. Furthermore, determining the energy lost, consequent economic and environmental implications associated with it, cleaning frequency are the other estimates. Following points have been observed about soiling of SPV modules from the literature review:

i. Dust deposition density has approximately a linear relationship with reduction of efficiency.
ii. Accumulation of dust and consequent reduction in efficiency increases with exposure time in absence of natural or artificial cleaning.
iii. SPV module efficiency diminishes with the type of dust on it.
iv. Soiling levels depends on the surrounding environment and source of pollutants.
v. SPV modules in the same location but with different orientation have different dust deposition densities.

3.3.2 APPROACH

In this project we can divide the methodology in two parts as follows:

Table 3.1: Mechanical and control aspect in Research methodology

S.No.	Mechanical Aspect	S. No.	Control Aspect
1.	Robot manipulator and end effector design	1.	Control System design

	➢ Design of low cost manipulator with less complexity		• Study of DC Geared Motor
	➢ Separate Stress , Strain Analysis of Robotics arm, Base		➢ Study of bidirectional Encoders and Interrupts
	➢ Selection of material.		➢ Study of DC Servo Motor
	➢ Fabrication of Robotic Arm		➢ Driving and exchanging data wirelessly of microcontrollers in SPI mode
2.	Automated Rail guided system		➢ Study and Testing of Ultrasonic sensor
	➢ Design of low cost rail guide system with less complexity.		➢ Incorporating of ultrasonic sensor in rail guide system for navigation.
	➢ Stress, Strain Analysis		➢ Study and testing of touch screen LCD
	➢ Incorporating of ultrasonic sensor in rail guide system for navigation.		➢ Designing of GUI for touch screen
3.	Fabrication of Robotic Arm, Rail Guided system etc.		• Study of chain sprocket and gear assembly for overall system
4.	Site construction for Solar PV and Rail setup.		• Analysis of all parameters, block diagram and transfer function design.
5.	Integration of mechanical and control aspects.		
6.	Testing and evaluation of robotic arm.		
7.	Comparative study of performance and efficiency of standard cleaning method and cleaning by robotic arm.		
8.	Physical observation (removal of dust particles, effect of dew drops, rain fall) of surface of panel to check the performance of robot for further improvement.		

3.4 CONFIGURATION OF SPCRA

The control of SPCRA links is achieved using joint actuators. There are basically three types of robot actuators available: hydraulic, pneumatic and electric motor [70]. As per the requirement and advantages of using electric motor, we opt for DC motors In below table 4.2 key advantages and disadvantages of actuator selection has been described[134].

Table 3.2: Robot Actuators [134]

Hydraulic	**Electric Motor**	**Pneumatic**
Advantages: i. Good for large robots and heavy payloads. ii. Can work in a wide range of speeds iii. Self-lubricating	Advantages: i. Good for all sizes of robots. ii. Good for high precision robots. iii. High power conversion efficiency.	Advantages: i. Inexpensive and simple ii. Good for on and off applications.
Disadvantages: i. Viscosity of oil varies with temperature. ii. Very prone to dirt and other foreign material in oil. iii. Low power conversion efficiency.	Disadvantages: i. Needs gears. ii. Needs break. iii. Backlash and elasticity.	Disadvantages: i. Low power to weight ratio. ii. Fluid compressibility errors.

The hydraulic actuators are suitable for heavy payload robots, but are susceptible to dirt, therefore they are not suitable for SPV cleaning. Pneumatic actuators are low power consuming type and have fluid compressibility but are not proper responsive towards contraction and rarefaction, hence not suitable for SPCRA. The electric motor advantages outweigh its disadvantages and also after reviewing commercially available articulated robot manipulators, electric motor has been chosen.

SPCRA consists of a robotic arm which is been powered with worm geared 12 V DC servo motor, it is having 4 DOF and is mounted with a base which is kept over a Rail guided platform. Base and Rail guided platform is coupled with a geared system which is been powered via another side shaft 12V DC geared motor. Chain sprocket assembly system is kept on the arm which is been powered by a side shaft 12V DC geared motor with bidirectional encoder fitted in it. Rail guided system rolls over a T beam which is made up of mild steel with the help of a gear mechanism attached with a side shaft 12V DC geared motor.

To visually monitor the whole process, camera surveillance has been provided using Logitech HD webcam. This camera can be mounted on the robotic arm end effector because of its small size or can be used for surveillance purpose, which will be kept at a distance from the Solar PV panel arrays to look after the whole working. Cleaning of the Solar PV panels can be based on periodic time intervals or depending upon the camera received data.

3.5 MECHANICAL DESIGN OF SPCRA

In the design of the Robotic arm many factors [8, 135, 136] are considered such as weight, assembly and disassembly of parts, workspace, load capacity, speed, repeatability and accuracy, volume, energy, efficiency and cost. Rigid – link manipulators require light, stiff structures to achieve high accuracy and low inertia. Several designs techniques have been studied for designing the manipulator [137, 138]. Analysis of stiffness [139], displacement of manipulators links has been done with the help of solid works. Optimization techniques and calibration techniques have been used to correct errors in accuracy. While designing manipulator arm light weight material with high strength has been chosen

The robotic arm is of four degree - of – freedom, it comprises of two revolute and two prismatic joints. Design of the robotic arm should be focused on its weight. The maximum payload is defined to be 500 g, which is in consideration with the weight of cleaning head mechanism, but it has been tested (in software) for 5 kg. The length of the Robotic arm is 1.4 m (as shown in fig.3.1 and 3.2). From this 1.4m the actual cleaning dimension is of 0.64 m (as shown in fig. 3.15 , rest is kept as clearance between the robot and the Solar PV array and mounting of ultrasonic sensor at top of Robotic arm. The robotic arm is connected with the worm geared 12 V DC servo motor placed at the bottom of the link in the base. The advantage of worm gear assembly is:

- Right angle power transmission.
- No need of stall torque, worm gear arrangement will hold the load during no power.

Workspace of SPCRA

:

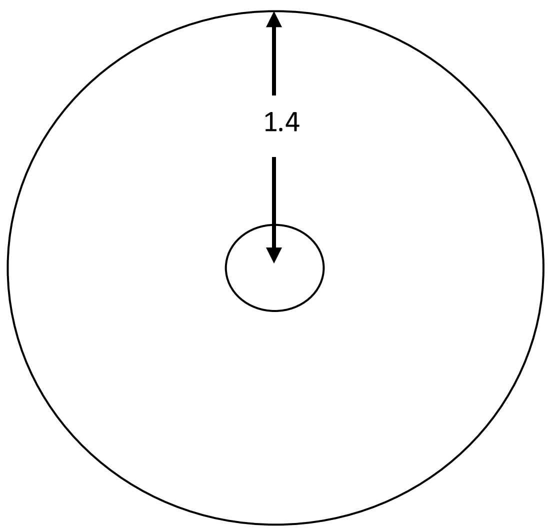


Fig. 3.1: Top View of the workspace of SPCRA

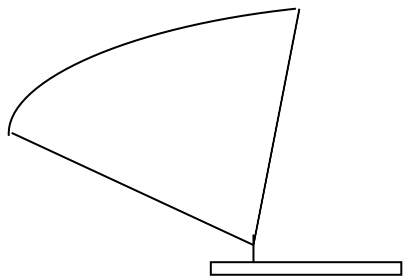


Fig 3.2: Side View of the Workspace of SPCRA

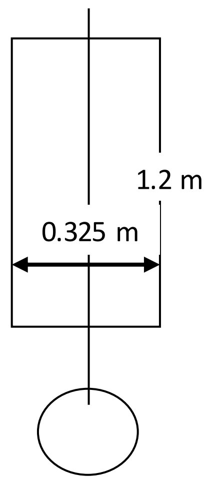


Fig 3.3: Cleaning Workspace of the SPCR (One Stroke)

Hence, less power consumption and protection of Solar PV panels from any mishap due to robotic arm. The material of the arm is chosen as aluminum (AI6063; Grade T5) for light weight and high strength.

The chain sprocket assembly from Vex Robotics is made up of reinforced material and can transmit heavy loads up to 22.6 kg over long distances.

To move this chain sprocket assembly side shaft geared DC motor (85 rpm) with bi-directional encoder is fitted. It is having a stall torque of 21kg/cm @ 12V.

The base holds the arm with the help of worm geared 12 V DC servo motor placed at the bottom of the link. It also holds few other parts of the robotic assembly like blower, mini water tank with pump, side shaft DC motor coupled with the guide rail. Because of the other items placed on it, the counterweight tilt while the robotic arm is tilted towards the Solar PV panels. To make the base area small and strengthy, we made it circular and the material is mild steel.

The rail guided platform is made up of mild steel. It carries the whole structure of the robot, which includes arm and base (and its components). Considering the total weight of the robot, strength of material and ease of fabrication we choose mild steel for the rail guided platform. Complete robot is moved with the help of a 12V side shaft DC motor which is coupled with the T beam rail (made up of cast iron) using gear mechanism. The inference we conclude after structural analysis of the above component of the robotic manipulator is that it is the major load bearing component and hence has to be structurally sound and stable. The base of the arm (along with gear system and other parts) and he arm itself is kept on top of it which exerts a combined load of few Kilo Newton of force. The self-weight of the structure is also considered in the analysis.

The structure is made purely out of mild steel except the arm which is made from Aluminum (Al 6063 T5). The types of load are exerted on this component which are:

1) Normal load due to the base and the arm arrangement
2) Torque applied via gear arrangement
3) Self weight of the component.

Stress, strain and displacement studies were done in SOLIDWORKS [140]. From fig. 3.4 it is apparent that the maximum stress is induced at the junction of the hollow rod and main structure. This is due to the maximum amount of strain occurs at that position. The junction is a welded joint and hence maximum amount of stress is concentrated at this point. The scale besides the fig. 3.4 shows, maximum and minimum stress strain ranges. This analysis gives us a clear idea that we need to release the stress from the specified location. It can be either done by heat treating the component to make bring it to a specified strength or using the same material for welding as the base material to maintain the uniformity in the properties. Hence welding was done using mid steel only.

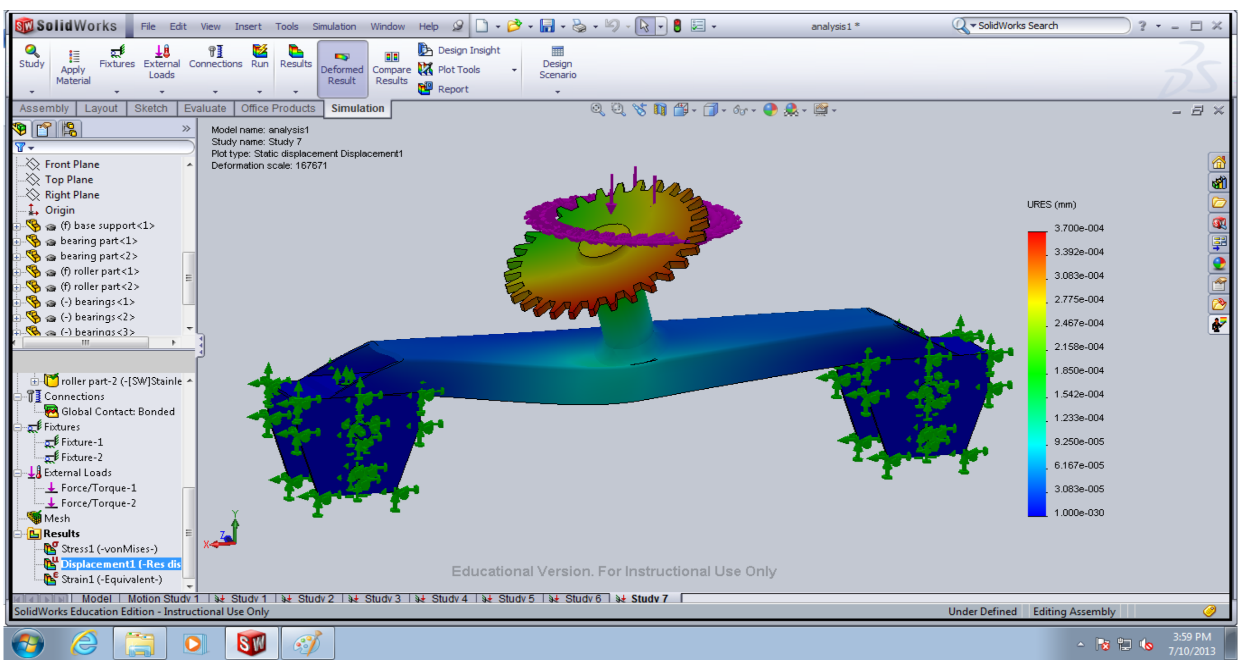


Fig 3.4: Displacement of Rail Guided System

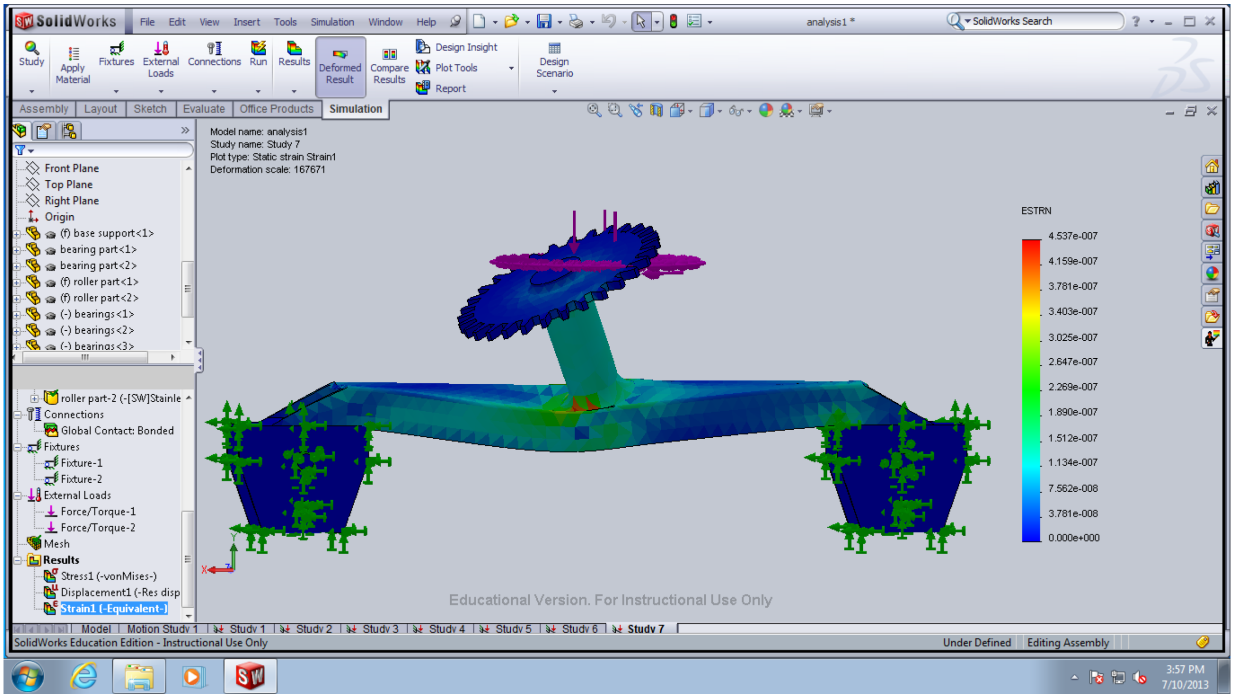


Fig 3.5: Strain of Rail Guided System

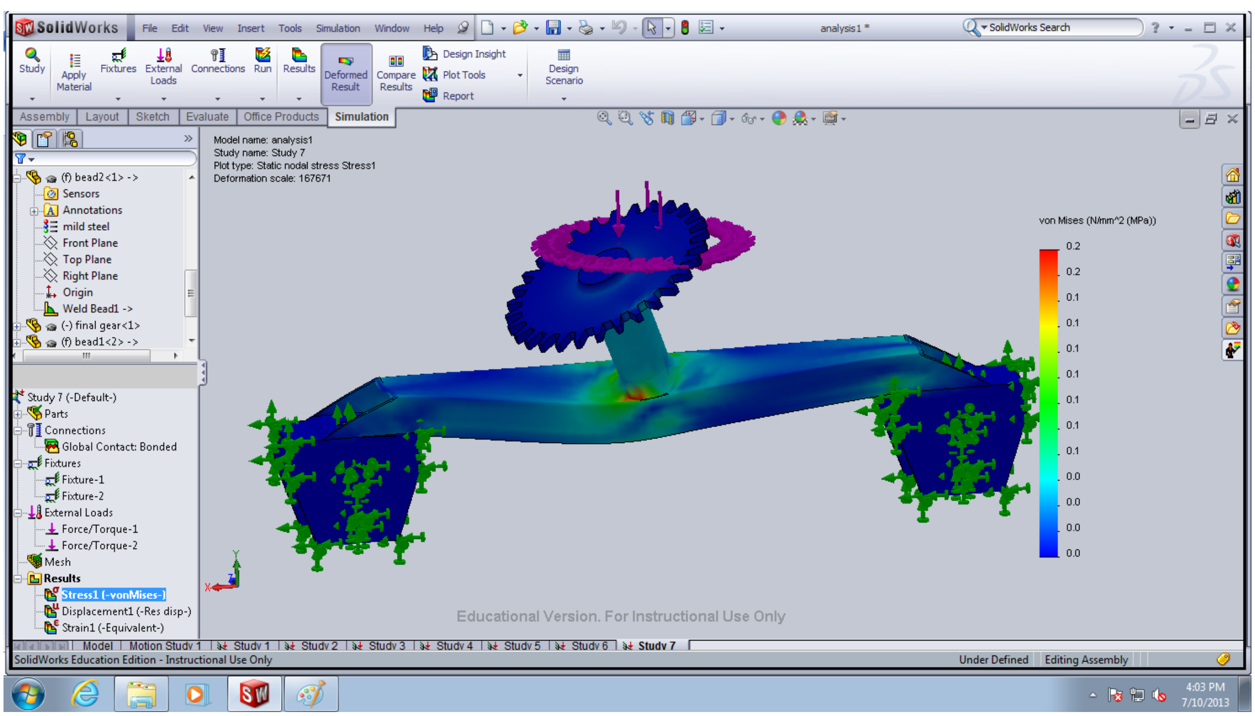


Fig 3.6: Stress of Rail Guided System

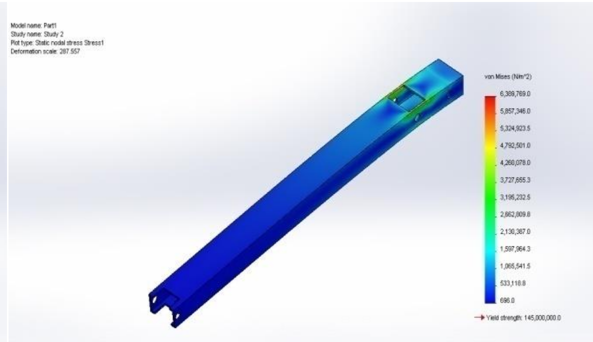
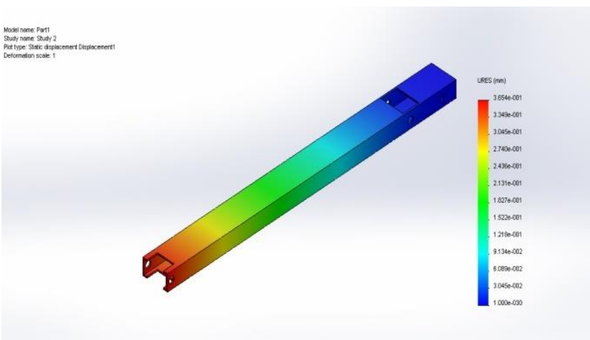


Fig 3.7: Mesh Diagram

Fig 3.8: Stress



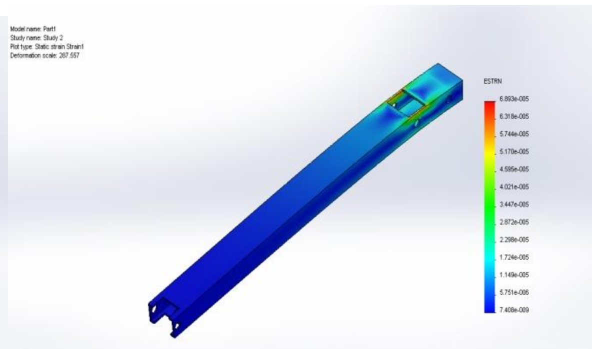


Fig 3.9: Displacement

Fig 3.10: Static Strain

The above fig. 3.7, 3.8, 3.9, 3.10 show the results produced by the load analysis on the robotic arm of the structure. Fig 3.7, shows the mesh diagram of the robotic arm which sustains the load of the cleaning head, chain and sprocket motion system and the driving motor.

Fig 3.8, shows the Von Misses stress analysis of the robotic arm. The values of the stress range from 696 (minimum) to 6,389,769 (maximum) N/m^2. The von Mises yield criterion suggests that the yielding of materials begins when the second deviatory stress invariant J_2 reaches a critical value. For this reason, it is sometimes called the J_2 -plasticity or J_2 flow theory. It is part of a plasticity theory that applies best to ductile materials, such as metals. Prior to yield, material response is assumed to be elastic.

Fig 3.9, shows the URES Resultant Displacement analysis of the robotic arm. The values of the displacement range from 1X10^{-30} mm (minimum) to 3.654X10^{-1} mm (maximum) under the maximum load condition. The load is assumed to be 50 N (~5.1 Kg) which is under the loading factor of safety of >3.

Fig 3.10. show the Static Strain analysis of the robotic arm. The values of the Static Strain the structure range from 7.4X10^{-9} (minimum) to 6.9X10^{-5} (maximum). A scalar quantity called the equivalent strain, or the von Mises equivalent strain, is often used to describe the state of strain in solids. Several definitions of equivalent strain can be found in the literature. A definition that is commonly used in the literature on plasticity is

$$\varepsilon_{\text{eq}} = \sqrt{\tfrac{2}{3}\boldsymbol{\varepsilon}^{\text{dev}} : \boldsymbol{\varepsilon}^{\text{dev}}} = \sqrt{\tfrac{2}{3}\varepsilon_{ij}^{\text{dev}}\varepsilon_{ij}^{\text{dev}}} \qquad \boldsymbol{\varepsilon}^{\text{dev}} = \boldsymbol{\varepsilon} - \tfrac{1}{3}\text{tr}(\boldsymbol{\varepsilon})\ \mathbf{1}$$

This quantity is work conjugate to the equivalent stress defined as

$$\sigma_{\text{eq}} = \sqrt{\tfrac{3}{2}\boldsymbol{\sigma}^{\text{dev}} : \boldsymbol{\sigma}^{\text{dev}}}$$

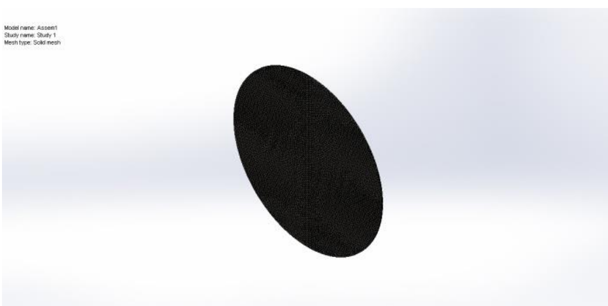


Fig 3.11: Mesh Diagram

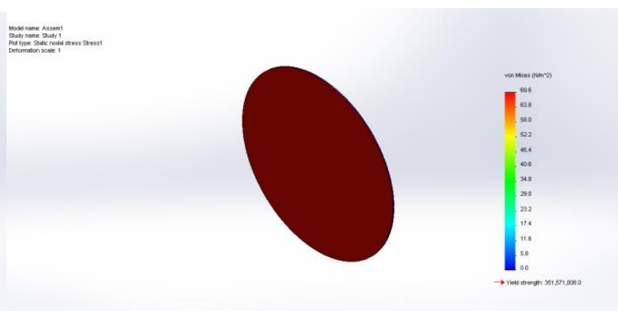


Fig 3.12: Stress

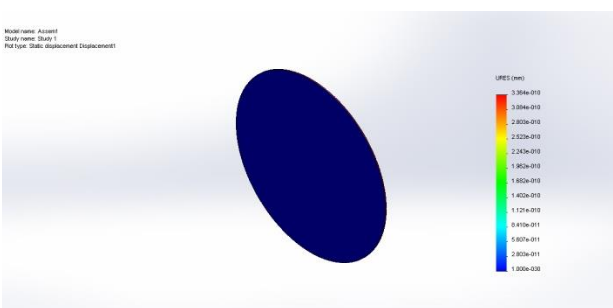


Fig 3.13: Displacement

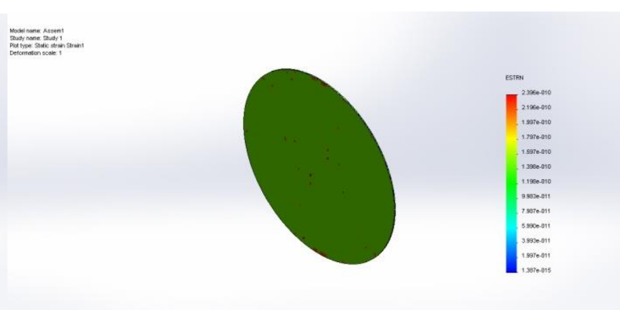


Fig 3.14: Static Strain

The above fig. 3.11, 3.12, 3.13, 3.14 show the results produced by the load analysis on the base of the structure. figure 4.12, shows the mesh diagram of the revolving base which sustains the load of the robotic arm, air blower, water tank, and battery.

Figure 3.13, shows the Von Misses stress analysis of the revolving base. The values of the stress range from 0 (minimum) to 69.6 (maximum) N/m^2. The yield strength is 351,571,008

N/m^2. The von Mises yield criterion suggests that the yielding of materials begins when the second deviatory stress invariant J_2 reaches a critical value. For this reason, it is sometimes called the J_2-plasticity or J_2 flow theory. It is part of a plasticity theory that applies best to ductile materials, such as metals. Prior to yield, material response is assumed to be elastic.

Figure 3.13, shows the URES Resultant Displacement analysis of the revolving base. The values of the displacement range from 1X10^{-30} mm (minimum) to 3.364X10^{-10} mm (maximum) under the maximum load condition. The load is assumed to be 150 N (~15.3 Kg) which is under the loading factor of safety of >3.

Figure 3.14, show the Static Strain analysis of the revolving base. The values of the Static Strain the structure range from 1.387X10^{-15} (minimum) to 2.386X10^{-10} (maximum). A scalar quantity called the equivalent strain, or the von Mises equivalent strain, is often used to describe the state of strain in solids. Several definitions of equivalent strain can be found in the literature. A definition that is commonly used in the literature on plasticity is

$$\varepsilon_{\rm eq} = \sqrt{\tfrac{2}{3}\boldsymbol{\varepsilon}^{\rm dev} : \boldsymbol{\varepsilon}^{\rm dev}} = \sqrt{\tfrac{2}{3}\varepsilon_{ij}^{\rm dev}\varepsilon_{ij}^{\rm dev}} \qquad \boldsymbol{\varepsilon}^{\rm dev} = \boldsymbol{\varepsilon} - \tfrac{1}{3}{\rm tr}(\boldsymbol{\varepsilon})\ \mathbf{1}$$

This quantity is work conjugate to the equivalent stress defined as

$$\sigma_{\rm eq} = \sqrt{\tfrac{3}{2}\boldsymbol{\sigma}^{\rm dev} : \boldsymbol{\sigma}^{\rm dev}}$$

The mechanical properties of the selected material are as follows in table 3.3 and 3.4:

Table 3.3: Mechanical properties of Cast Iron (to check the load bearing capacity)

Property	**Value**	**Units**
Elastic Modulus	6.61781 X 10^{10}	N/m^2
Shear Modulus	5 X 10^{10}	N/m^2
Density	7200	Kg/m^3
Tensile Strength	1.51658 X 10^8	N/m^2
Compressive Strength	5.72165 X 10^8	N/m^2

Table 3.4: Mechanical properties of Aluminium (Arm)-6063-T5 (to check the load bearing capacity)

Property	Value	Units
Elastic Modulus	6.9×10^{10}	N/m^2
Shear Modulus	2.58×10^{10}	N/m^2
Density	2700	Kg/m^3
Tensile Strength	1.45×10^{8}	N/m^2
Compressive Strength	5.72165×10^{8}	N/m^2

Considering the array based positioning of SPV panels, following steps are taken in to account:

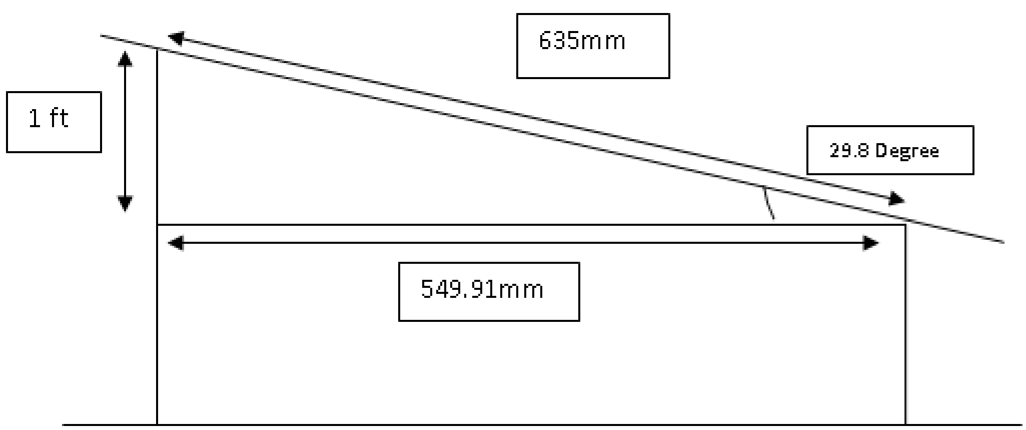


Fig. 3.15: Fixed type SPV module placing

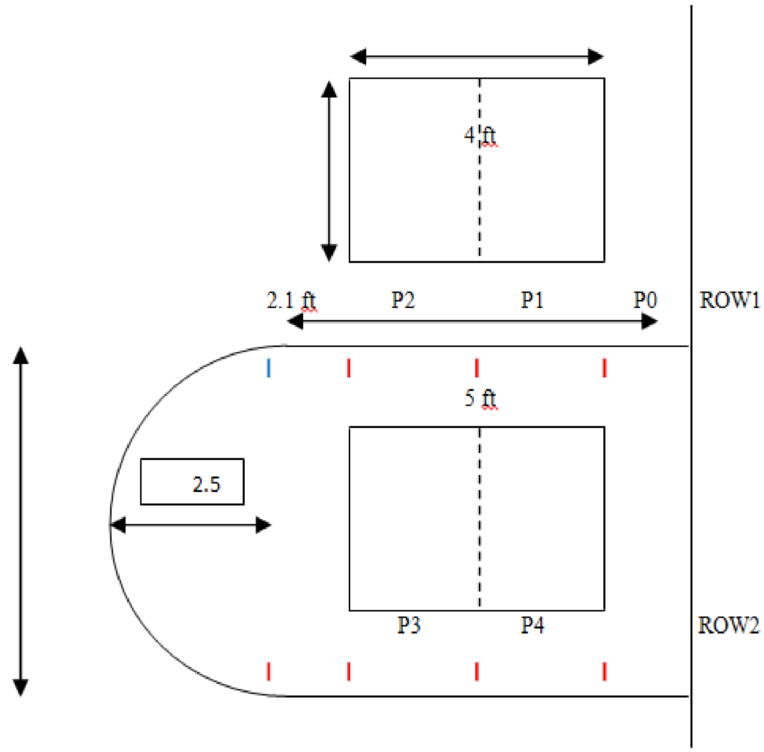


Fig. 3.16: Rail Guided and SPV module placing

- Initially SPCRA will come to its home position P0 shown in Fig. 3.16.
- From its home position, it will go to its position P1 which will be determined via the no. of ticks.
- On reaching its first position, guide rail system will stop and arm will start tilting towards the SPV panels.
- Cleaning head starts from the top of the inclined SPV panels to its base, where it stops.
- After cleaning of row1, SPCRA comes out and enters the semi curricular path where it stops in between and rotates 180°. and proceeds further

3.6 COMPONENT SPECIFICATIONS

#	Component	Specification	Description
1.	**Robotic arm (aluminium 6063-**		• Light weight and high strength

	T5)		
	Worm geared dc Motor [141]	Operating voltage: 12/24 V No load current:1.5-2.5 A Load current: 3.5-5 A Nominal power: 50 W Torque: 56 N-m Stall torque: 29 N-m No load speed: 45 rpm Load speed: 40 rpm Weight: 2 kg	• Right angle power transmission. • No need of stall torque, worm gear arrangement will hold • The load during no power)
	Side shaft bi directional encoded motor [142]	Operating voltage: 12 V Stall current: 1.8 A Nominal power: 50 W No load speed: 85 rpm Load speed: 85 rpm Weight: 320 g	• Bi directional encoder for the cleaning head motion, up and down. • PWM based speed control
	Motor driver [143]	Operating voltage: 6- 16 V Continuous o/p current: 8A Peak current: 30 A Current sense: 0.13 V/A. Dimension: 51.3 x 27.7 mm^2	• As per battery rating and spcra current consumption. • Over voltage and under voltage shutdown • Thermal shutdown • Motor fault diagnostics outputs for over temperature or short circuit
	High Strength sprocket & chain kit [144]		Reinforced sprockets and chain can transmit higher loads over long distances.

			Length has been chosen as per arm length.
2.	**Rail guided system (mild steel)**		
	Side shaft dc motor	Operating voltage: 12/24 V Stall current: 1.8 A Nominal power: 50 W No load speed: 85 rpm Weight: 320 g	High torque
3.	**End effector**		
	Wiper	Material: Rubber Width: 614 mm	• Flat aerodynamic blade. • Ensures even pressure to Reduce smears
4.	**Controller**		
	ATMEGA 16		• Speed control by pwm (ocr pins) • 16 kb of flash memory for storing code. • 1 kb of sram for permanent storage • Data retention rate of 20 yrs. (85° C) • 10 bit ADC • Write / Erase cycles: 10k flash
	Proximity Switch	Type: DC 3 wire type Switch appearance type: Cylinder type	• To detect the upward and downward edge of SPV panels. Detecting distance is

		Theory: Induction Sensor Output type: NPN NC (normal closed) Detecting Distance: 1.5 mm Work Voltage: dc 10-35 V Consumption Current: max 200 mA	taken low, so that the cleaning head reached till end. • Water and moisture protection. • Over-current and short Circuit protection, with led Indicate, easily identifiable.

CHAPTER 4

EXPERIMENT DESIGN

4.1 TRAJECTORY PLANNING

An industrial robot is a specific application based machine for industrial automation. As per the requirement, robots are precisely formulated to perform the desired performance and functionality. The required motion control performance depends on the application. For better performance and application subjected to automation by a specific robot model. Some requirement examples are:

i. High path accuracy for continuous application.
ii. Small overshoots and a short settling time in discrete process applications.
iii. High control stiffness in contact applications, etc.

4.1.1 PATH VERSUS TRAJECTORY

A path is defined as the collection of a sequence of configurations a robot makes to go from one place to another without regard to the timing of these configurations while a trajectory is related to the timing at which each part of the path must be attained [134]. Also depending on how fast each portion of the path is traversed, the trajectory may differ.

4.1.2 JOINT SPACE TRAJECTORY PLANNING

In due course of moving a robotic arm from point A to B, there would be several ways to achieve so, but we have to choose the trajectory which suites the following criteria:

i. Slow start and stop of the robotic arm, which will help in minimizing the damping by virtue of inertia.
ii. At the beginning of the path traversing the robotic arm has to accelerate and before reaching the destination point it should decelerate.
iii. Follow the boundary conditions:

$$\theta(t_i) = 90°; \qquad \dot{\theta}\,(t_i) = \frac{0°}{sec}; \qquad \theta\,(\ddot{t_\iota}) = \frac{0°}{sec^2}$$

$$\theta\,(t_f) = 30°; \qquad \dot{\theta}\,\,(t_f) = \frac{0°}{sec}\,; \qquad \ddot{\theta}\,\,(t_f) = \frac{0°}{sec^2}$$

Where t_i = *0 sec (initial time)* and t_f = *2.75 sec (final time)* are boundary conditions.
$\theta, \dot{\theta}$ *and* $\ddot{\theta}$ are the angular position, velocity and acceleration.

iv. As the actual path is a smaller one, hence blending required is as follows, as shown in Fig. 4.1:

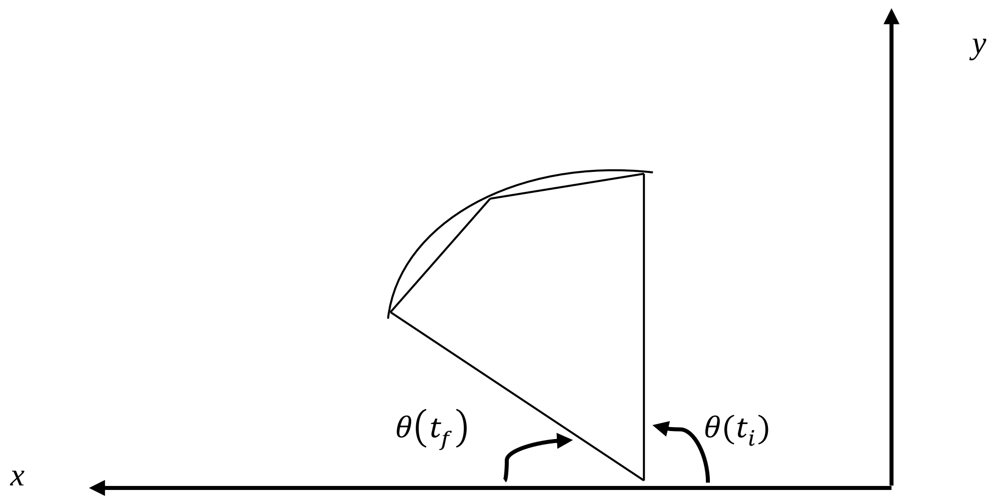


Fig. 4.1: Graphical representation of trajectory planning

$\theta\,(t) = c_0 + c_1 t + c_2 t^2 + c_3\, t^3$
$\dot{\theta}(t) = c_1 + 2c_2 t + 3c_3 t^2$
$\ddot{\theta}(t) = 2c_2 + 6c_3 t$
where, $c_0 = 90$; $c_1 = 0$; $c_2 = -23.8119$; $c_3 = 5.7741$

Table 4.1: Actual and Simulated torque

Sl. No.	Simulated Torque (Nm) (Via Simulation)	Actual Torque (Nm)
1.	18.256	15.032

4.2 DYNAMICS OF SPCRA

The chapter describes the mathematical modeling for obtaining the dynamics of SPCRA. To accelerate a robot's links, it is necessary to have actuators capable of exerting large enough forces and torques on the links and joints to move them as desired velocity and acceleration. Otherwise, the links may not be moving as fast as desired and consequently, the robot may not maintain the desired positional accuracy. To calculate how strong each actuator must be, it is necessary to determine the dynamic relationships that govern the motions of the robot. These relationships are the force –mass –acceleration and the torque –inertia –angular –acceleration equations. Based on these equations, and considering the external loads on the robot, the designer can calculate the largest loads to which the actuators may be subjected, thereby designing the actuators to be able to deliver the necessary forces and torques.

In general, the dynamic equations may be used to find the equations of motion of mechanisms ie. by knowing the forces and torques, we can predict how a mechanism will move. We will use these equations to find what forces and torques may be needed to induce desired acceleration in the robot's joints and links.

In general, techniques such as Newtonian mechanics can be used to find the dynamic equations for robots. However, due to the fact that robots are 3-D and multi –DOF mechanisms with distributed masses, it is very difficult to use Newtonian mechanics. Instead, we may opt to use other techniques such as Lagrangian mechanics, which is based on energy terms only, and therefore, in many cases, easier to use. Lagrangian mechanics is based on the differentiation of the energy terms with respect to the system's variables and time. Lagrangian mechanics is based on the following two generalized equations: one for linear motions and one for rotational motions.

For mathematical modeling of SPCRA, we have to individually model its sub parts as:

i. The arm-wiper system (as shown in fig. 4.2)

ii. Heading / Yaw motion (as shown in fig. 4.2)

iii. Transitional motion about the rails. (as shown in fig. 4.3)

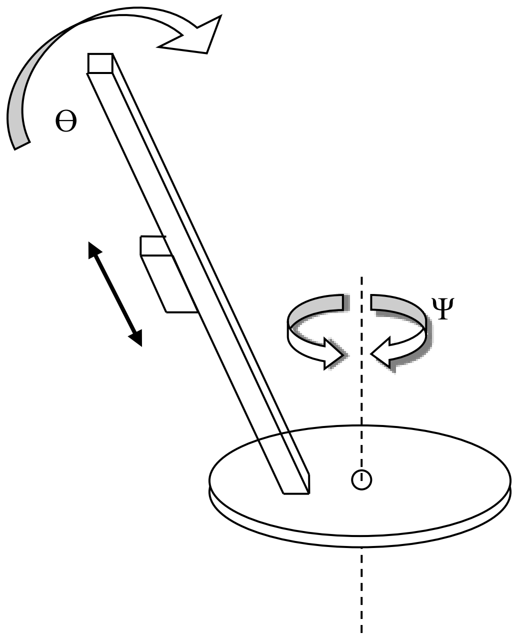


Fig. 4.2: Schematic diagram of Arm-wiper system and Heading/ Yaw motion

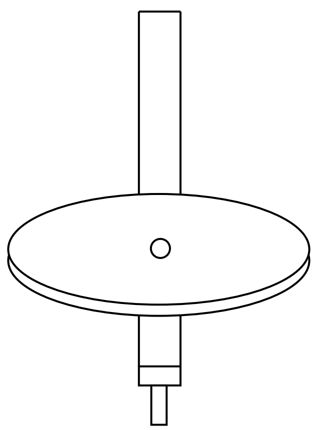


Fig. 4.3: Transitional motion about the rails

A. The arm-wiper system

i. Two Degrees of freedom: Θ, Ψ

- $m_{1:}$ Mass of Arm.
- $r_{1:}$ Constant distance, where the center of mass of the arm can be said to be concentrated.

- $m_{2:}$ Mass of wiper system.

- r: Distance of the wiper system from the center of rotation

ii. Inputs to the system:
  - T_Θ: Torque applied at the hub in the direction of 'Θ'. (as shown in fig. 4.18)
  - F_r: Translational force applied in the direction of 'r'. (as shown in fig. 4.18)

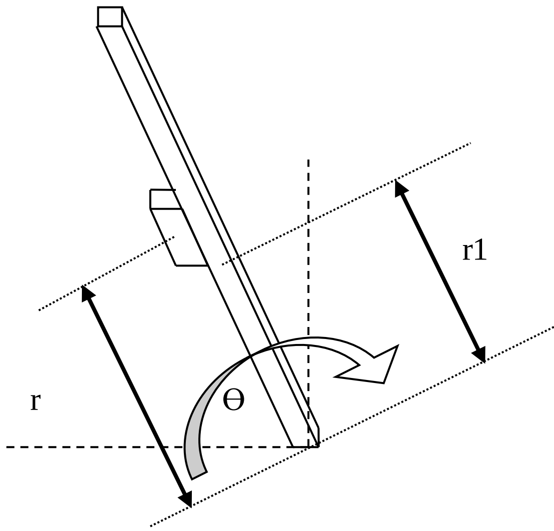


Fig. 4.4: Torque and transitional force

i. Lagrangian Equations of motion for the system:
  - Total Kinetic energy of the system

    Position of mass m_1:

$$x_1 = r_1 \cos\theta$$
$$y_1 = r_1 \sin\theta$$
$$\dot{x}_1 = -r_1\dot{\theta}\sin\theta$$
$$\dot{y}_1 = r_1\dot{\theta}\cos\theta$$

Magnitude squared of the velocity vector of mass m_1:

$$v_1^2 = \dot{x}_1^2 + \dot{y}_1^2 = r_1^2\dot{\theta}^2 sin^2\theta + r_1^2\dot{\theta}^2 cos^2\theta$$
$$v_1^2 = r_1^2\dot{\theta}^2$$

Kinetic Energy of mass m_1 is:

$$k_1 = \frac{1}{2}m_1 v_1^2$$
$$k_1 = \frac{1}{2}m_1 r_1^2\dot{\theta}^2$$

Position of mass m_2:

$$x_2 = r\cos\theta$$
$$y_2 = r\sin\theta$$
$$\dot{x}_2 = \dot{r}\cos\theta - r\,\dot{\theta}\sin\theta$$
$$\dot{y}_2 = \dot{r}sin\theta + r\dot{\theta}\cos\theta$$

Magnitude squared of the velocity vector of mass m_1:

$$v_2^2 = \dot{x}_2^2 + \dot{y}_2^2 = (\dot{r}\cos\theta - r\,\dot{\theta}\sin\theta)^2 + (\dot{r}sin\theta + r\dot{\theta}\cos\theta)^2 \quad v_2^2 = \dot{r}^2 + r^2\dot{\theta}^2$$

Kinetic Energy of mass m_2 is:

$$k_2 = \frac{1}{2}m_2 v_2^2$$

$$k_2 = \frac{1}{2}m_2\,\dot{r}^2 + \frac{1}{2}m_2\,r^2\dot{\theta}^2$$

Hence, total kinetic energy of the system: $k = k_1 + k_2$

$$k = \frac{1}{2}m_1 r_1^2\dot{\theta}^2 + \frac{1}{2}m_2\,\dot{r}^2 + \frac{1}{2}m_2\,r^2\dot{\theta}^2$$

- Total Potential Energy of the system:

For mass m_1:

$$u_1 = m_1 g r_1 \sin\theta$$

For mass m_2:

$$u_2 = m_2 g r \sin\theta$$

Total Potential Energy:

$$u = u_1 + u_2 = m_1 g r_1 \sin\theta + m_2 g r \sin\theta$$

- The Lagrangian function for the system considering distributed mass of the robotic arm:

$$l = (k - u) + \frac{I_{C1}\dot{\theta}^2}{2}$$

$$l = \frac{1}{2}m_1 r_1^2\dot{\theta}^2 + \frac{1}{2}m_2\,\dot{r}^2 + \frac{1}{2}m_2\,r^2\dot{\theta}^2 - m_1 g r_1\sin\theta - m_2 g r \sin\theta + \frac{I_{C1}\dot{\theta}^2}{2}$$

Where, $\frac{d}{dt}\left(\frac{\partial l}{\partial\dot{\theta}}\right) - \left(\frac{\partial l}{\partial\theta}\right) + \left(\frac{\partial q}{\partial\dot{\theta}}\right) = 0$

$q = \frac{C_1}{2}\dot{\theta}_1^2$; q is Rayleigh Damping

$\frac{\partial q}{\partial\dot{\theta}_1} = C_1\dot{\theta}_1$ and

$I_{C1} = \frac{ml^2}{12}$

- The system has two degrees of freedom. Hence, we have two Lagrangian equations of motion for this system:

$$\frac{d}{dt}\left(\frac{\partial l}{\partial \dot\theta}\right) - \frac{\partial l}{\partial \theta} = T_\theta \qquad \text{……….(a)}$$

$$\frac{d}{dt}\left(\frac{\partial l}{\partial \dot r}\right) - \frac{\partial l}{\partial r} = F_r \qquad \text{……….(b)}$$

Solving for equation no. (a).

$$\frac{\partial l}{\partial \dot\theta} = m_1 r_1^2 \dot\theta + m_2 r^2 \dot\theta$$

$$\frac{\partial l}{\partial \theta} = -(m_1 g r_1 \cos\theta + m_2 g r \cos\theta)$$

Hence, the first Lagrangian equation yields:

$$T_\theta = m_1 r_1^2 \ddot\theta + m_2 r^2 \ddot\theta + 2 m_2 r \dot r \dot\theta - g\cos\theta\,(m_1 r_1 + m_2 r) + I_{C1}\ddot\theta$$

Solving for equation no. (b).

$$\frac{\partial l}{\partial \dot r} = m_2 \dot r$$

$$\frac{d}{dt}\left(\frac{\partial l}{\partial \dot r}\right) = m_2 \ddot r$$

$$\frac{\partial l}{\partial r} = m_2 r \dot\theta^2 - m_2 g \sin\theta$$

Hence, the second Lagrange equation yields:

$$F_r = m_2 \ddot r - m_2 r \dot\theta^2 + m_2 g \sin\theta *$$

In state space form :

Let $x_1 = \theta, x_2 = \dot\theta, x_3 = r, x_4 = \dot r$

Then,

$$\begin{bmatrix} \dot x_1 \\ \dot x_2 \\ \dot x_3 \\ \dot x_4 \end{bmatrix} = \begin{bmatrix} x_2 \\ \frac{-2m_2 x_2 x_3 x_4 + g\cos x_1 (m_1 r_1 + m_2 x_3) + u_1}{m_1 r_1^2 + m_2 x_3^2 + I_{c_1}} \\ x_4 \\ x_2^2 x_3 - g\sin x_1 + {u_2}/{m_2} \end{bmatrix}$$

Where $u_1 = T_\theta$ and $u_2 = F_r$

*(*Calculation including Wind forces etc. has been shown in Annexure I)*

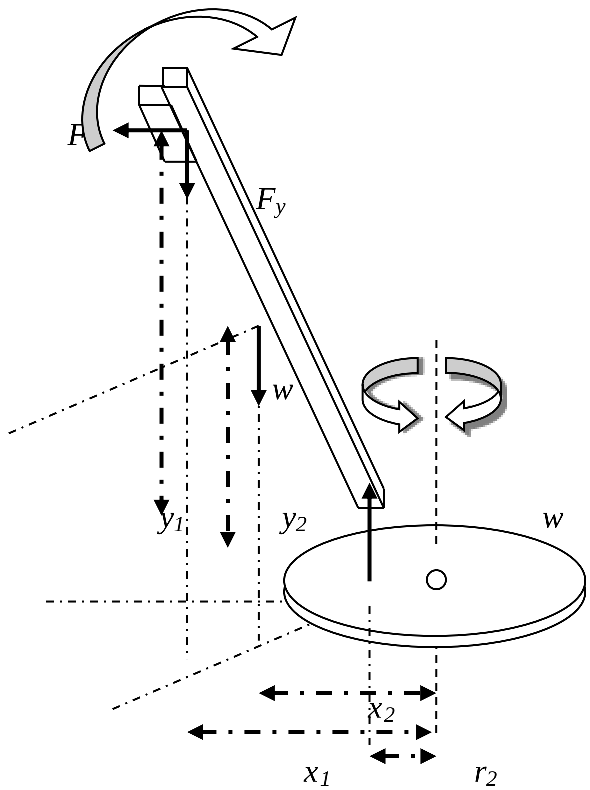


Fig. 4.5: Forces acting on SPCRA

- Effect of Robotic arm on the circular base, when the Robotic arm is in use.

  Two types of forces acting on the circular base (as shown in fig. 4.5),

  i. Weight of the robotic arm 'w'

  ii. Reaction force applied by the robotic arm on the circular surface 'F_r'

$$F_x = F_r \cos\theta$$

$$F_y = F_r \sin\theta + w$$

$$M_{xy} = F_r \sin\theta x_1 + F_r \cos\theta y_1 + w x_2$$

Where x_1 and y_1 are the distance of the perpendicular arm from the end effector. x_2 and y_2 are the distance of the perpendicular arm's centre of gravity point.

- Analysis of Circular base (considering robotic arm)

$$M_c = M_{xy} + F_y r_2$$

From figure 4.6, it is clear that the robotic arm is tending towards stability in due course of time as the vibration of the arm is diminishing. Although its effect has been damped as the wiper is made up of vulcanized rubber, hence there will be no practical adverse effect on SPV panel.

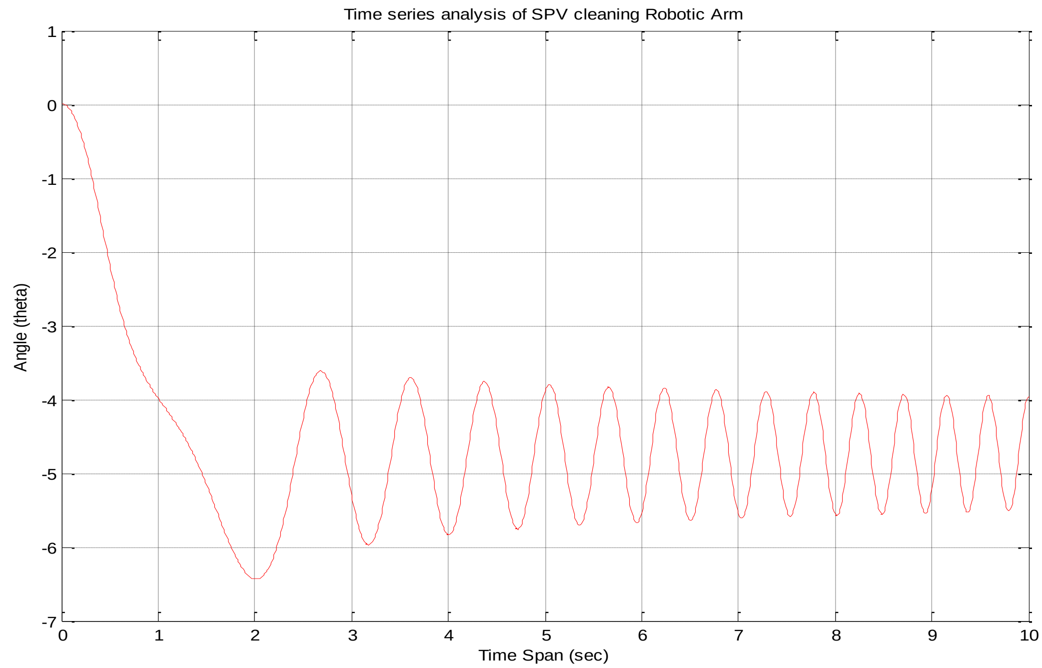


Fig. 4.6: Time series analysis of SPCRA

From figure 4.7, it is clear that the phase plot is concentrated in a particular region which implies that the arm is stable in a particular which is also validating figure 4.6.

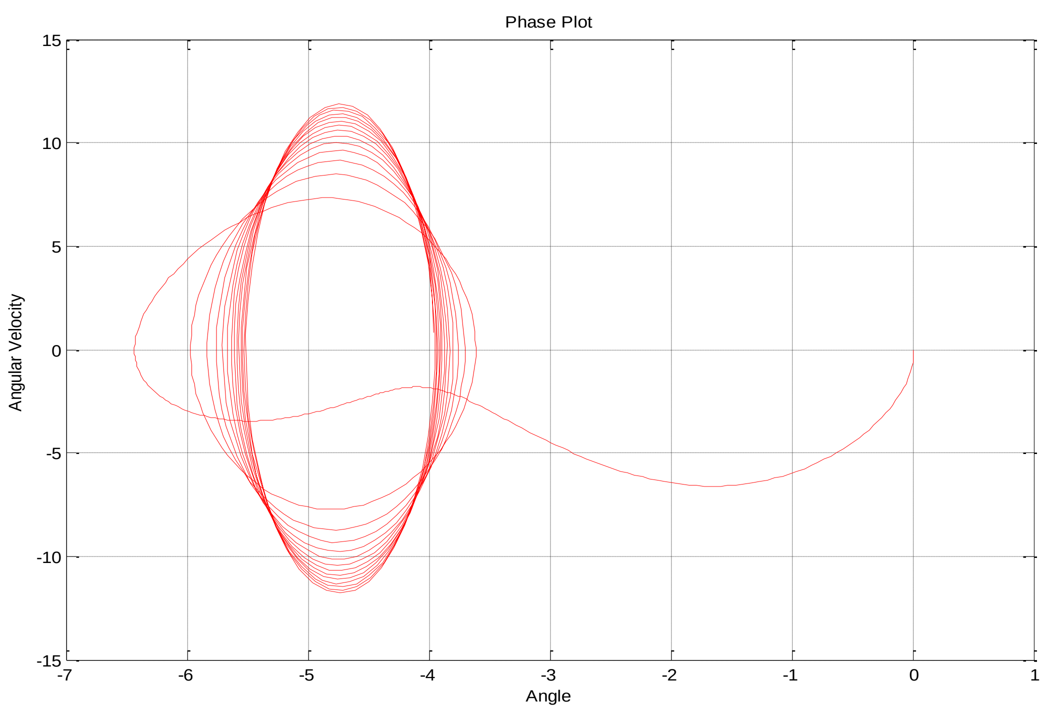


Fig. 4.7: Phase Plot of SPCRA

4.3 BLOCK DIAGRAM

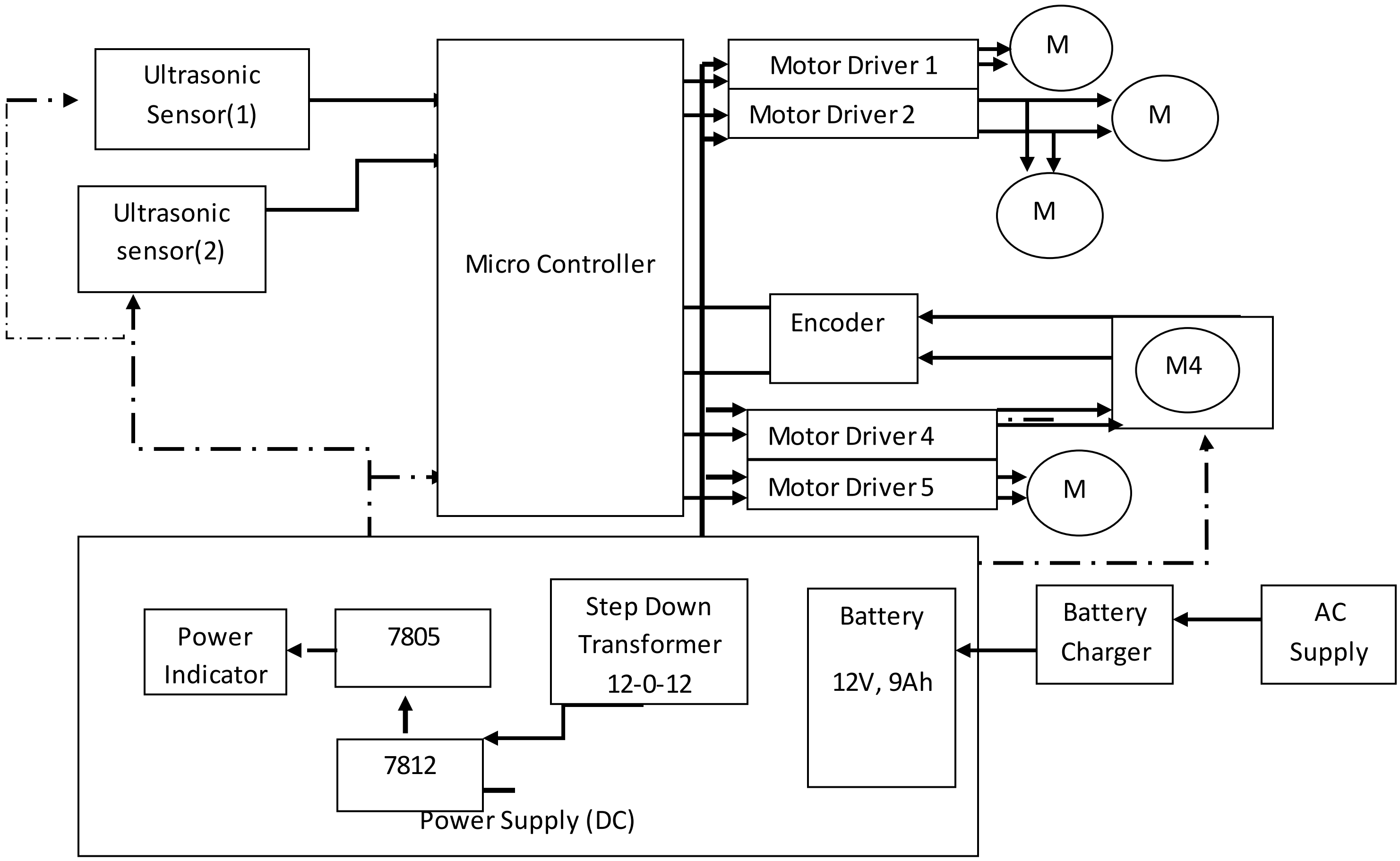


Fig. 4.8: Block diagram of SPCRA

In figure 4.8, control circuit of SPCRA using microcontroller is been described and the same has been shown in figure 4.9 with proper pin connections with Atmega 16. As the system can be controlled by using any microcontroller having few basic requirements like pulse width modulation (PWM), Analog to Digital converter ports, interrupts etc. PWM is required for proper speed control. ADC port is required for reading the battery voltage level and reading the path clearance using ultrasonic sensors. Interrupts are required for counting encoder values of motor for accurate positioning. Motors are driven using motor driver IC's, using control pulse from the microcontroller.

4.4 CIRCUIT DIAGRAM

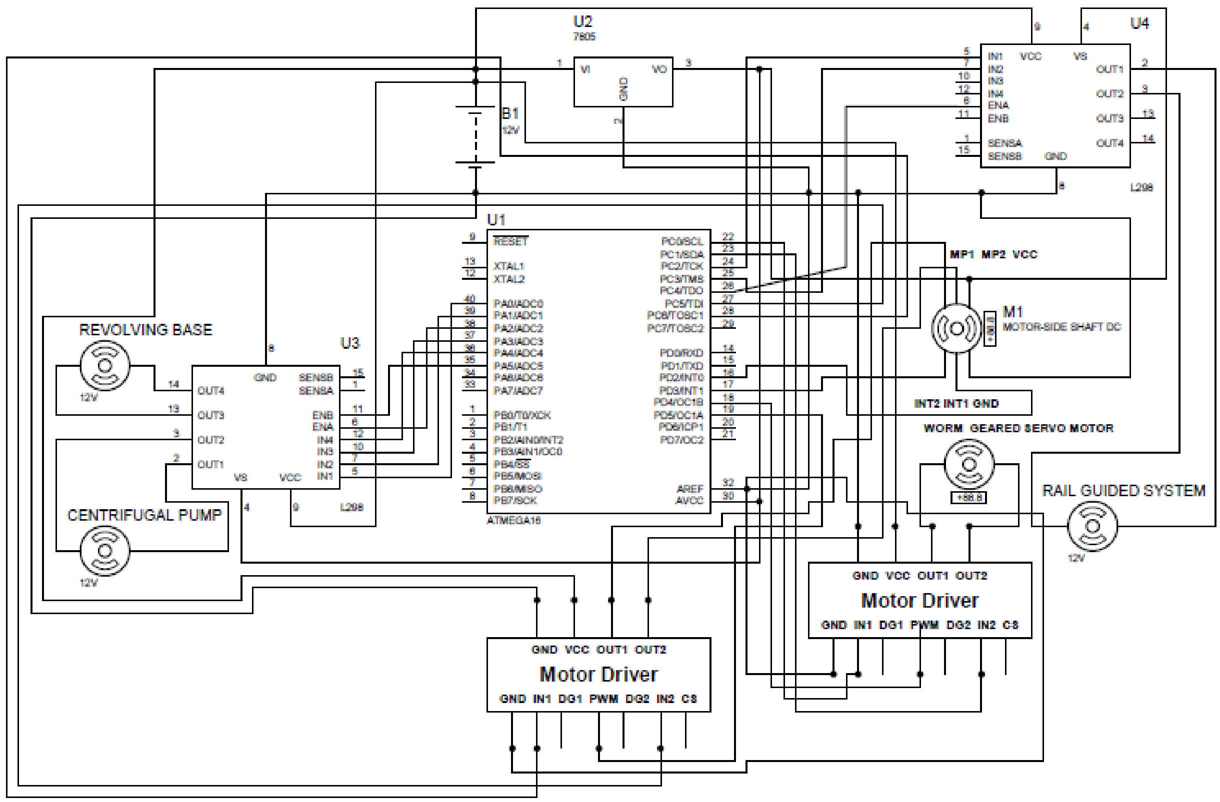


Fig. 4.9: Circuit Diagram of SPCRA

4.5 ALGORITHM

Few algorithms have been followed for the working of SPCRA:

- Main Loop
  - i. Status Check Loops
    - a. Path Clearance
    - b. Water Level
    - c. Battery Charge
  - ii. Rail Guide Algorithm
  - iii. Arm Down Algorithm
  - iv. End Effector Cleaning Algorithm
  - v. Arm Up Algorithm

4.5.1 Main Loop

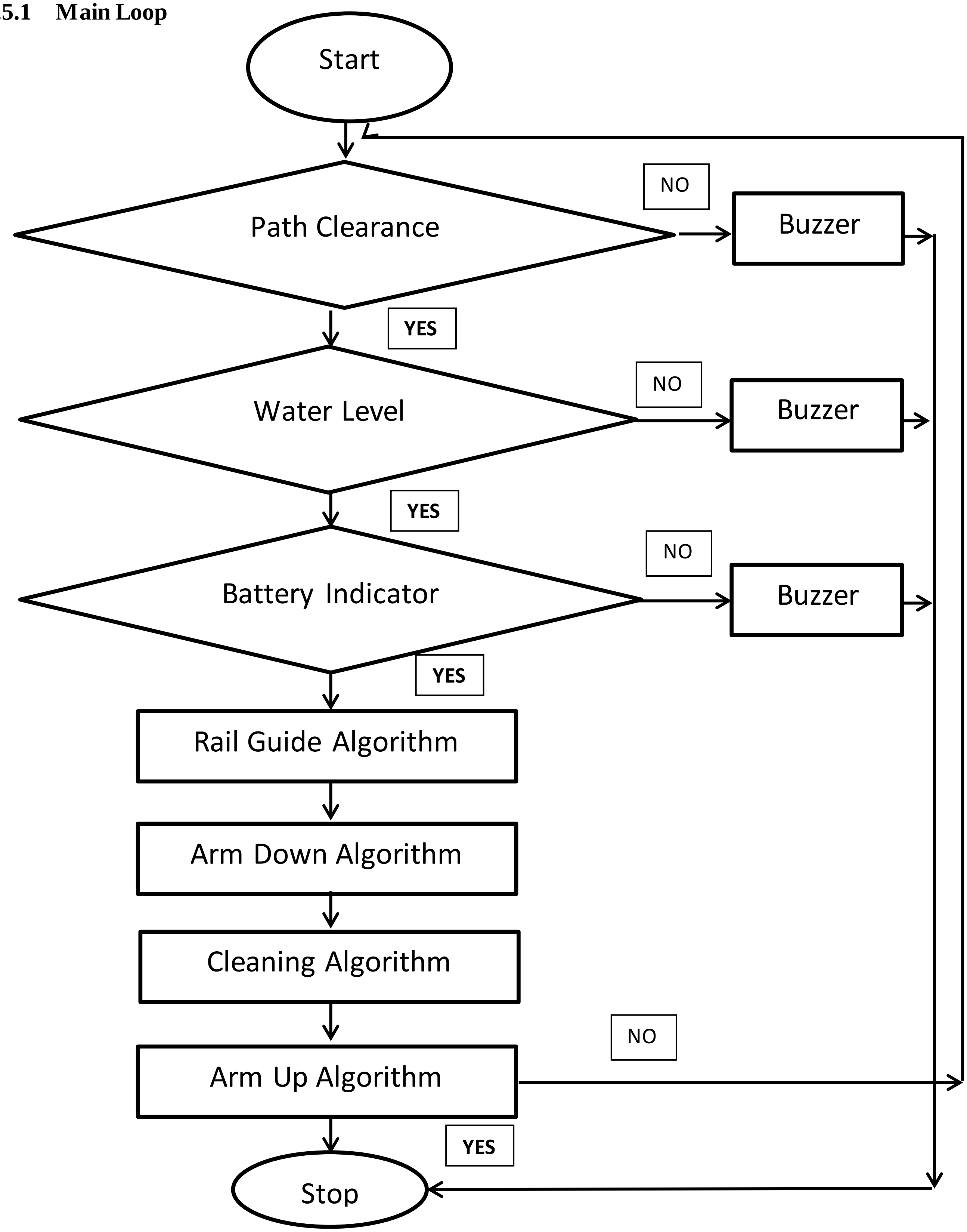


Fig. 4.10: Main Loop

4.5.2 Path Clearance Algorithm

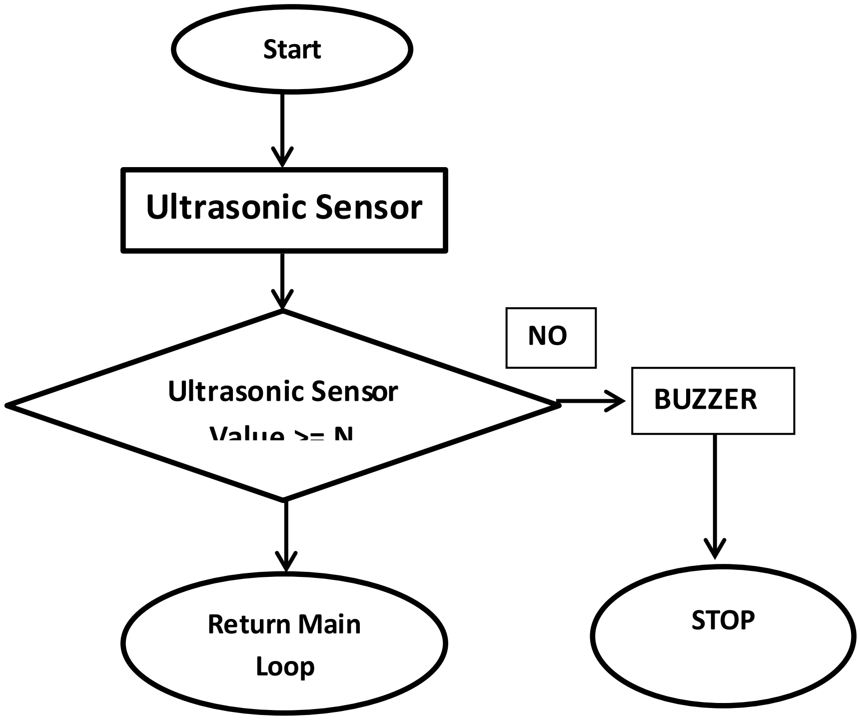


Fig. 4.11: Path Clearance Algorithm

4.5.3 Water Level Algorithm

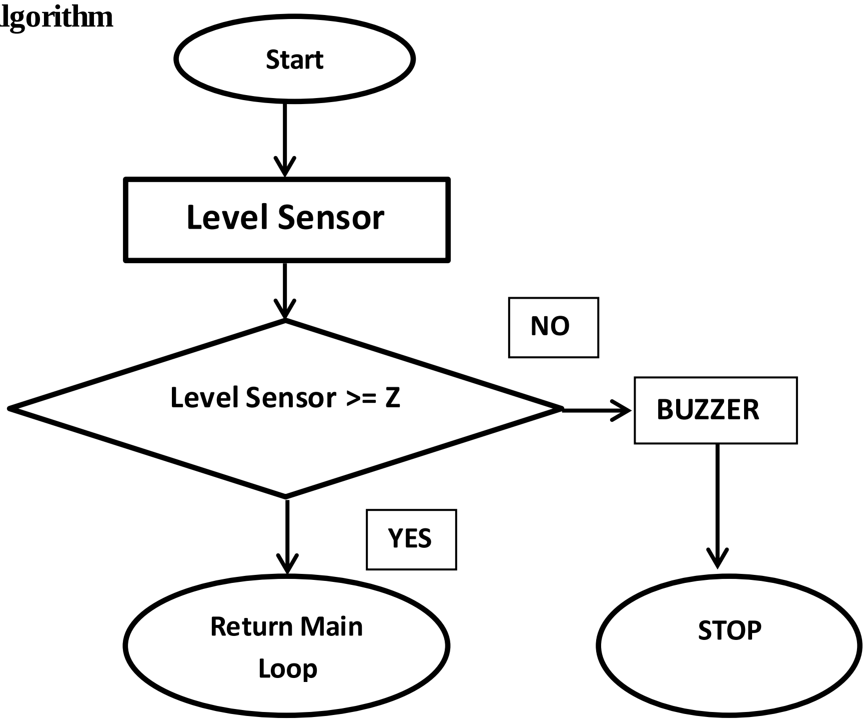


Fig. 4.12: Water Level Algorithm

4.5.4 Battery Status Algorithm

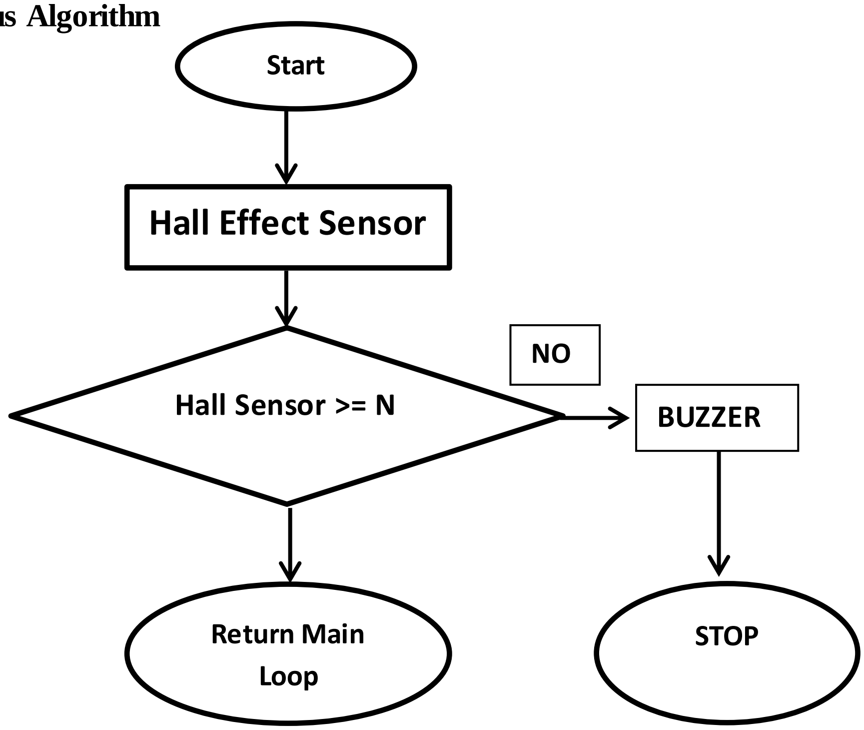


Fig. 4.13: Battery Status Algorithm

4.5.5 Rail Guide Algorithm

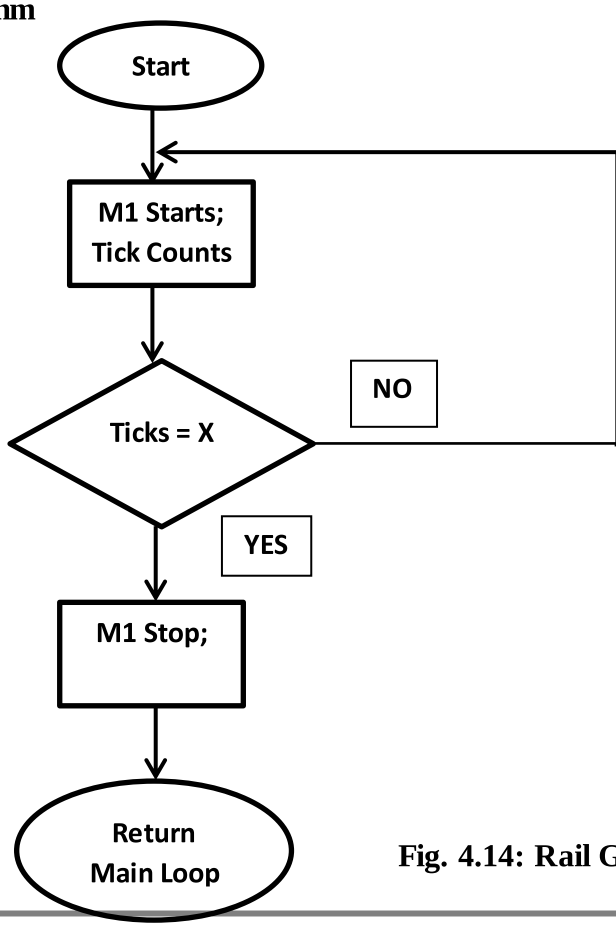


Fig. 4.14: Rail Guide Algorithm

4.5.6 Arm Down Algorithm

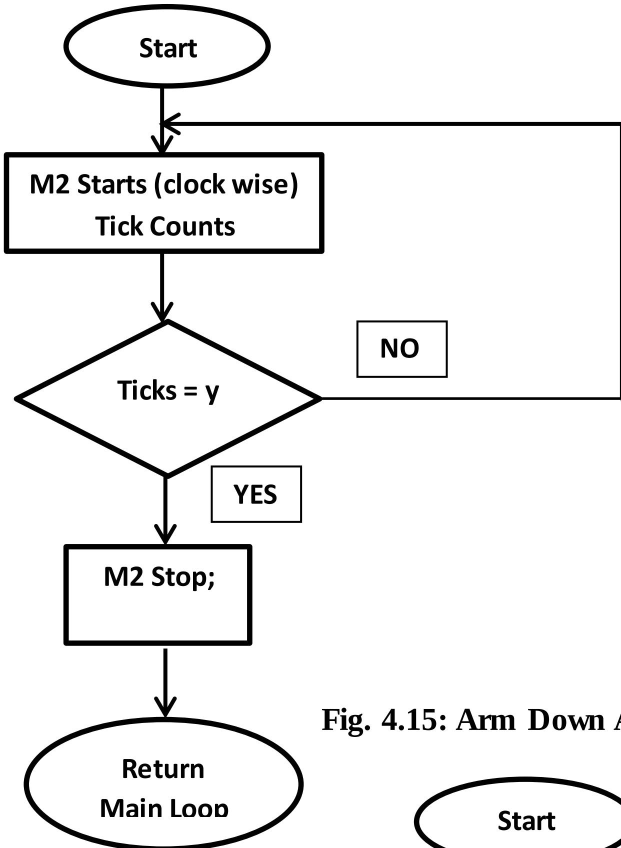


Fig. 4.15: Arm Down Algorithm

4.5.7 Arm Up Algorithm

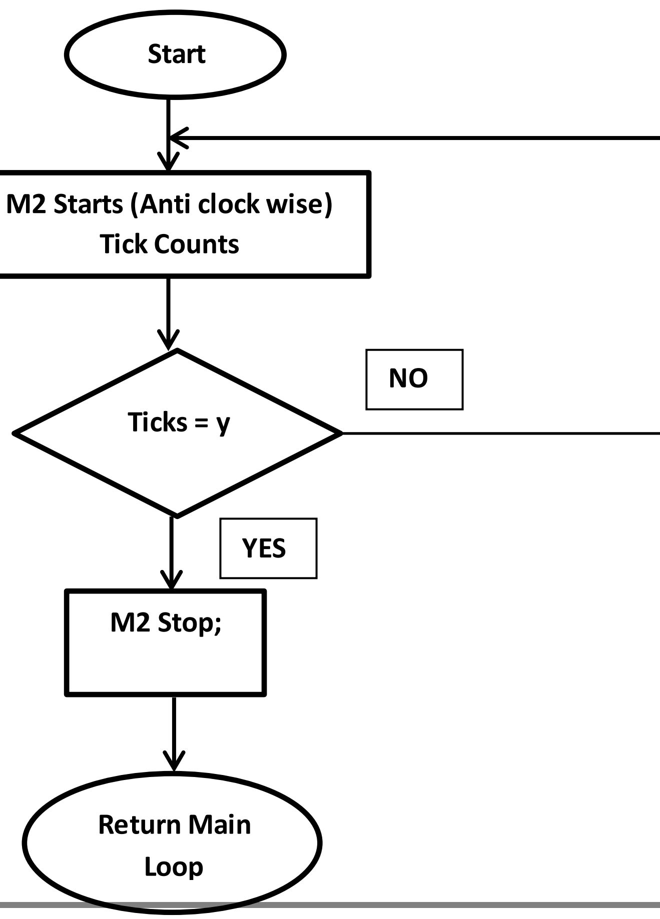


Fig. 4.16: Arm Up Algorithm

4.5.8 End Effector Cleaning Algorithm

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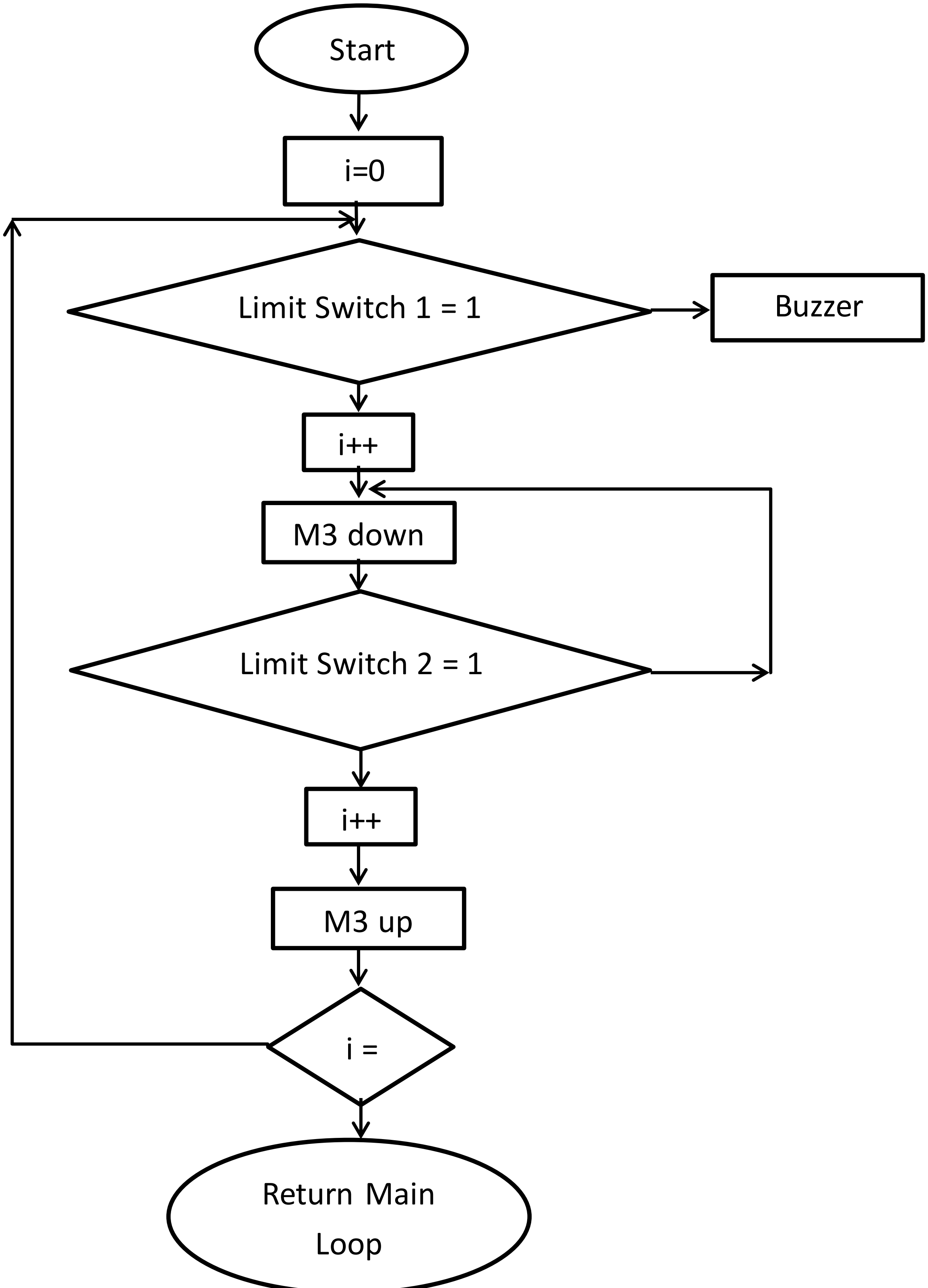

Fig. 4.17: End Effector Algorithm

CHAPTER 5

RESULTS

The PV system has an installed capacity of 100 kW_p , which consists of two modules covering a total area of 0.790 m^2 . It was installed on a flat concrete base in ground in University of Petroleum and Energy Studies. The SPV modules were thin film silicon wafers with anti-reflective coatings to maximize sunlight absorption. The modules were installed at an angle of 29.8°C (≈ 30°C).

One of the SPV was left un cleaned (periodically) throughout the monitoring period and the other was been cleaned every time before taking the readings, this was been done to mimic and compare the actual scenario. As the comparison is based on the efficiency enhancement and Short circuit current difference, hence one of the SPV modules was kept uncleaned and the other cleaned. During this process both the SPV modules were kept in similar conditions like solar radiation, surface temperature etc.

Table 5.1: SPV Specifications

PV module/ array	Specification
Type	Thin Film Solar Module (Double junction a-Si)
Application Class	Class A
Nominal P_m	50 W
Maximum System Voltage (V_{sm})	1000 V
Open circuit voltage (V_{oc})	62 V
Short circuit current (I_{sc})	1.42 A
Dimension	1245 X 635 X7.5 mm

5.1 PV SYSTEM TERMINOLOGIES

Power is the rate at which energy is used or generated and is measured in Joules per second (Watts). Electrical energy is watts multiplied by time and it is measured in Watt-hr. Table 5.2 shows the principal parameters of solar cells.

Table 5.2: Principal parameters of Solar Cells [145]

Parameter	Formula Sign	Unit	Description
MPP Power	P_{MPP}	W_p	Maximum power under STC (nominal power)
Fill Factor	FF	-	Quality yardstick for Solar Cells, generally between 0.5 and 0.85
Efficiency	H	%	Ratio of the power delivered by the cell and the solar irradiance
MPP Voltage	V_{MPP}	V	PV voltage at MPP (nominal voltage)
Open – circuit voltage	V_{oc}	V	Open circuit voltage, generally specified for STC: Voltage that the solar cell supplies when both terminals are directly connected
MPP Current	I_{MPP}	A	PV Current, generally specified for STC.
Short- circuit current	I_{sc}	A	Short-circuit current, generally specified for STC: current that the solar cell supplies when both terminals are directly connected.

5.2 MONITORING RESULTS

Monitoring of the test rig, data collection, performance analysis and reporting were shown below. Data was collected for a period of four weeks from morning 1000 hrs to evening 1700 hrs over an interval of 30 minutes. Data was been monitored for the both the SPV modules (cleaned and uncleaned), and following observations are made:

i. Short Circuit Current (I_{SC}): Drop in Short circuit current (I_{sc}) due to soiling, as shown in figure 5.1.

ii. Energy Yield: The effective loss in terms of power has been shown in Table 5.3. The power difference is being increased, as the days are increasing for consecutive weeks, which is been clear from the trends of fig.5.1 also it shows an increasing behavior in terms of power loss.

iii. SPV Module Temperature: Day wise variation of SPV module surface temperature and Short circuit current I_{SC}

Table 5.3: Weekly power loss (in Watts) due to natural soiling depending on ambient conditions

DAYS	Week1	Week2	Week3	Week4
1	-17.3567	20.0256	3.4166	-28.6655
2	-5.95497	14.23332	0.23062	49.50207
3	-3.97074	4.05834	12.62366	4.67615
4	29.37738	25.29583	8.8253	25.08953
5	20.15533	12.37975	14.78451	24.89871
6	27.76095	17.34945	21.72536	51.53253

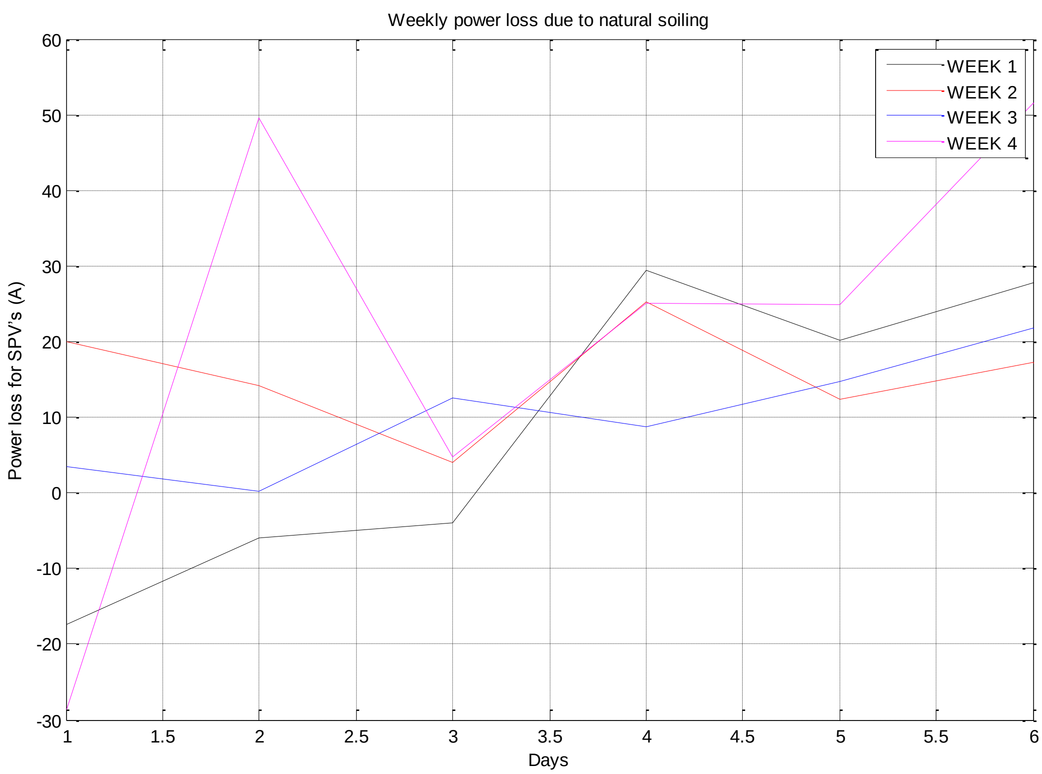

Fig 5.1: Weekly power loss due to natural soiling under ambient conditions

5.2.1 POWER CONSUMPTION BY SPCRA

Table 5.4: Current consumption of SPCRA parts in different conditions

Current Ratings in Different conditions		
Part Of SPCRA	**No Load**	**With Load**
	0.19 A - 0.24 A	0.34 A - 0.43 A
Arm : Worm Geared DC motor		
Position of Cleaning Head	**Going down towards Solar Panel**	**Going away from the Solar panel**
Far	0.49 A - 0.58A	0.58 A - 0.72 A
Middle	0.49 A - 0.65 A	0.59 A - 0.70 A
Near	0.54 A - 0.58 A	0.58 A - 0.67 A
Base : Rotating Motor		
Left to Right/ Right to Left	0.39 A - 0.43 A	

For entire one time cleaning operation (which includes moving along the guide rail, rotary motion of the arm, up and down cleaning head motion, rotation in guide rail) for a single SPV module.

Table 5.5: Energy Consumption by SPCRA

Action	**Avg. Current (A)**	**No. of cycles**	**Total time consumed (sec)**	**Energy consumed (mAhr)**
SPCRA platform motion on guide rail	0.385	3	18	5.775
ARM motion (rotatory)	0.65	6	8.25	8.9375
Base platform rotation	0.41	1	6	0.6833
Cleaning head	0.39	12	24	31.2
Total				**46.5958**

From the above table, the power consumption for cleaning a single SPV is **35.708 W** using SPCRA.

Considering the peak sunshine condition at 1100 hrs on 14th Nov, 2014, Voc, Isc values for both the panels were taken and compared.

Voc_1 = 54.06 V, Isc_1 = 1.147 A, and P_1= 62.00682 W

Voc_2 = 54.03 V, Isc_1 = 1.042 A and P_2 = 56.29926 W

Amount of power loss due to natural soiling for a particular instant of a day = 8.95661 W

Considering the above value for a week= 63 W

Amount of Energy Saving for a single SPV module = 63 – 35.708= **27.292 W**

% Enhancement in Efficiency = **9.1%**

5.3 PERFORMANCE COMPARISON (WITH OTHER PRODUCTS AVAILABLE IN THE MARKET)

Table 5.6: performance comparison (with other products available in the market)

		Gekko Solar [24]	**Gekko Solar Farm[25]**	**National Instruments Prototype[26]**	**PV Cleaner Robot V1.0**	**Solarbrush [30]**	**Washpanel [28]**	**SPCRA (Proposed)**
Cleaning	Performance Area (m^2/hr)	400	2900; 2000; 1500		60	60		46.8
	Max. Speed (m/min)	7.8	7.8	16.66		1	7	19.38
Dimensions	Length X Width X Height (mm^3)	1175 X 1383 X 657	2276 X (6800; 4900; 3800) X 820					
	Weight (kg)	68	220; 210; 200	3500	40	2.5	10	17
Operatio	Water	0.5-	3.5;			NA		

nal Parmeter s	Consumpt ion	1.5 l/min	3;2.5					
	Nominal Power (kW)N	0.8	1.5; 1.35; 1.2		0.5			0.03570 8
	Air Consumpt ion (l/min)	180	180		0.666	NA		
	Pressure Tank	50 lt.				NA		NA
Usage Range	Max. gap width (mm)	250	600		80	20		Any Gap
	Max. Obstacle height (mm)	40	50					1400
	Max. panel inclinatio n (deg)	45	30		45	35		90

Actual Structure

Fig. 5.2: Actual Structure of SPCRA

CHAPTER 6
CONCLUSION AND FUTURE SCOPE

6.1 CONCLUSIONS

1. The efficiency enhancement of SPV panels can be increased more than 9.1%.
2. Efficiency enhancement by cleaning using SPCRA depends on the area coverage, which also depends per unit area ie. for SPV panel's of 500 W and 50 W (of same dimension and under same condition), efficiency enhancement in 500 W SPV panel would be more than 50 W SPV panel.
3. Dust and dirt remains a problem, especially in desert areas, where solar energy potential is in abundance. Few reasons for it are:
    - Lack of natural cleaning by rain and shortage of indigenous water resources.
    - Sandy storms and dry climate
4. Dust and dirt degrades the energy output of SPV module by: Reduction in solar intensity in the range of 20% to 50% or more.
5. Reduction in output power of SPV system in the range of 15% to 30% for moderate dust condition.
6. Frequency of cleaning is an important factor for efficiency enhancement and it varies from place to place.
7. It is recommended that electromechanical cleaning solution should be implemented in the small/ medium utilities where the power generation through SPV is upto 100 kW,
8. Whereas hybrid system (coating+ Electromechanical) should be implemented in the larger utilities where the power production is more than 1 MW.

6.2 FUTURE SCOPE

1. In the current research, robot is traversing along a guided platform, which can be further modified so that the guide rail can be removed and on the basis of line following mechanism using sensor networks can be implemented.
2. In the current SPV cleaning robotic arm, arm is of fixed length, which can further be modified to a telescopic arm.
3. In the current SPV cleaning robotic arm, arm is of single link which can further be modified to two link for better outreach performance in terms of cleaning and area coverage.
4. In the current research cleaning is done on periodical/ manual inspection basis, which can be further modified in the following ways:
    a. Applying image processing based algorithm to detect the dust deposition/ partial shading conditions.
    b. Using open circuit voltage and short circuit current of SPV module to find the drop in output.

CHAPTER 7

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ANNEXURE I

During working in open environment, several other factors acts upon SPCRA, like wind Speed, wind direction etc.

$$F_r = m_2\ddot{r} - m_2 r\dot{\theta}^2 + m_2 g \sin\theta + k_b \sin\theta$$

Considering different wind speed conditions, acting from front at different tilt angles of SPCRA has been shown in below table no. 5.7. Also, keeping in mind that wind can act from any direction and the same has been shown in table no. 5.7.

Table No. 5.7: Wind force acting on SPCRA at different tilt angle of SPCRA

ARM - 90 Degree		
Inlet Velocity (m/s)	**Pressure Load (Pa)**	**Force on Arm (N)**
1.2	0.8128	0.0934
5	14	1.609
10	55.54	6.406
13	93.74	10.816
16	141.9	16.379
20	222.2	25.629
25	346.8	40.01
ARM - 60 Degree		
1.2	1.028	0.0637
5	17.69	1.0918
10	70.55	4.3445
13	119.1	7.329
16	180	11.0863
20	281	17.2952
25	438.7	26.9771
ARM - 29.8 Degree		
1.2	0.9495	0.0159
5	16.36	0.2638
10	65.34	1.0366
13	110.3	1.7335
16	167.2	2.6125
20	261	4.0626
25	406.9	6.3176

PUBLICATIONS

PhD Publications

Sl. No.	Details
1.	Amit Kumar Mondal, Kamal Bansal. *"A brief history and future aspects in Automatic Cleaning Systems for Solar Photovoltaic Panels"*. Advanced Robotics. Vol. 29, Issue 8. Page No. 515-524. Taylor & Francis. DOI: 10.1080/01691864.2014.996602
2.	Amit Kumar Mondal, Vivek Kaundal, Vindhya Devalla, Kamal Bansal. *"Development of a damper control system for combined cycle thermal gas power plant"*. ASME Gas Turbine India 2014, New Delhi. 15th -17th Dec, 2014. doi:10.1115/GTINDIA2014-8118
3.	Amit Kumar Mondal, Kamal Bansal. *"Structural analysis of Solar Panel cleaning Robotic Arm"*. Current Science. Vol. 108, Issue 6. Page No. 1047-1052. Current Science.
4.	Vivek Kaundal, Amit Kumar Mondal, Paawan Sharma, Kamal Bansal. *"Tracing of Shading Effect on Underachieving SPV Cell of a SPV Grid using WSN"*. Journal of Engineering Science and Technology. Vol. 18

Other Publications

Sl. No.	Details
1.	Amit Kumar Mondal, Paawan Sharma, Mukul Gupta. *"Robotics in India: Current scenario and future prospects in Education System"*. IEEE Robotics and Automation Magazine. **(Under Review)**
2.	Shival Dubey, Abhishek Sharma, Amit Kumar Mondal. *"Integration of Solidworks and MATLAB (SimMechanics)"*. IEEE Robotics and Automation Magazine. **(Under Review)**
3.	N Dinesh Reddy, Amit Kumar Mondal, Gurshaant Malik. "*Incremental Real-time Multibody VSLAM with Trajectory Optimization Using Stereo Camera*". European Conference on Mobile Robots 2015, University of Lincoln, UK.
4.	Amiya Sagar Das, Prashant Dwivedi, Amit Kumar Mondal, R. Manohar Reddy, Adesh Kumar, Roushan Kumar. "*Implementation of Breadth First Search for storage optimization in Random storage assignment of Automated Storage and Retrieval Systems*". 1st International Conference on Nano-electronics, Circuits & Communication Systems. Ranchi, Jharkhand.
5.	Vindhya Devalla, Amit Kumar Mondal, A J Arun Jeya Prakash, Om Prakash. *"Development of position tracking and guidance system for Unmanned powered parafoil aerial vehicle"*. 4th International Conference on. Reliability, Infocom Technologies and. Optimization (ICRITO 2015), Amity University, Noida, India. (**Paper Accepted**)
6.	Amit Kumar Mondal, Vivek Kaundal, Paawan Sharma, Vindhya Devalla. "*ARM7 Based Multiparameter Fitness Monitoring System Using WPAN*". Measurement. IEEE 10th

	International Conference on Industrial and Information Systems (ICIIS), University of Peradeniya, Peradeniya, Sri Lanka (**Under Review)**
7.	Vindhya Devalla, Amit Kumar Mondal, Om Prakash. *“Angle of Attack, Pitch Angle and Glide Angle Modeling at Various Thrust Inputs for a Powered Parachute Aerial Vehicle”*. First Aerospace Engineering Doctoral Student’s Symposium, IIT Kanpur. 12th May, 2014.
8.	Vindhya Devalla, Amit Kumar Mondal, Anant Wadhwa, Vivek Kaundal, “Design and Development of Autonomous Library Book Sorting Robot Using Wireless Sensor Networks and Color Detection” International Conference on Electrical and Electronics Engineering (ICEEE-2013), 11th March, 2013

Bio-Data

01.	Name in Full (Block Letters)		Amit Kumar Mondal
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	(c)	Mobile No.	9557355689
04.	Date and Place of Birth		March 16th ,1988; Durgapur, West Bengal
05.	Father's Name Mother's Name		Nemai Chandra Mondal Lipika Mondal
06.	(a)	Name of the State to which you belong and your permanent residence with Tehsil & District	Permanent Residence: Durgapur, District: Burdwan, State: West Bengal
	(b)	State whether you belong to Scheduled Caste/Tribe/Backward Class	Scheduled Caste

7. ACADEMIC QUALIFICATIONS (Please attach attested copies of certificates including date of Birth). Give details in chronological order starting with the highest degree)

Degree	Year	College/University	Divn.	% of Marks /CGPA	Remarks
PhD		University of Petroleum and Energy Studies			Thesis Submitted
M. Tech	2012	University of Petroleum and Energy Studies	1st	84.8% (CGPA: 3.24/4)	
B. Tech	2009	Bankura Unnyani Institute of Engineering/ West Bengal University of Technology	1st	70.6% (CGPA: 7.81/10)	

8. Teaching & Professional Experience

Position Held	Name of Organization	Period		Pay	Nature of Work
		From	To		
Doctoral Research Fellow	University of Petroleum and Energy Studies	May 21st ,2012	Till Date		Research activities and administrative functioning.
Course Coordinator	University of Petroleum and Energy Studies	July 1st ,2013	June 31st ,2014		Coordination of departmental activities for students
Sales & Service Engineer	Ladder Automation Solutions Pvt. Ltd.	June 2009	June 2010		Servicing, Commissioning and Installation of PLC, SCADA, Electrical Panels

9 Course Taught (Give details in chronological order starting with the latest)

Name of the Course	Level (UG/PG)	Year in which taught	Class Strength
Programmable Logic Controller	UG	2015, 2014	60
Programmable Logic Controller and SCADA	PG	2014	20
Basic Electronics	UG	2014, 2013	60

10. Research Experience

(a) Post-doctoral Fellowship (Should have been availed at an institution other than the Ph.D. degree awarding Institution)

Organization, Country	Period from	To	Duration

(b) Sponsored Research Projects (Including in-house industrial projects)

Year of Funding	Sponsoring Organization	Title of Project	Amount of Grant (In Lacs)	Co-Investigators (if any)
2014	Incubation Funding- University of Petroleum and Energy Studies	Automatic Air Filling System for 4 Wheelers	1.98 (Phase 1)	Yes
2013	DST- SERB	Pipeline Surveillance Parachute Aerial Vehicle (PAV)	6.00	Yes

2012	Internal RnD Seed Fund- University of Petroleum and Energy Studies	Design and development of 3D Robotic Arm for Solar Photovoltaic Panel Cleaning using Atmel's AVR microcontroller platform	4.00	No

(c) Student Research – Doctoral Degrees

S.No.	Name of Student	Year of Completion	Title of Thesis	Co-Supervisors (if any)

(d) Student Research – Masters Degrees

S.No.	Name of Student	Year of Completion	Title of Thesis	Co-Supervisors (if any)
1.	Vaishali Gupta	2014	Human portable Unmanned Ground Vehicle	Mr. Sushabhan Choudhury

11. Publications

(a) Papers in SCI Journals (*At the time of application, journal should be in latest Thomson Reuters SCI/SCIE/SSCI list)*

S.No.	Author(s)	Year of Publication	Title of Paper	Name of the Journal, volume/ page numbers,	Name of the Publisher	Impact Factor

1.	Amit Kumar Mondal, Kamal Bansal	2015	Structural analysis of solar panel cleaning robotic arm	Current Science, Vol. 108, Issue 6, Page No. 1047 - 1052	Indian Academy of Science	0.833
2.	Amit Kumar Mondal, Kamal Bansal	2015	A brief history and future aspects in Automatic Cleaning Systems for Solar Photovoltaic Panels	Advanced Robotics, Vol. 29 ; Issue 8	Taylor and Francis	0.562

Accepted

S.No.	Author(s)	Year of Publication	Title of Paper	Name of the Journal, Volume/ page numbers,	Name of the Publisher	Impact Factor
1.						

(b) Papers in Non-SCI/SCIE/SSCI Journals

Published

S.No.	Author(s)	Year of Publication	Title of Paper	Name of the Journal, Volume/ page numbers,	Name of the Publisher

1.	Vivek Kaundal, Amit Kr. Mondal, Dr. Paawan Sharma, Dr. Kamal Bansal	2015	Tracing of Shading Effect on Underachieving SPV Cell of a SPV Grid using WSN	Journal of Engineering Science and Technology. Vol. 18 (Accepted and Proof Reading Copy Supplied)	Elsevier

Accepted

S.No.	Author(s)	Year of Publication	Title of Paper	Name of the Journal, Volume/ page numbers,	Name of the Publisher

(c) Papers in International Conferences (those held outside India)

S.No.	Author(s)	Year of Publication	Title of Paper	Name and Place of Conference
1.	N Dinesh Reddy, Amit Kumar Mondal, Gurshaant Malik	Paper Accepted	Incremental Real-time Multibody VSLAM with Trajectory Optimization Using Stereo Camera	European Conference on Mobile Robots 2015, University of Lincoln, UK

(d) Papers in Indian Conferences

S.No.	Author(s)	Year of Publication	Title of Paper	Name and Place of Conference
1.	Amit Kumar Mondal, Vivek Kaundal, Vindhya Devalla, Kamal Bansal	2015 (doi:10.1115 /GTINDIA2014-8118)	Development of a damper control system for combined cycle thermal gas power plant	ASME Gas Turbine India 2014, New Delhi. 15th -17th Dec, 2014.

2.	Vindhya Devalla, Amit Kumar Mondal, Om Prakash	2014	Angle of Attack, Pitch Angle and Glide Angle Modeling at Various Thrust Inputs for a Powered Parachute Aerial Vehicle	First Aerospace Engineering Doctoral Student's Symposium, IIT Kanpur. 12th May, 2014.
3.	Amiya Sagar Das, Prashant Dwivedi, Amit Kumar Mondal, R. Manohar Reddy, Adesh Kumar, Roushan Kumar	2015	Implementation of Breadth First Search for storage optimization in Random storage assignment of Automated Storage and Retrieval Systems*	International Conference on Nano-electronics, Circuits & Communication Systems. Ranchi, Jharkhand. May 9^{th} – 10^{th} , 2015.
4.	Vindhya Devalla, Amit Kumar Mondal, A J Arun Jeya Prakash, Om Prakash	Paper Accepted	Development of position tracking and guidance system for unmanned powered parafoil aerial vehicle	4th International Conference on. Reliability, Infocom Technologies and. Optimization (ICRITO 2015), Amity University, Noida, India

* Using Bosch Rexroth PLC L 20 DP and Automation Studio Software.

(e) Books

Published

S.No.	Name of Book	Year of Publication	Name of Publisher	Co-authors (if any)

In Press

S.No.	Name of Book	Expected Year of Publication	Name of Publisher	Co-authors (if any)

12. Patents

S.No.	Author(s)	Year of Award	Title of Patent	Patent Number	International/ Indian
1,	Om Prakash, **Amit Kumar Mondal**, Vindhya Devalla, Anant Wadhwa, Shival Dubey	Filed	A System for Monitoring and Maintaining Air Pressure in Vehicles	Indian Patent- #1205/DEL/2014 A	Indian
2.	Anant Wadhwa, **Amit Kumar Mondal**, Vindhya Devalla, Shival Dubey et al.	Filed	A System for Preventing Fuel Theft from Vehicle	Indian Patent- #365/DEL/2014 A	Indian

13. Projects

Serial No.	**Company, Place**	**Machine**	**Worked On**
1.	Relaxo Footwear, Bhiwadi, Rajasthan	Bumping Machine	PLC: Schnieder
2.	Sri Sai Krishna Hydro Power Plant(Luni Unit 3), Baijnath, Himachal Pradesh	PLC Panel	SCADA: Win CC Flexible 2007
3.	Alex Packers, Rudrapur, Uttarakhand	Dimension Measuring Machine	PLC:Unitronics
4.	Bindal Paper Limited, 8th km Bhopa Rd. Muzzafarnagar, Uttar Pradesh	PLC Panel	SCADA: Win CC Flexible 2008
5.	Jindal Industries Limited, Hissar,Haryana	Hydrotester Pressure Machine	SCADA: Win CC Flexible 2008

6.	Havell's India Pvt. Ltd. Baddi, Himachal Pradesh	SPM	SCADA: Win CC Flexible 2007

14. Industrial Experience

Period	Organization	Description of Work and Responsibilities
June 2009-June 2010	Ladder Automation Solutions Pvt. Ltd.	Servicing, Commissioning and Installation of PLC, SCADA, Electrical Panels

15. Administrative Experience

Period	Organization	Designation	Nature of Responsibility
May 21st ,2012 – Till Date	University of Petroleum and Energy Studies	Doctoral Research Fellow	• To be responsible for all activities leading to University development • Undertake research work in doctoral area • Assisting Guide in developing research/ consultancy projects in concerned area of expertise • Providing guidance to the students during tutorial/ assignment/ project work • Coordinating with internal & external faculty for coursework development & up gradation • Providing academic advice to all Centre for Continuing Education students to overcome their academic afflictions. • Any other duties assigned by the management from time to time.
March 1st ,2014 – Till Date	University of Petroleum and Energy Studies	Technical Assistant (to Dean)	Research activities and administrative functioning for Dean, College of Engineering Studies, University of Petroleum and Energy Studies, Dehradun
June 1st ,2013 – July 31st ,2014	University of Petroleum and Energy Studies	Course Coordinator	• Coordination of departmental activities for students • Bridging the gap between College and the students etc.

16. Details of Foreign Visits, if any

S.No.	Purpose	Place, Country	Duration

17. Membership of Professional Bodies/Societies (Please specify National/International)

S. No.	Activity	Details of the activity
1.	IEEE Membership	91149514
2.	ASME Membership	100768773

18. Awards, Honor's and Recognitions

S. No.	Year	Name of the Award/ recognition	Awarding Institute/ Organization
1.	2015	RnD C^3 Research Publication Awards presented by Dr. C N R Rao, FRS	University of Petroleum and Energy Studies
2.	2014	RnD C^3 Patent filing Award, presented by Dr. Rajendra Dobhal (Director-UCOST)	University of Petroleum and Energy Studies
3.	2014	2nd Prize in Start Up Weekend	University of Petroleum and Energy Studies
4.	2013	Demonstrated PhD project "Design and Development of Autonomous Manipulator for Solar Photovoltaic Cleaning" to Honourable President of India Dr. Pranab Mukherjee.	

19. H-Factor:

Scopus H-Factor	
Scopus Citations (excluding self citations)	
Google H-Factor	1

Google Citations	4

https://scholar.google.co.in/citations?user=tPRaUCUAAAAJ&hl=en

20. Any Other Relevant Information supporting this application for a faculty position

1.	24th National Conference on I.C. Engines and Combustion	Working as an organizing committee member http://www.24ncicec-upes.com/

21. References: (At least three names of referees with their clear and complete addresses. Referees should be persons with or under whom the candidate has worked and one of the referees should from the last Organization/Institute served).

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