Full Sky Image Based Solar Power Level Monitoring System

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***Abstract*— Sri Lanka is moving towards utilizing the renewable energy sources to generate electricity to meet the future demands. Solar PV power generation has been identified as one of the viable options and thus initiatives have been taken to introduce net metering facilities to households. However, due to the intermittent and unpredictable nature in solar irradiation, solar power has been non-dispatchable. Movement of the cloud is the main cause to the intermittent and unpredictable nature of solar PV power output. With an efficient and accurate cloud movement model, solar power can be made dispatchable. This paper presents a novel methodology to collect cloud data, an algorithm to process sky image videos, measure the cloud speed and a model to predict the solar output level. This paper also discusses the development of hardware to capture cloud movements. This system can be used to predict the solar irradiation accurately.**

***Keywords*— Photovoltaic, Solar power, Prediction, Open CV.**

I. Introduction

Sri Lankan National Energy Policy published by the Ministry of Power and Energy in 2008 has set a target to achieve 20% of electricity generation, out of the total generation by means of renewable energy in 2020 [1]. In 2030 target is to achieve the total energy demand from renewable sources and by other indigenous sources [1]. With the aim of achieving the set target the Sri Lankan government has introduced net metering facilities to households in 2007. Flat dry zone of Sri Lanka has a solar radiation between 4.0 - 4.5 kWh/m^2/day and an average of 2.0 - 3.5 kWh/m^2/day in the high plains [2]. There are 127,000 households which use roof mounted Solar PV panels to generate electricity in the country [2]. However, the intermittent nature of Solar PV energy generation affects the system stability as the energy is non-dispatchable. By an efficient and effective model of solar output prediction, the effect of non-dispatchable behavior of solar PV can be minimized.

Electrical power output of a solar PV is directly proportional to the solar irradiance incident on the solar PV cells. Level of clouds is the major factor which minimizes the solar irradiance level. By predicting the cloud coverage of the sky, electrical power output of the solar PV can be predicted.

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There are only few solar irradiation prediction models or systems available which can predict the electrical power output of a solar PV. One of such system in the TSI-880(Total Sky Imager Model) system is an automatic, full color system which collects and displays the sky images in real time [3]. Therefore, TSI- 880 can be developed to predict the solar power output based on its sky images. Reference [4] has used a web cam system to capture the cloud images for solar power level prediction. However, images of this system were highly distorted and thus the accuracy was very low. There were few other researches that have developed solar prediction models [5]-[7] but have difficulties in implementing in real time.

Therefore, an efficient full sky imaging system with solar irradiation prediction model will help the system control operators to manage the power system by dispatching the power plants according to the predicted power output of the solar power plant. This paper describes the hardware implementation of full sky cloud image capturing system and proposes a short term model of predicting the electrical power output of a solar PV module based on the cloud images and the historical data

II. Hardware Implantation

A. Camera Module

The Solar power level prediction model which is primarily based upon sky images, need to have a sky-image capturing device. That image capturing device should inherit following properties such as comparatively high image capturing quality, resolution and large viewing angle than in a normal camera. The above mentioned qualities can affect the quality of the images and therefore can directly affect the accuracy of the power level prediction. A web-camera with a built in fisheye lens of 2 Megapixel, 1920x1080 resolutions and with a viewing angle of approximately 180 degrees is used as the sky image capturing device.

Fig. 1 The constructed hardware model

B. Solar Irradiation Calculation Methodology

To get the current solar irradiation level which used as a prediction model correcting parameter in the solar power level prediction algorithm, a commercially available pyrometer can be used. But due to its expensiveness a cost effective measuring method is used as a part in the hardware. To implement the measuring device a Mono-crystalline 5W solar panel, MAX 471 current sensor and a voltage divider used. As the platform of implementing the algorithm, Arduino Uno microcontroller was selected. In the above mentioned hardware, MAX 471 current sensor measures the output current of the Mono-crystalline 5W solar panel. The output voltage measured by the voltage divider is calculated using (1). A proportional value to the solar irradiation can be measured by using the calculated voltage and current measurements according to the (3).

Actual current = A.C (A), Actual voltage = A.V (V)

Analog voltage measured from the voltage divider = $V_{voltage}$

Analog voltage measured from the current sensor = $V_{current}$

$$A.V = V_{voltage} \times \left(\frac{R_1 + R_2}{R_2}\right) \quad (1)$$

$$A.V = V_{current} \quad (2)$$

$$Actual\ solar\ irradition \propto \left(\frac{A.C \times A.V}{Area\ of\ solar\ panel\ (\mathrm{m}^2)}\right) \quad (3)$$

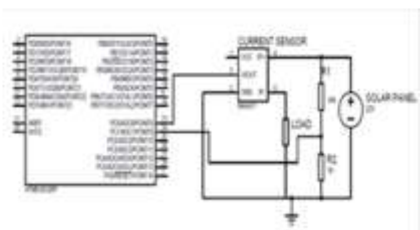

Fig. 2.Solar power measuring circuit

The following graph shows the solar power level measured for 2015.11.29 0700 hours to 1700 hours using the above described hardware.

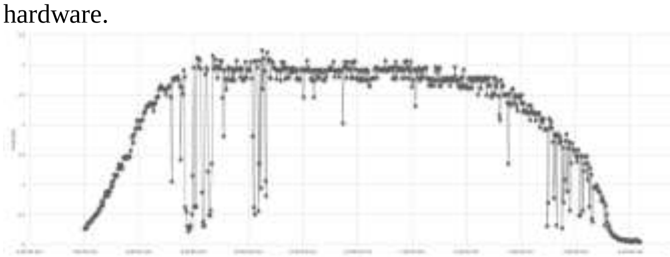

Fig. 3.Solar power measured

C. Camera Protection System

Optical sensors in the camera are sensitive to the direct sunlight. When the camera is exposed to direct sunlight there is a high possibility of damaging its optical sensors. The direct exposure to the sunlight causes a sun glare which can result a low contrast distorted image. By implementing a camera protection system the possibility of damaging the optical sensors can be reduced and the sun glare can be minimized.

D. Solar Tracking Mechanism

In practice open loop and closed loop are the two methods available for solar tracking. In closed loop solar tracking mechanism, a solar sensor feedback was given to the controller. This feedback can be camera images or optical sensor output. This closed-loop controlling mechanism can produce ambiguities, especially when clouds passing across the sun covering it completely. In open loop sun tracking mechanism a predefined solar position algorithm is used [9]. Due to its open-loop controlling system, malfunctioning incidents can be reduced. Due to the above mentioned advantage the solar protection system was implemented using open-loop solar tracking method.

E. The Control mechanism

The control mechanism to cover the direct sun light can be introduce as a single axis tracker, as it only uses azimuth angle of the sun to track it. In this system solar zenith angle is neglected and one servo motor is capable of driving the mechanism. The control mechanism of the servo motor is implemented on Arduino Mega platform using the solar position algorithm [9]. To get the time, a real time clock (RTC) is used in the hardware developed.

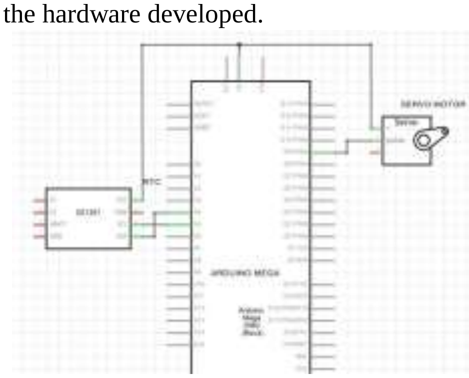

Fig. 4.Servo motor control circuit

III. Software Implementation

Software implementation of solar power level prediction system is split into two stages. At the first stage, required data is collected and construct the power output model. Then using this model, a solar power prediction algorithm is implemented in the second stage.

A. Solar Power Level Prediction Model (first stage)

Main requirement of the first stage is to collect the data associated with the variation of the solar panel output. Main concern is the data associated with the clouds, which are the factors that affect the power output of solar panel. Main task of the first stage is to obtain the cloud images. Then analyzing those images using the OpenCV/visual C++ computer vision tools and obtain the speed of the clouds. This speed calculations process is consists with the sub processes, removal of fisheye distortion, cloud identifications and speed calculation. Those processes are discussed in detail in the next section.

B. Removal of the Fish Eye Lens Distortion

In developing a solar prediction model which is mainly based upon cloud images, the area of the sky that the particular sky-imager is capable of capturing is an important parameter. By using a webcam with an inbuilt fish eye lens, a larger viewing angle is achieved. But due to the fish eye effect, captured images are distorted. This distortion of the sky images can result in erroneous cloud images that can directly affect the accuracy of the power level prediction model.

Therefore to correct the fish eye effect of the images, calibration of the camera need to be done. The following are the identified distortions that are associated with the fish-eye lens web-camera [10].

1) Radial distortion.

2) Tangential distortion.

In the fish-eye lens web-camera that is used, the tangential distortion was absent. Therefore the radial distortion parameter calculation was performed. If (X, Y) are two pixel points in the distorted image, the calibrated (corrected) pixel point can be written as follows [6],

$$X_{\text{CORRECTED}} = X\,(1 + k_1 r^2 + k_2 r^4 + k_3 r^6) \quad (4)$$

$$Y_{\text{CORRECTED}} = Y\,(1 + k_1 r^2 + k_2 r^4 + k_3 r^6) \quad (5)$$

By determining the above distortion coefficients k_1 k_2, k_3, the matrix (i.e. {k_1 k_2, 0, 0, k_3}) can be construct. For the unit conversion following camera-matrix can used.

$$\begin{bmatrix} x \\ y \\ w \end{bmatrix} = \begin{bmatrix} f_x & 0 & c_x \\ 0 & f_y & c_y \\ 0 & 0 & 1 \end{bmatrix} \begin{bmatrix} X \\ Y \\ W \end{bmatrix}$$

Where,

f_x, f_y : camera focal lengths

c_x,c_y : optical centers expressed in pixel coordinates

After the distortion-coefficients matrix and the unit conversion camera-matrix is determined, it can be given as an input to the OpenCV/Visual C++ software as the calibrated camera model. The parameters of the distortion coefficient matrix and camera matrix was determined using a 9x6 classical black and white chess-board. The determined values are as follows.

TABLE I: DISTORTION COEFFICIENT OF THE FISH EYE LENS

Parameter	Value
K_1	-0.2804
K_2	0.065112
P_1	0
P_2	0
K_3	-0.0057218

TABLE II: CAMERA MATRIX COEFFICIENTS

Parameter	Value
f_x	237.8712
f_y	237.8712
c_x	319.5000
c_y	239.5000

Fig. 5.Sky image before and after calibration

C. Cloud Identification

Captured sky images from the camera are the main input data to the solar prediction system. They are processed using the OpenCV / Visual C++ image processing tools to extract the cloud cover data and speed of the cloud which are directly related to the solar panel output. sky images are segmented to identify the clouds. In the segmentation, captured image is converted to either HSV format or gray scale image. Converted HSV image is threshold by choosing appropriate hue values. If the image is converted to gray scale, normally thresholding is done by choosing suitable gray values. In this thresholded binary image, cloud cover areas and other areas are clearly separated and hence using the simple pixel count, cloud cover is determined.

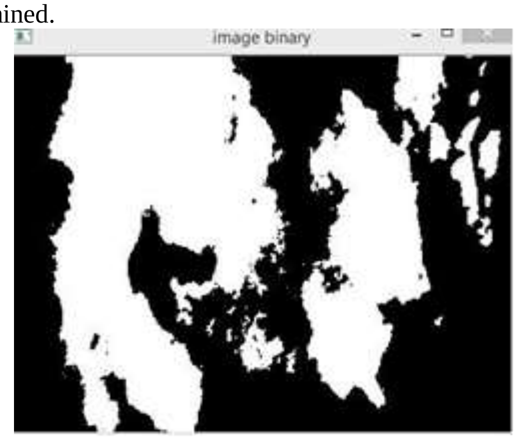

Fig. 6.Cloud identification using thresholding

D. Cloud Speed Calculation

Speed of the each cloud has to be calculated separately. It is achieved by segmenting each cloud. This segmentation is achieved by drawing contours around the clouds of the image.

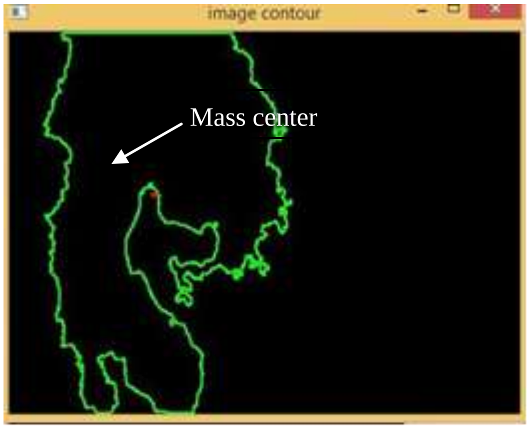

Fig. 7.Drawn contour to the largest contour detected (in green) and mass center distribution (in red)

Each contour is an array of points which defines the boundary of a cloud. Hence, after drawing the contours, mass centers and cloud areas can be easily determined as follows. The concept of moments is used in the mass center calculation.

Central moment of a contour M_{pq} is given by [8],

$$M_{pq} = \sum_{i=1}^{n} I(x,y)\, x^{p} y^{q} \tag{6}$$

Where *I(x, y)* is the gray value of the pixel *(x, y)*. Normally this is varied according to the x and y values, but in the context of contours this intensity is same inside the boundary of a contour regardless of the x and y values and hence,

$$M_{pq} = I_0 \sum_{i=1}^{n} x^{p} y^{q} \tag{7}$$

Therefore, the mass center of j^{th} contour;

$$m_j \propto \left(\frac{M_{j,10}}{M_{j,00}}, \frac{M_{j,01}}{M_{j,00}} \right) \tag{8}$$

Considering the displacement of mass center over measured period, the speed v_j of cloud can be obtain.

$$v_j \propto \frac{m_{j,(t=t_1)} - m_{j,(t=t_1)}}{t_1 - t_0} \tag{9}$$

In speed calculations priority is given to the clouds those have the largest covering area. For area calculation, central moment of the respective contour is considered and the 0^{th} moment of the contour is given by M_{00}.

According to the (9), two mass centers at two different time frames are required. Therefore proper coordination between two frames is essential. The respective contours of a cloud at different two frames are checked to verify the validity of the calculated mass centers and a matching coefficient is introduced. This coefficient is a measure of the difference of the shapes. It is calculated using the hue moments [10], which gives a unique value for contour regardless of the transformations, rotation and translation.

If the contour has changed, no longer the results obtaining by (9) are correct. Therefore an optical-flow technique like Lucas-Kanade is used [10]. Following data table was obtained during the solar power measurements on 24.11.2015, before the completion of the hardware.

TABLE III: THE ARRANGEMENT OF CHANNELS

Area	Speed		Actual Speed	
	V_x	V_y	V_x	V_y
111088	0.025	0.055	0.077	0.042
110285	0.234	0.309	0.235	0.0069
109611	0.017	0.0277	0.185	0.19
105461	0.0124	0.0113	0.081	0.203
97583	0.064	0.49	0.09	0.08

Speed has been calculated only to the largest contour, using the instantaneous values of center of mass velocity. Actual speed is calculated using the following equation.

$$\text{Actual Speed} = \frac{\text{Mass centre at } t = t_f - \text{Mass centre at } t = t_i}{t_f - t_i} \tag{10}$$

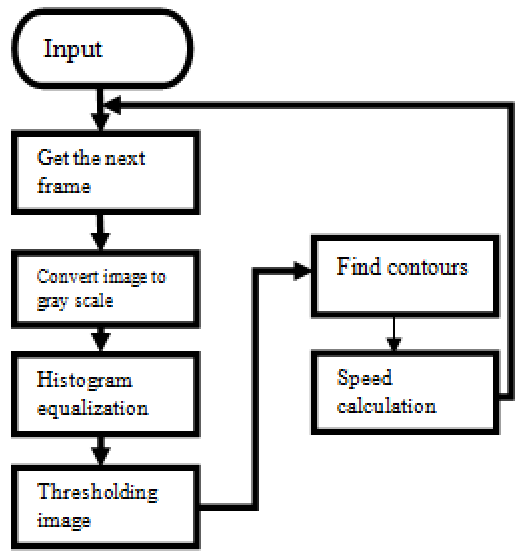

Fig. 8.Flow diagram of speed calculation

Lucas-Kanade method for speed vector determination

In addition to above technique of motion determination, in OpenCV environment there are two other techniques to determine the motion of a particular object of interest. They are Lucas-Kanade and Horn-Schunck technique [8]. In the software for cloud speed determination the motion of the clouds are calculated by Lucas-Kanade method. In Lucas- Kanade optical flow algorithm the following three assumptions are made [11].

1) Brightness Constancy.

$$f(x,t) = I(x(t),t) = I(x(t+dt), t+dt) \tag{10}$$

2) Temporal persistence.

$$I_x V + I_y = 0 \tag{11}$$

3) Spatial Coherence.

Due to use of binary images, to identify the clouds separately from other objects, the validity of assumptions are essential in the software developed.

In the pyramid Lucas-Kanade algorithm that has implemented, the corner points of the binary image are given as feature points to track. These good features to track are implemented according to Shi and Tomasi definition [8]. These points of good features are identified in two consecutive frames with 1.5 seconds time delay. They are stored in an array and given as an argument to the pyramid Lucas-Kanade function to determine the speed.

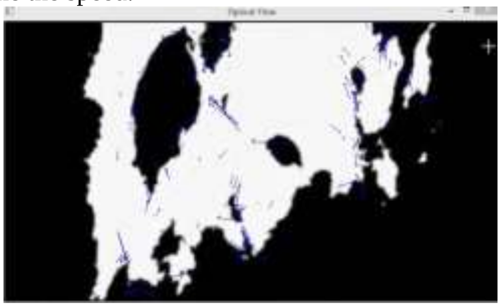

Fig. 9.Determined flow vectors (arrow) using Lucas Kanade technique

IV. Discussion

In our system, the viewing angle was enhanced by mounting a fisheye lens on top of the camera. However some of previously implemented systems have used a camera with wide angle lenses, which distorts edges of the image and thus reduced the accuracy [4]. We have overcome this issue by a fisheye lens, but the camera lens and fisheye lens need to be aligned accurately, otherwise objects in the infinity will not be focused clearly and image quality can also reduce. It can also reduce the speed calculation and cloud identification. A 2MP 1080p 1/2.7" CMOS OV2710 web-camera with an inbuilt fish eye lens is used in over system and it increased the viewing angle more than 180 degrees (full sky).

In our system, a contour based speed calculation is combined with Lucas-Kanade technique. This approach has increased the accuracy when determining the speed of the cloud. In this system, only azimuth angle was used, and thus the zenith angle covering rod was eliminated from new design. Thus the lens protector needs only single servo motor.

In this system, a mini solar panel was introduced to monitor the real time solar power output. This is important to measure solar irradiance level in order to develop a statistical mode for prediction.

V. Conclusion

This paper describes a methodology of developing hardware and a software to predict the solar power level in a higher accuracy level. The hardware was developed using a webcam with a fish eye lens which can capture full sky, a solar panel to determine a value proportional to the solar irradiation and a solar tracker arm. The algorithm was developed to remove the fish eye distortion. The cloud movement tracking and cloud speed determination was based upon contour matching technique which is enhanced by the Lucas-Kanade technique. This system can be used to predict the short term cloud coverage and thus the solar irradiation level.

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