Vision-Based System for the Safe Operation of a Solar Power Tower Plant

M.López-Martínez[1], M.Vargas[1], and F.R.Rubio[1]

Dpto.Ingeniería de Sistemas y Automática.
Escuela Superior de Ingenieros.
Universidad de Sevilla, SPAIN.
{mlm,vargas,rubio}@cartuja.us.es

Abstract. In this paper several vision-based systems for the operation of a solar power tower plant are shown. These systems detect the presence of clouds next to the sun and compute a field coverture factor which features the area of the heliostat field that is shadowed by them. This cloud detection process is fundamental in order to preserve the integrity of the solar central receiver located at the top of the tower of these solar plants. These systems prevent the rupture of the receiver by thermal stress.

1 Introduction

Solar power provides an energy source which varies independently and cannot be adjusted to suit the desired demand. Although solar radiation does have predictable seasonal and daily cyclic variations, it is also affected by unpredictable disturbances caused by atmospheric conditions such as cloud coverture, humidity and air transparency. The ability to predict when a cloud will cover the field is one of the main problems in the operation of the solar power tower plants. In this kind of plants there is a heliostat field that reflects the solar radiation to a central receiver located at the top of a tower. At normal operating conditions the mean temperature of the receiver reaches up to 800^oC. When a cloud covers the sun, a sudden reduction of radiation occurs, and consequently the temperature of the receiver goes down. Besides this, at the moment the cloud lets the sun shine again, the receiver will suffer a thermal shock. If this phenomenon occurs several times the receiver will get damaged due to thermal stress. In this paper a system capable of detecting the presence of clouds next to the sun is presented. This system will send this information to the master control which, in turn, will order several heliostats to turn away, so that the receiver temperature can decrease before the cloud covers the sun, and hence will reduce the risk of the receiver rupture. In [4] and [3] advanced master controls of solar plants are shown.

In this paper three different aspects are presented: A method for the location and tracking of the sun based on artificial vision. Then, an algorithm for the segmentation of clouds based on artificial vision. Finally, a geometric method to determine, using the captured images, which zones of the heliostat field are shadowed by clouds.

When vision-based methods are used, the following characteristics have to be considered: The brightness in the scene changes with the day hour and with the orientation of the camera. The brightness distribution of the sky is not uniform and there is a descending gradient towards the horizon. The clouds have a random form and a random luminosity.

These characteristics make more difficult the segmentation of the elements present in the scene. In order to help the segmentation process, the color information of each element has been used [5].

This paper is organized as follows: Section 2 describes the method used to locate the sun. In section 3 a method to segment the clouds surrounding the sun is given. Section 4 presents a method to estimate the area of the heliostat field that is covered by clouds. Conclusions are given in section 5.

2 Sun Location Procedure

High concentration solar systems require the sun to be tracked with high accuracy. Normally, heliostat positioning control used to follow the sun is made based on computation of the solar vector in open loop like done in [1]. In the system proposed in this paper, the solar vector is also employed in an upper level to position a pant-tilt platform, but a second control level is added, based on the detection of the sun through vision methods in a closed-loop (figure 1). The color information of the image has been used to make the detection process

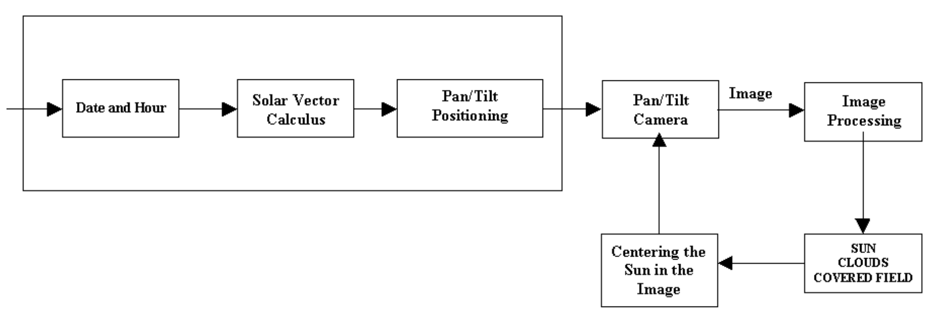

Fig. 1. Positioning System Diagram.

easier. The HSV color decomposition has been chosen because it enables to distinguish among the hue, saturation and value of each element of the scene [5]. The high variation of these color components in the different elements in the scene will help in the segment process.

After a thorough study of the HSV components in the image of the sun, clouds and sky, the following characteristics have been determined.

Value: When the sun is visible, its value is over 90% of the absolute maximum.

Saturation: The Clouds and the Sun have a similar saturation but the sky's one is clearly different.

Hue: The sky is blue and the sun is yellow, however the clouds used to be of many colors.

According to this, it is proposed to use the Value to do a preliminary segmentation, and in a second step to verify it through the Saturation and Hue components.

The detailed procedure for the sun location is as follows:

First of all, the image has to be captured (figure 2) and its color model has to be transformed into HSV, so that the three needed components are available (figure 2). Next, a Wiener filter will be applied at each color component. Notice that the saturation will be used in a complementary form 1-S, which represents a color with high content of white with a highly valued index. The

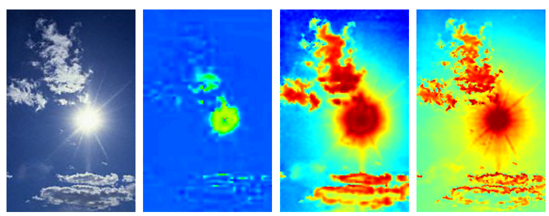

Fig. 2. From left to right Sun and Clouds Image. Decomposition H,S,V with Wiener Filter

algorithm applies a threshold of 93% to the Value Image. This image will be denoted Threshold Value Image (TVI) and will be used next(figure 3). The next

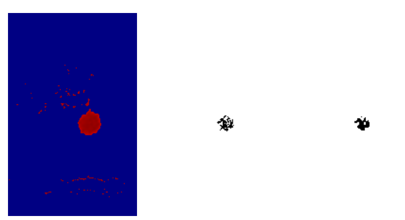

Fig. 3. From left to right, Threshold in Value Component, Threshold in edges over it, median filter

step consists in applying edge detection using the Sobel Method. The algorithm calculates the minimum value of the image and applies a threshold slightly upper to it. This takes advantage of the fact that the statistical distribution of the Sun Value fits to a gaussian one. Therefore the sun appears with the lowest levels in the edge detection(figure 4). Next, a median filter is applied to the resultant binary image (figure 3). The algorithm identifies connected regions and removes

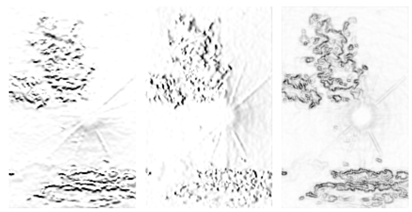

Fig. 4. From left to right, edge detection in columns, rows, and fusion of them

those of less size (figure 5). It also calculates the mass center and the charac-

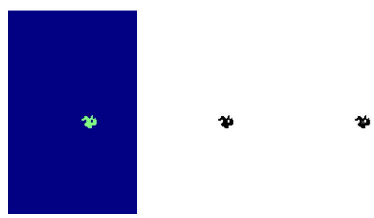

Fig. 5. From left to right, Connected regions, Bigger Region, Mass Center

teristic length of the resultant region. This length will be taken as the initial estimation of the sun radius (figure 5).

The algorithm increases or decreases the sun radius using the information of the Value component, and varies the center position until the sun circle fits with the TVI mentioned before (figure 6). It also adjusts the position and radius

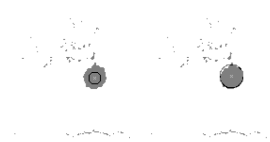

Fig. 6. From left to right, Initial Sun Circle, Final Circle, Mass Center

of the sun inside the circle, that has been previously calculated with the Value information, using the information of the Saturation component. The algorithm calculates the mass centre of those zones which have a saturation higher than the average saturation, and calculates the characteristic length of the sun using this average saturation (figures 7 and 8). As a final step, the algorithm verifies

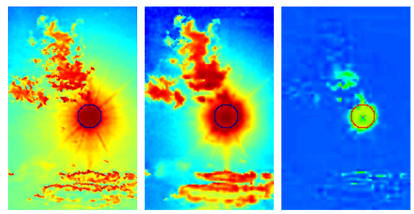

Fig. 7. From left to right, Sun Circle in Value, Sun circle in Saturation, Sun in Hue

the sun position using the Hue component (figure 7), transforms the image into

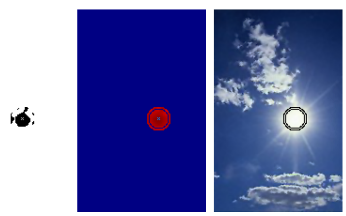

Fig. 8. From left to right, Mass Center in Saturation, Internal Circle in Saturation, Sun Circle in Saturation

RGB and represents over it the sun circle (figure 9). It also represents the sun as an artificial image, using a gaussian node (figure 9).

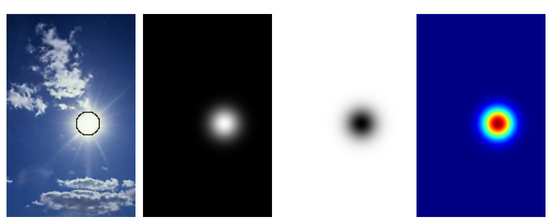

Fig. 9. From left to right, Sun Circle, Sun as a gaussian node in several color representations

3 A Method To Segment The Clouds

As mentioned before, in order to preserve the integrity of the receiver, it is necessary to detect and identify the clouds next to the sun. The proposed method makes that possible, and also determines the minimum distance between them at each instant.

The method is described in several steps: The algorithm computes the edge image starting from the original Value image. Figure 11 shows how the edges of the clouds appear very clear. This fact will be used to generate an automatic threshold using statistical information like the image histogram and its probabilistic distribution. The curve slope changes sharply when reaching a particular value. This value is chosen as the threshold (figure 10). After this, a median filtering is applied to the resultant image (figure 11). Next, the algorithm com-

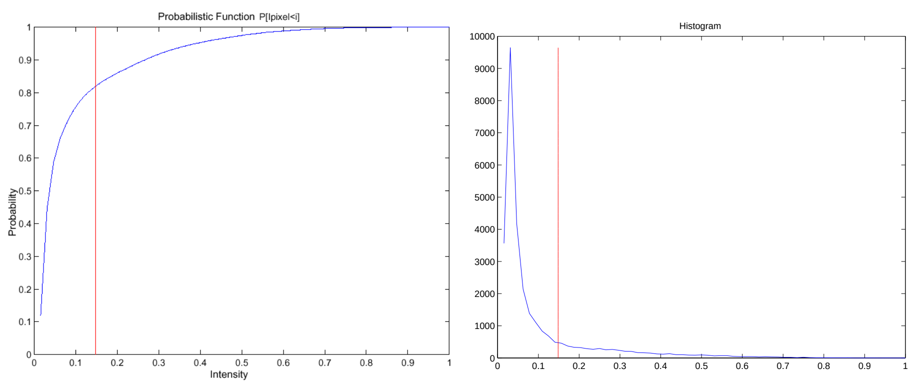

Fig. 10. Automatic Threshold for the edge detection of clouds based on the slope of the probabilistic function.

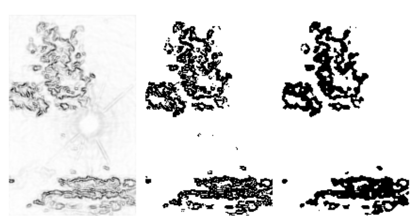

Fig. 11. From left to right, Edges Image, Thresholded Image, Median Filter

putes the growth of regions in the edges of the clouds using the saturation image and excluding the position of the sun (figure 12). In the following step, the al-

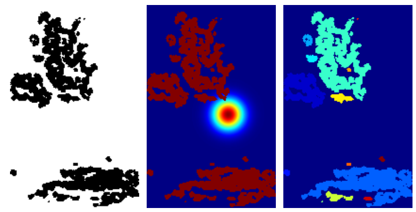

Fig. 12. From left to right, Growth of clouds using Saturation, Clouds with Gaussian Node, labeled clouds

gorithm detects connected regions and labels them (figure 12). It also calculates the minimum distance from each cloud to the sun, and saves these points (figure 13). Finally, the algorithm represents a grid around the sun and labels its elements (figure 13). Both procedures, the sun and cloud segmentation, have

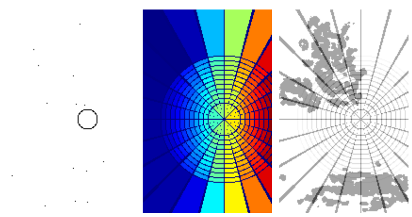

Fig. 13. From left to right, Minimum distance Sun-Clouds, Labeled Regions, Clouds and Regions

been achieved taking into account only the static information of the images. In order to improve these procedures it will be added the dynamic information in a similar way as the ones shown in [4] and [6].

The following step is to associate a region of the image next to the sun to a region of the heliostat field. In this way, when a particular region of the image is covered by a cloud, that means that a cloud is covering a specific region of the field. That will be shown in the next section.

4 A Method To Determine The Coverture Of The Heliostat Field

A vision-based method to determine which regions of a heliostat field are covered by clouds, is presented in this section.

Several methods can be used in order to estimate the altitude of a cloud: They are mainly stereo vision and infrared vision. The method presented here is based on infrared vision. It is well known that the atmosphere temperature varies with the altitude. The higher altitudes, the lower temperatures. Obviously, this same principle applies to the temperature of the clouds. In figure 14a, the variation of temperature as a function of the altitude and the type of cloud, is shown. Ground and clouds temperatures will be measured with an infrared

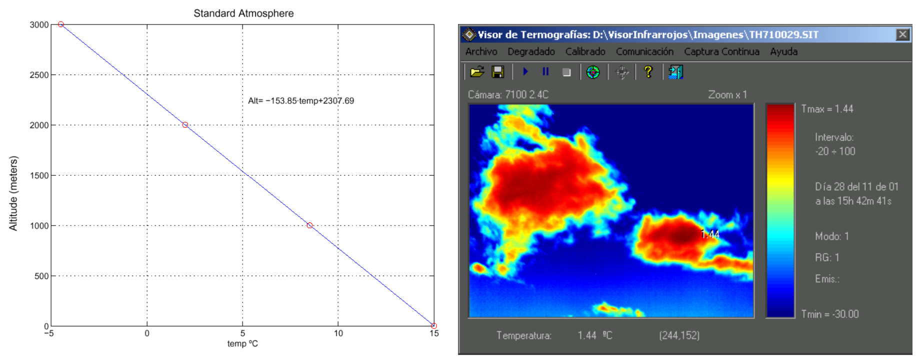

Fig. 14. Standard Atmosphere and Infrared Image

camera. Using this information the clouds altitude can be estimated.

Figure 14b shows an infrared image in which the estimated temperature is under than 2^oC. Therefore, using the hypothesis of standard atmosphere, the estimated altitude is 2km.

Using the information about the segmentation of the sun and the clouds, the covered field area will be estimated. In order to achieve this, a template, which represents the field as if it was seen from fixed axis, will be used. A triangle will be taken as the field template, which will change its form as a function of the solar time (figure 15a). The size of this triangle will depend on the estimation of the cloud altitude.

In this way, with an image of the sun, the surrounding clouds, and the altitude estimation, it will be possible to estimate the covered field area. In order to calculate the triangle, which represents three points of the field as seen from a camera located in the sun, the field has been projected taking into account the elevation and azimuth angles. These angles have been calculated using the algorithm in [1], which gives the solar vector.

As a first approximation, it has been considered that the solar vector is the same for the three points of the triangle due to the huge distance between the sun and the earth.

On the other hand, the field with the orientation of the solar vector, has been projected at a parallel plane to the ground at the altitude of the clouds H (figure 15b). Next, each point of this projection has been prolonged towards the position of the camera and over the image plane. As it is known, the image plane is perpendicular to the optical axis of the camera. The camera attitude is controlled so that the sun is in the center of the image. Therefore, in the image, the sun corresponds to the camera which is located in the mass center of the triangle that delimits the heliostat field.

Analyzing figure 15a, the following geometric relations can be established in order to obtain the attitude of the triangle as a function of θ_{Solar}, the azimuth angle of the sun taking the East as reference.

$$\begin{aligned}
d_{1S} &= d_{1C} \cdot cos(\theta) \\
d_{3S} &= -d_{3C} \cdot cos(\frac{\pi}{2} - \theta - \alpha_3) \\
d_{4S} &= d_{4C} \cdot sin(\theta - \alpha_4) \\
d_{CS1} &= -d_{1C} \cdot sin(\theta) \\
d_{CS3} &= -d_{3C} \cdot sin(\frac{\pi}{2} - \theta - \alpha_3) \\
d_{CS4} &= d_{4C} \cdot cos(\theta - \alpha_4)
\end{aligned} \quad (1)$$

The signs have been defined in this way in order to make easier the correspondence of the triangle in the image and the triangle in the field. In the center of the image, where the sun will be located, an axis system has been situated. As mentioned before, this point corresponds to the situation of the camera. Similarly, the following equations (obtained from figure 15b) allow to locate the

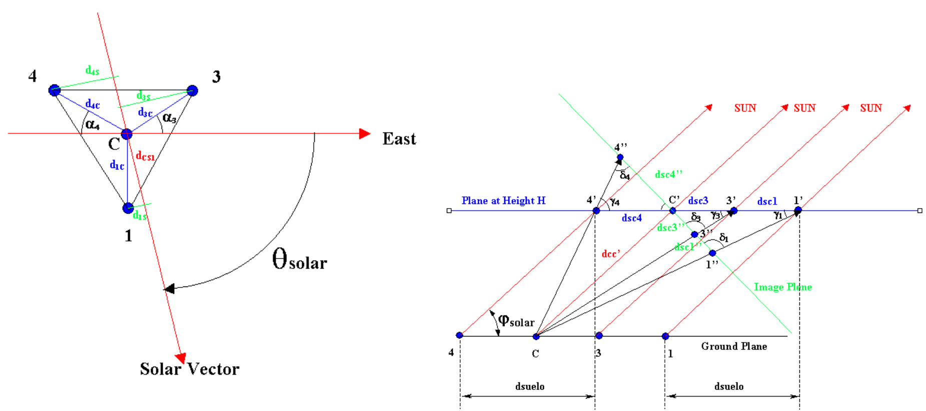

Fig. 15. From left to the right, Heliostat field plant sight and Azimuth angle of the sun. Heliostat field - Projection over the image plane

triangle as a function of the elevation angle of the sun, φ_{solar}.

$$\begin{aligned}
d_{CC'} &= \frac{H}{sin(\varphi)} \\
d_{suelo} &= \frac{H}{tan(\varphi)} \\
\widehat{d_{SC4}} &= d_{suelo} - d_{SC4} \\
\gamma_4 &= arctan(\frac{H}{\widehat{d_{SC4}}})
\end{aligned}$$

$$\delta_4 = \frac{\pi}{2} + \varphi - \gamma_4$$
$$d_{SC4''} = \frac{sin(\gamma_4)}{\sin(\delta_4)} \cdot d_{SC4} \qquad (2)$$

With these expressions, the triangle that represents the heliostat field, can be drawn over the image of the sun. If a cloud covers part of the triangle then the corresponding part of the field will be covered.

5 Conclusions

A method to segment the sun and the clouds and determine geometrically the covered area in a heliostat field has been shown.

This information is fundamental to achieve a correct operation of the solar power tower plant, and will let the master control system to take into account these factors, in order to reduce the number of heliostats aiming to the receiver and decrease the incident radiation when clouds are about to shade the heliostat field.

6 Acknowledgements

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