CONTROL SYSTEM FOR THE HIGH-FLUX SOLAR FURNACE OF CIE-UNAM IN TEMIXCO, MEXICO. FIRST STAGE

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Abstract

This paper presents the control system design of a new high flux solar furnace that is being developed in Mexico at the Center for Energy Research of the National University of Mexico. The control of the whole system is critical for the correct operation of it. The control system consists of a rugged PC running state machine-based software which manages the operation of all the user interfaces for the furnace systems which are the heliostat, shutter, cooling, visual and data acquisition subsystems, as well as the positioning desk control. The control routines run in real-time controllers dedicated for each subsystem. The computer routines used by the main program and the tests made for characterizing the heliostat follow-up system is also described. Preliminary results obtained shows that the heliostat control presents great versatility due to the type of control it has, including the possibility of accepting feedback through images projected by it.

Key words: Solar Furnace, Control, Heliostat and Shutter.

1. Introduction

Mexico has an ideal position for the implementation of solar technologies, due to its favorable geographical location in the Sunbelt of the planet. With the aim of promoting the development of concentrating solar technologies in México, the construction of a high flux solar furnace (HFSF) was proposed and approved. This installation is part of a larger project known as National Laboratory for Solar Concentration Systems and Solar Chemistry, which involve also the development of a Heliostat Test Field and a Solar Photocatalytic Water Treatment Plant. The HFSF is located at Center for Energy Research (Centro de Investigación en Energía) of the National University of Mexico (Universidad Nacional Autónoma de México CIE-UNAM), in the City of Temixco, in the State of Morelos. Its development has been funded by the *Consejo Nacional de Ciencia y Tecnologia* (CONACYT) and UNAM. The HFSF has several components that need to be controlled. Actually, the control of the whole system is critical for the correct operation of it. The main applications of this infrastructure are expected to be in the areas of solar chemistry and solar materials processing [1]. The architectonic, optical [2], and mechanical design of the subsystems have been carried out, and construction of the components is on its final stages [3]. The objective of this work is to develop a control system for the different components and subsystems of the HFSF. The control also attends the parameters needed for experimental studies [4], which also could be reported through the Web in real time.

2. Description of the system

Solar furnaces may vary in their configurations; nevertheless all of them consist essentially of three main components: a concentrator, a heliostat, and a shutter (see fig. 1). The function of each of these components is as follows:

The concentrator is at the heart of the system, and its function is to concentrate solar radiation to very high levels in order to reach high temperatures (up to 3000 K) in the focal zone. The concentrator in a solar furnace does not move; all the movement required for tracking the sun is carried out by the heliostat. This is done in order to have a static focal zone, which in turn provides a more controlled environment for experiments. Much of the quality performance of the solar furnace depends on the capacity of the heliostat for tracking the sun accurately. The shutter is opened and closed partially to different degrees to provide an accurate way of controlling the amount of radiation that is allowed to enter the system. In particular, the HFSF of CIE-UNAM was designed for a heliostat with an area of 81 m^2, a shutter of 42.2 m^2, and an optical concentrator consisting of 409 hexagonal first surface polished glass mirrors [2]. At its first stage, the HFSF has a heliostat of 36 m^2, a shutter of 42.2 m^2, and 211 hexagonal first surface polished glass mirrors as concentrator [3].

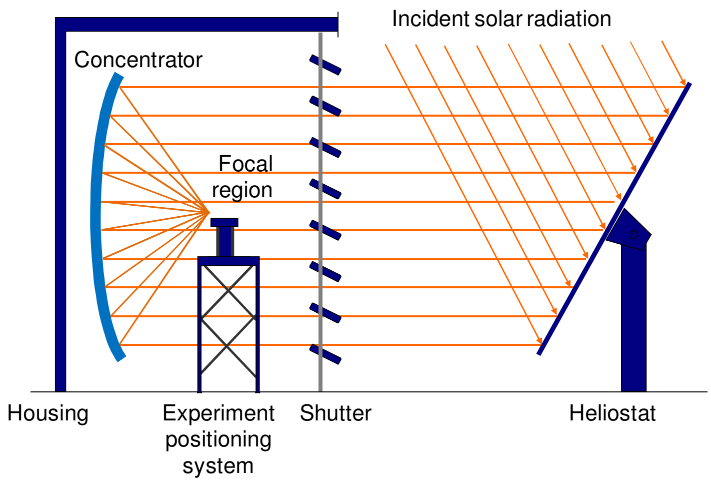

Fig. 1. Schematic of the components of a solar furnace

In addition to the above components, there is a moving platform that allows precise positioning of the experiments in different points of the focal region. Also, an acquisition system is required for monitoring different experimental variables, such as temperature, pressure flow, flow velocity, solar radiation, concentrated radiative flux distribution, etc. Some of these variables can be used in a closed loop for furnace control, depending on the nature of each experiment. All furnace components, except for the heliostat and some solar radiation and wind speed sensors, are located in the housing.

The control and data acquisition hardware of the HFSF consists of a Compact FieldPoint data acquisition system, and several CompactRIO real-time controllers for each subsystem. A rugged Windows-based PXI Controller is used as the central terminal for operation of the furnace. All control and operation software was developed using *LabVIEW* (National Instruments) [4]. Experimental data is managed and processed in the central unit and is published simultaneously to the Web. The control system of the HFSF is a parallel system capable of operating the main functions of the subsystems (heliostat positioning, opening and closing of the shutter, and location of the experimental set up by using a mechanical 3D positioning system). The system also has the capability of making an emergency stop under any unexpected event. In the present paper the control system architecture is described, as well as three main control subsystems: heliostat control, shutter, and experiment positioning subsystems.

3. Control block diagram

The central control is coordinated through a state machine calling the HFSF main systems, one by one or simultaneously without any interference, adding a lot of versatility. The state machine is shown in figure 2. This control is executed and synchronized from the central computer as well as from a touch-panel in which all subsystems of HFSF are represented. The main functions of each subsystem are described below:

- Heliostat: A selection of the type of follow-up control desired, starting and stopping, offset adjustment and emergency stop
- Shutter: Regulated opening and closing

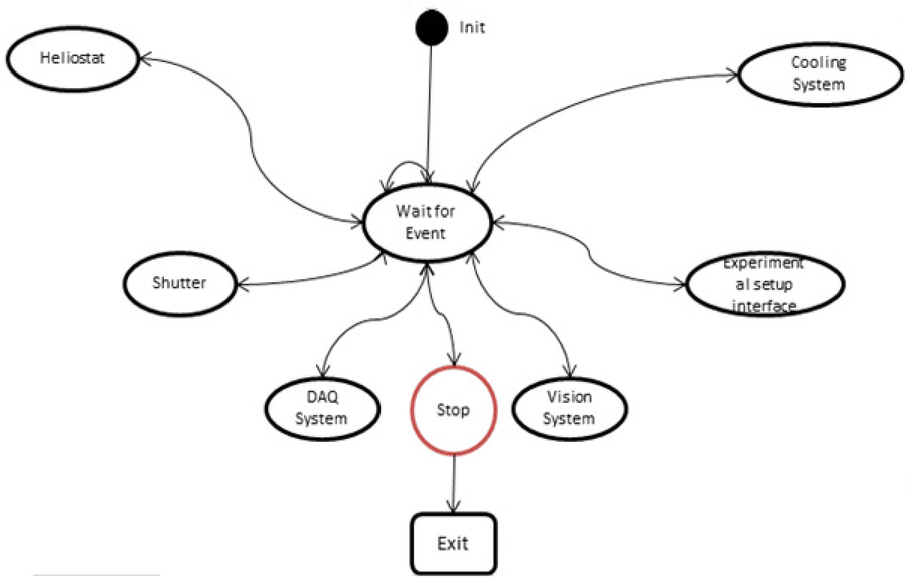

Fig. 2. State machine diagram of the central control

- DAQ system: Experimental parameters acquisition (temperature, pressure, flux, radiation, etc.)
- Vision system: Image acquisition of experiments and its processing in order to determine distribution of radiation found in the HFSF focal zone
- Experiment positioning system: Control positions inside and outside the focal zone
- Cooling system: Starting and shutting down cooling pumps.

These subsystems are distributed inside the HFSF building, as shown in figure 3. The way all control (blue boxes) and acquisition (orange boxes) systems are interconnected with the central computer (green box) through Ethernet LAN network connections can also be seen.

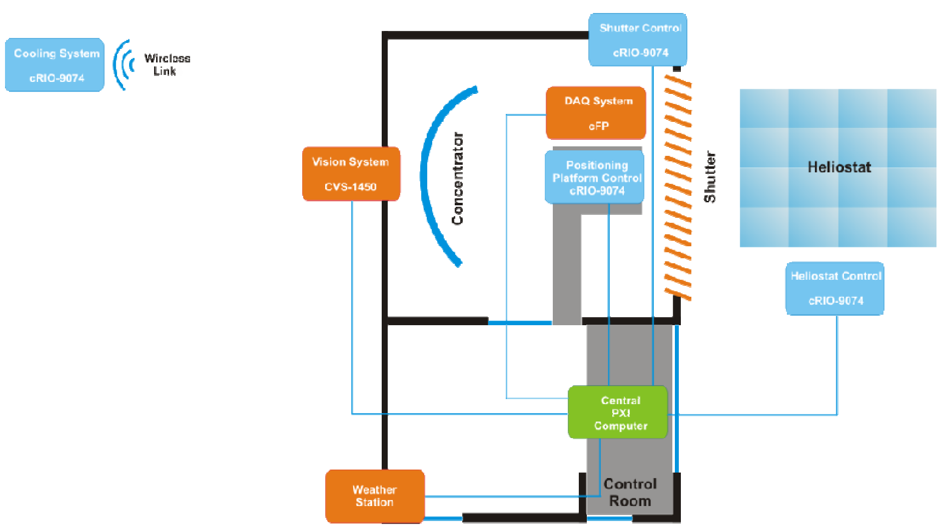

Fig. 3. HRFSF control and data acquisition diagram

Several options of components for the design and architecture of the control and data acquisition systems were evaluated. The best option for integrating control and data acquisition turned out to be the LabVIEW programming platform from *National Instruments*. As mentioned earlier, the whole control and data acquisition systems are coordinated through a central computer and each system is programmed in a deterministic way. Each subsystem has an assigned controller, which is programmed in LabVIEW Real Time to perform the required tasks. The controllers communicate with the central terminal through a network protocol, as shown in figure 3. The development of the three main controllers and their integration are presented below.

4. Heliostat

The HRFSF heliostat has a surface of 36 m^2 and comprises 25 facets, which must be aligned between them carefully in order to ensure that all rays reflected over the concentrator focal axis are parallel, with a variation no greater than 1 mrad. In order to follow the sun through the day, the heliostat structure has a set of transmissions connected at 90° transmitting the motors movement in the azimuth and elevated axes. These transmissions have a worm drive with a very high ratio (18400 to 1). For this reason, the motors required to move the heliostat are very small. The motors used for the heliostat transmission are DC Brushed motors running at 24 V @ 2.6 A, which generate a torque of 1.5 Nm. Each motor has been fitted with a 5 V encoder with a resolution of 2000 pulses per rev, which allows knowing the angular position with accuracy < 0.0002 mrad on each axis outlet. These motors are controlled by a cRIO 9074 controller (National Instruments) and two modules NI 9505, which do the control through a bridge H with the encoder feedback.

In order to develop the control software, it was necessary to develop a program to move and sense with accuracy the angular position of the motors. Also, the implementation of an algorithm to determine the sun position was needed in order to calculate the heliostat normal vector, so that the sunrays could be reflected to a specific objective on the concentrator focal axis. For this reason, two stages of development, described below, were proposed.

Phase 1: Base program development

In this phase, all input and output parameters required for moving of motors, the turn direction, and their angular position are established. This is basically the central program of the system, and is deployed directly to an FPGA (Field Programmable Gate Array) integrated in the cRIO 9074. This FPGA is connected directly to the motor control modules (NI 9505), which makes possible the execution of the main functions of this phase in real time. This program performs the most basic functions and is executed through the main program, as can be observed in the front panel in figure 4. This program is also used to control the shutter motors and those for moving the experiment positioning system.

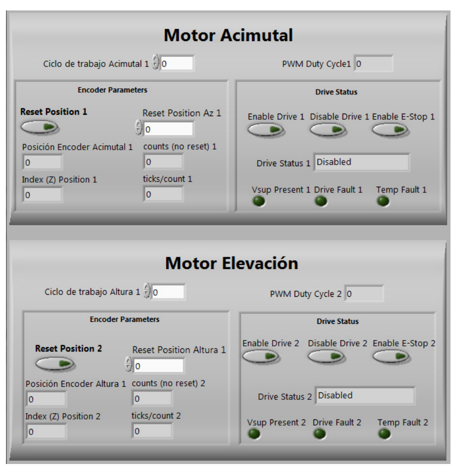

Fig. 4. Front Panel of the basic program for motor movement

Phase 2: Main program development

This phase is essential due to the fact that as a user this is the only screen one has access to. In this phase, the variables can be manipulated according to the actions one wants to perform with the system. The control program for the heliostat is coordinated through a state machine, which calls the main tasks for the heliostat control. These tasks allow for the operation of the heliostat in a manual way, or through a closed control loop with feedback through images of the solar disk concentrated in the focal zone, or finally, through an open control loop through an estimation of the solar position. This allows for a lot of versatility in the heliostat operation, as shown in figure 5.

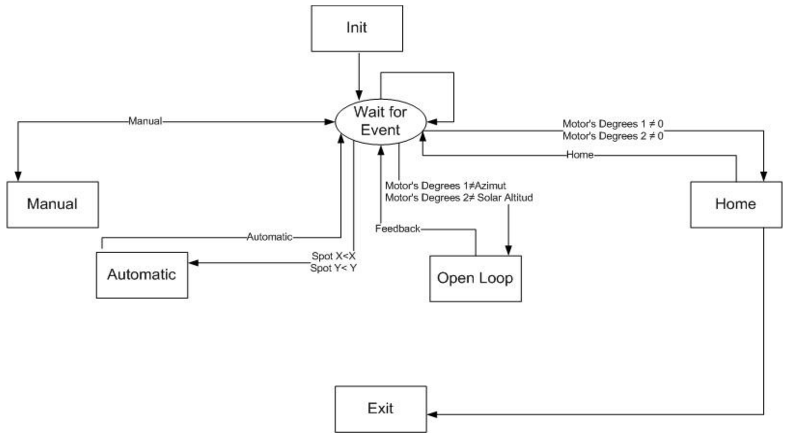

Fig. 5. Diagram of the state machine for the heliostat control.

1. Manual mode

This option gives the possibility of positioning the heliostat wherever is desired, managing the motors left and right, and up and down until finding the desired position. Velocity can be modified in percentages of 0% to 100%, in order to establish the desired revolutions. This velocity is controlled adjusting the pulse width in the PWM (Pulse Width Modulation) pulse train applied to the motor; the manual mode heliostat control screen can be observed in figure 6.

Fig. 6. Main screen for manual mode.

2. Automatic mode through feedback with visual setting

In this mode, the values of x and y, given by the visual program in pixels, are taken as reference, as well as the values established by the user, also in pixels, in order to keep the heliostat in the desired coordinates. The velocity for both motors is constant. The smaller the value of this velocity is, the smaller the oscillation movement, obtaining more accuracy in this way. This part of the program is a closed loop that is feeding itself to keep the coordinates values constant and comparing them with the values in the setpoint (fig. 7).

Fig. 7 Automatic mode.

3. Automatic mode using the equations of the solar position

The program also indicates the solar position in real time regarding the latitude (ϕ) and longitude (L) of the user. These data is obtained using the sun apparent motion equations [5]. It was necessary to perform an adjustment to these equations in order to use them south of the tropic line. The solar hour (H_S) can be obtained from the standard hour (H_E) and the equation of time measuring the daily sliding of the solar hour in regards to the standard hour.

Zenith angle: $$\theta_Z = \text{acos}\left(\text{sen}(\phi)\,\text{sen}(\delta) - \cos(\phi)\cos(\delta)\cos(\omega)\ \right)$$

Azimuth angle: $$\gamma_S = C_1 C_2\, \gamma_S' + 180 C_3\,(1 - C_1 C_2)/2$$

Where solar elevation angle is $\alpha = 90 - \theta_Z$ and the hour angle is given by $\omega = 15(H_S - 12)$.

It is necessary to use the azimuth angle:

$$\gamma_S' = \text{asen}\left(\frac{\cos(\delta)\,\text{sen}(\omega)}{\text{sen}(\theta_Z)}\right)$$

With the adjustment constants:

$$C_1 = \begin{cases} 1, & \delta \geq \phi \\ \dfrac{\omega_{ew} - abs(\omega_{ew})}{abs(\omega_{ew} - abs(\omega_{ew}))}, & \delta < \phi \end{cases} \qquad C_2 = \frac{\phi - \delta}{abs(\phi - \delta)}$$

$$C_3 = \omega / |\omega| \qquad \omega_{ew} = \text{acos}(\tan(\delta)/\tan(\phi))$$

The time equation is obtained first in order to adjust in minutes; then the declination is obtained; afterwards the complement to the zenith angle is calculated and last the azimuth angle. The equations above have the necessary correction for the azimuth calculation when being in the tropics. Angular results of elevation and azimuth are shown in degrees. These degrees are compared with the degrees from the motors outlet data in order to establish, in a second version, an open link so the program can keep the same point and follow a sequence. The aim of this mode of follow-up is to set the conditions for the heliostat to be capable of reflecting the sun in a specific point previously established, as time goes by.

In order to accomplish that, it was necessary to create a subprogram where the incidence and reflection vectors could be established, using as entry values the sun height and azimuth obtained from the main program. The subprogram of "Vectors Routine", as we call it, allows for modifying the heliostat and the objective positions, which are always variables. The reflection vector ($\hat{R}$) is constant as we are interested in having the sun radiation coming from the heliostat always reflecting in one constant direction. This direction is defined by a unitary vector going in the direction from the turning center in the heliostat to the furnace center. This direction is parallel to the focal axis of the system. The unitary vector pointing in the direction of the Sun ($\hat{S}$), can be obtained from the solar zenith and azimuth angles:

$$\hat{S} = \left(sen(\theta_Z)sen(\gamma_S),\ \ sen(\theta_Z)cos(\gamma_S),\ \ cos(\theta_Z)\right)$$

Finally, the normal vector for the heliostat is calculated through the following vector relation:

$$\hat{N} = (\hat{S} + \hat{R})/\|\hat{S} + \hat{R}\|$$

This normal vector is used by the program in order to estimate the azimuth and elevation angles for the heliostat as outlet data, which the main program uses to compare with the values from the encoders, and then establishes the motors at that point.

Several follow-up tests were carried out for more than four hours, two hours before and two hours after the solar noon: Although there was some movement, the image was fairly stable, as shown in the images of figure 8. As can be seen in the follow-up images, in a period of one and a half hours, the image projection of the heliostat drifted 80 mm in the x axis (azimuth); the drift in the y axis (elevation) was imperceptible. This implies a drift of 0.9 mrad in azimuth and less than 0.1 mrad in elevation, which implies a need to sharpen the azimuth follow-up to similar terms to those of the elevation.

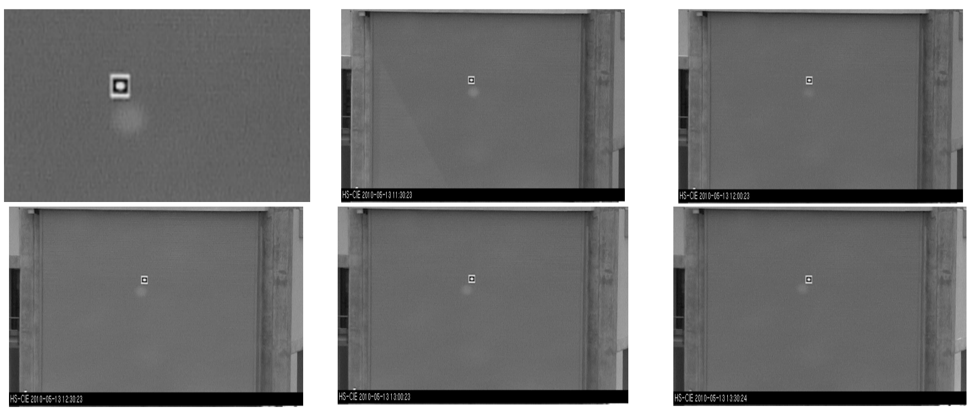

Fig. 8 Follow-up test for the heliostat from 11:05 to 12:30.

5. Shutter

The shutter control is operated through a small state machine coordinating the opening and closing of the curtain in the HRFSF and the shutter control itself, regulating the percentage of the opening area, as can be observed in figure 9.

Fig. 9 Main program to control the shutter.

The control for opening and closing the curtain is done through a program. A digital output card is used, as well as three relays, which operate the three respective contactors controlling the curtain: OPEN, CLOSE and STOP. For managing the opening and closing of the shutter, a NI 9505 module is used. This module controls the polarity, speed of the motor and senses the position of the encoder, which is synchronized with the mechanism operating the opening of the blinds. For this, an algorithm relating the angular aperture with the percentage of the area exposed in the aperture, through the cosine factor of the blinds inclination, is solved. As a security measure, there is an option for bringing the motor back to a position we have called HOME in which the shutter is totally closed. This position is detected through a micro-switch. When the emergency stop signal is sent in the user interface the controller acts immediately and makes the shutter move towards the HOME position and when the micro-switch activates, indicating that the HOME position has been reached, the shutter stops moving and stays in that position until further command is received.

6. Focal zone coordinate system

For the experiment positioning system, the user can define a set of x, y, and z coordinates to which the device is taken, or a sequence of points to which the target needs to be taken through the experiment, setting as reference the focal point of the optic of the system. The control takes place through three NI 9505 modules which control the position of the three motors the system has with feedback of their respective encoders. Figure 10 shows the front panel for system control.

Fig.10. Front panel of the focal zone coordinate system.

7. Master control through SCADA System

Figure 11 describes the functioning of the SCADA (Supervisory Control and Data Acquisition) System for the HRFSF control through a dynamic system diagram. The upper part is a state machine of the main program running in the central computer and having states where interfaces of each system embedded in other computers are executed. For this reason they are “local replicas”. This consists in bringing (monitoring) and taking (control) some data from and to each control system. This is common in a distributed computing application like this one.

7. Conclusions

Preliminary results about the development of the control system for the Solar High Radiative Flux Furnace at CIE-UNAM have been presented. This system must be flexible in order to accept different control approaches, depending on the nature of the experiment to be carried out on the system. The system should also be capable of accepting different types of experimental variables and the possibility of one of the values of these variables taking the control of the system. To date, three different control methods for the heliostat have been implemented as well as the shutter and curtain controls. The master control is implemented in a SCADA system, which integrates all the control systems required for the operation of the furnace.

The heliostat control presents great versatility due to the type of control it has, including the possibility of accepting feedback through images projected by it.

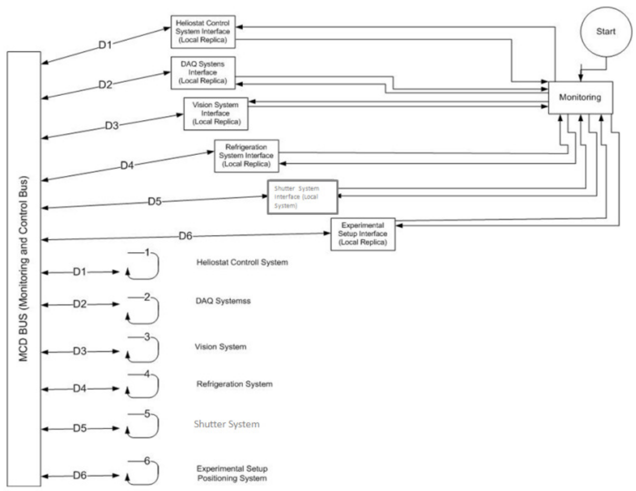

Fig.11. Diagram of SCADA System for controlling the HRFSF.

The master control integration through state machines in a visual setting allows for the simultaneous operation of all systems in a coordinated way without interfering with each task that is executed in real time.

Acknowledgements

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References

1. Fletcher, E.A., 2001. Solar thermal processing: a review. J. Solar Energy Eng. 123, 63–74.
2. D. Riveros-Rosas, J. Herrera-Vázquez, C. Pérez-Rábago, C.A. Arancibia-Bulnes, S. Vázquez-Montiel, M. Sánchez-González, F. Granados-Agustín, O. Jaramillo, Estrada C.A., 2010, "Optical design of a High Radiative Flux Solar Furnace for Mexico", Solar Energy 84, pp. 792-800.
3. C.A. Estrada, C.A. Arancibia-Bulnes, S. Vazquez, D. Riveros, C.A. Pérez-Rábago, R. Perez-Enciso, J. Quiñonez, R. Castrejón, M. Montiel, F. Granados. A NEW HIGH-FLUX SOLAR FURNACE AT CIE-UNAM IN TEMIXCO, MEXICO. FIRST PHASE. SolarPACES 2011 Congress, 20-23 September, Granada, Spain.
4. Pérez-Rábago, C.A., Marcos, M.J., Romero, M., Estrada, C.A., 2006. Heat transfer in a conical cavity calorimeter for measuring thermal power of a point focus concentrator. Solar Energy 80, 1434–1442.
5. Flores-Guzmán N., Sossa-Azuela J.H., Bizuet-García R., A Decision and Communication Management Methodology for Embedded Multi-Smart Camera Systems, Applied to Real-Time Inspection in Lamps Production, The second ACM/IEEE International Conference on Distributed Smart Cameras ICDSC 08, Universidad de Stanford, California, 30-06-08
6. Duffie J. and Beckman W. "Solar Engineering of Thermal Processes", John Wiley and Sons, Inc. New York, 1991.