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On Achieving a Desired Flux Distribution on the Receiver of a Solar Power Tower Plant *

N.C. Cruz[1], J.L. Redondo[1], J.D. Álvarez[1], M. Berenguel[1] and P.M. Ortigosa[1]

[1]*University of Almería, ceiA3, Dpt. of Informatics* {ncalvocruz,jlredondo,jhervas,beren,ortigosa}@ual.es

Abstract The heliostat field of solar tower power plants must be carefully configured to get the maximum profit of solar energy while keeping the system in a regular operation state. Field control tasks include both deciding what heliostats need to be activated and assigning each one a certain aiming point over the receiver. In fact, current plants have hundreds, even thousands, of available heliostats. In this context, there are desirable flux distributions of the concentrated energy over the receiver that should be achieved to grant an efficient operation while also avoiding thermal stress, premature aging and undesirable temperature gradients over the receiver surface. In this work, a meta-heuristic algorithm is presented to be able to reproduce any desired flux distribution over the receiver, what implies solving a large-scale optimization problem. It selects both the subset of active heliostats and their corresponding aim points for a given operational instant on minimizing an error function.

Keywords: Global Optimization, Heliostat field flux distribution, Solar power tower plant, Aiming strategy

1. Introduction

Solar tower power plants (STPP) are one of the most interesting facilities to generate large-scale clean electricity due to their overall efficiency, their mature technological basis and their relative stability of production. This kind of systems mainly consist of a set of steerable highly-reflectance mirrors with solar tracking capabilities, known as 'heliostats', which are responsible for concentrating the incident solar radiation over a receiver along the day. Then, the concentrated energy over the receiver is transferred to a working fluid (the heat transfer fluid (HTF)) in circulation, whose temperature gets increased, and can be used for electrical energy generation on a classic thermodynamical cycle. In Figure 1 a basic schema of an STTP is shown. The interested reader is referred to [2, 7] for further information of this technology.

The operative field of modern STPP is generally formed by a vast set of heliostats as it is commonly over-dimensioned to face unfavorable operating conditions such as cloudy days. However, not all of them need to be operated for the nominal case to achieve the expected power requirements. In fact, the receiver should not be exposed to an excessive or uncontrolled income of power over its surface. The flux distribution of the reflected solar radiation over the receiver must be controlled to avoid dangerous temperature gradients, thermal stress and premature aging of its components [1, 3, 5, 8]. This is a key factor for increasing the operative life of the receiver, which has a direct influence on the production costs of STTP as highlighted in [5]. The flux distribution over the receiver is a direct consequence of which heliostats are active and to which aiming point they are targeting to. In this context, it is necessary to face a two-layered optimization problem in which it must be decided both the subset of available heliostats to activate and their corresponding aiming point at the receiver. These

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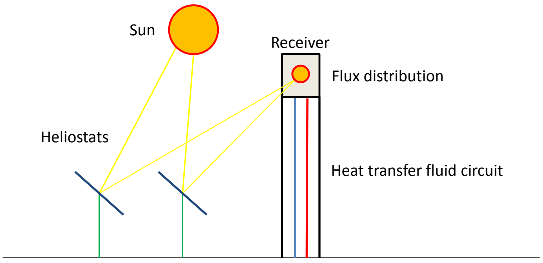

Figure 1. Scheme of a solar tower power plant.

tasks are usually supported by manual human decisions, what is an implicit limitation of the number of aiming points that can be handled and the adaptability of the field.

In the recent works of [3, 5], two similar optimization problems related to predefined aiming points assignation are addressed. They are focused on minimizing the standard deviation of the flux density distribution and flux spread minimization respectively. In [3] a Genetic Algorithm is successfully used while in [5] a TABU search is applied with good results. However, this work aims two define and solve a two-layered optimization problem in which both the subset of heliostats to activate and their corresponding aiming points are optimized to achieve any user-given flux distribution (instead of being linked to static general ideas such as flux spread minimization) by minimizing an error function. Additionally, the aiming point assignment is expanded to a continuous search-space. By proceeding this way, the field would be significantly more adaptable and configurable. We have been working with a meta-heuristic algorithm for heliostat selection and a local gradient-based search procedure for final aiming points assignation with promising results. In the next section, we introduce the mathematical formulation of the problem at hand. Then, the optimization procedure is summarized. Finally, some experimental results are shown and conclusions are drawn.

2. Mathematical formulation

As commented in the previous section, the key idea of the present problem can be summarized in this sentence: the intention is to replicate a desired flux distribution over a flat plane receiver by selecting both a subset of heliostats to be activated and their corresponding aiming points over the receiver. This idea leads to face a complex large-scale optimization problem.

In order to model this problem, we can start by defining the whole heliostat field as an ordered set $H = \{h_1, h_2, \cdots, h_N\}$ with cardinality N. The reference flux distribution to be achieved in a certain common instant t is defined by a two-dimensional function F which expresses, for any point (x, y) on the receiver plane, the radiation density (kW/m^2) at that point. We consider the X and Y directions to be positive towards the East and North respectively over the plane of the receiver, which is due North. Every heliostat h projects a certain flux distribution f_h over the receiver when it is operative, which is also a known two-dimensional function of the radiation density. A certain candidate solution C can be seen as an ordered sequence of length N with the structure $C = \{c_1, c_2 \cdots, c_N\}$. In C, the position of every element is directly mapped to the corresponding heliostat in H so c_h defines the particular configuration of the heliostat h, which can be $\emptyset$ when it is not active or a certain position (x, y) on the receiver plane. Therefore, there are $2N^*$ variables under optimization at the second layer of the problem, where N^* is the number of finally active heliostats. In this context, a certain valid field configuration C defines the corresponding achieved flux distribution F^* over the receiver, which is formed by the convolution of every sub-flux distribution f_h (discarding non-active heliostats). Then, the objective function of the problem at hand can be defined as the difference between the reference and the achieved flux distributions $O = |F - F^*(C)|$. Consequently, the optimization problem is defined, from a minimization perspective, as:

$$min\, O = min\, |F - F^*(C)| \tag{1}$$

Assuming that the flux distribution expressions are assumed to be continuous, Eq. 1 implies a de facto discretization for both the reference and the achieved flux distributions, that can be seen as monochromatic images, in order to study their differences. Therefore, after defining a discretization grid over the receiver plane, the problem can be formulated as

$$min\, O = min \sum_{x=X_1}^{X_T} \sum_{y=Y_1}^{Y_T} |F(x,y) - F^*(C)(x,y)| \tag{2}$$

where $\{X_1, \cdots, X_T\}$ and $\{Y_1, \cdots, Y_T\}$ are the discrete sets of X and Y coordinates on the receiver respectively. However, both sets can be defined with different cardinalities.

In relation to the definition of every heliostat-linked flux f_h over the receiver plane, we work with the analytical definition of a bi-dimensional Gaussian density function to model it:

$$f_h(x,y) = \frac{P}{2\pi\sigma_x\sigma_y\sqrt{1-\rho^2}} e^{\left(-\frac{1}{2(1-\rho^2)}\left(\frac{(x-\mu_x)^2}{\sigma_x^2} + \frac{(y-\mu_y)^2}{\sigma_y^2} - \frac{2\rho(x-\mu_x)(y-\mu_y)}{\sigma_x\sigma_y}\right)\right)} \tag{3}$$

where x and y are the coordinates on the plane defined by the receiver rectangular aperture, P is the power contribution of the heliostat h over the receiver, ρ is the correlation between x and y, σ_x and σ_y are the standard deviation along x and y respectively and μ_x and μ_y, which are the mean in the Gaussian probability function, define the central point of the flux distribution, i.e. the aiming point of the heliostat h. This approach is similar to the one selected by [3, 5], where a specific circular Gaussian density function is applied according to the HFLCAL model [6].

As previously commented, the flux information of every heliostat needs to be known, what is usually achieved by using CPU-time demanding ray-tracing or convolution-based simulations as done in [3, 5]. However, for this work, a synthetic fluxes database has been generated to be used as a plain input for the optimization procedure. Finally, the reference flux distribution to achieve, F, can be also defined by using Eq. 3 or any other user-given bi-dimensional expression. The most recommendable testing approach is to form the reference flux by convolving a known sub-set of existing heliostat. By proceeding this way it is known that it is possible to achieve the reference flux with the deployed heliostats.

3. Optimization procedure and preliminary results

The algorithm starts by solving the first layer of the problem, what determines an active subset of heliostats and their initial starting points, according to the reference flux, for the second stage. Then, a local gradient-based optimizer is used to sharpen the selected aiming point of every heliostat to minimize the error between the reference and the obtained flux maps.

At its first stage, the algorithm generates different candidate configurations C and looks for the most promising one until the termination criteria are satisfied (i.e., an user-defined number of cycles or a certain threshold). There are two initial solutions that are always considered in this procedure: the sets formed by the most and less number of available heliostats to achieve the total power in the reference flux (with independence of its shape). These solutions fix two thresholds for any other future candidate solution: its number of active heliostats must be between the two initial. Then, new candidate solutions are formed by mutating and mixing the existing ones along a search procedure to minimize the objective function O. It must be noted that the aiming points of candidate solutions at the first stage, which are used for relative evaluations, are assigned according to the power of the heliostats and the shape of the reference flux. Then, the second stage of the algorithm takes the best solution obtained from the first part of the search and tries to improve its quality by applying a gradient-based local search while minimizing O until the termination criteria are fulfilled (i.e., an user-defined

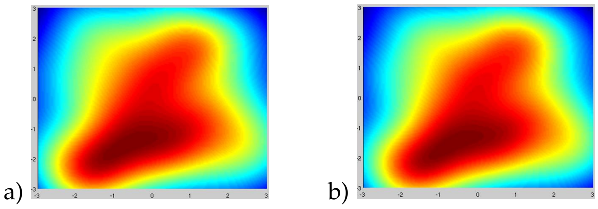

Figure 2. Result of flux distribution replication of the reference in a) is shown in b).

number of cycles or a certain threshold). At this point, the active heliostats subset will not been changed any more but only their corresponding aiming points.

In Figure 2 a result for the local optimizer is shown. In that test, the reference flux has been formed by randomly convolving 50 heliostats over a 6x6 receiver and defining the reference flux in Figure 2 a). The local optimizer has been able to replicate the desired map by optimizing the aim point of the original 50 active heliostats from a totally random start as shown in Figure 2 b). Additional experiments have been carried out up to 200 heliostats with positive results.

4. Conclusions

A generic two-layered optimization procedure is being developed for STPP which is intended to be able to configure the heliostat field to achieve a given distribution flux by selecting both the active heliostats and their aiming points. The preliminary results are promising, i.e. the flux distribution replication for a defined active set is operative with a good overall performance. For future work, the applicability of the procedure in control tasks could be studied.

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