A Lightweight Heliostat Field Post-Optimizer

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Abstract. Maximizing the power that the heliostat field of a solar power tower facility concentrates on its receiver requires solving a difficult optimization problem. The traditional design methods rely on forcing heliostats to follow geometric patterns and on working with discrete sets of positions. Some recent strategies bet for working on a continuous search space with promising results. In any case, it is not easy to know if a field is optimal or not, especially from the perspective of the method used. This work proposes an external and fast post-optimizer that takes as input a heliostat field and tries to improve its performance. It follows a combinatorial strategy, and it is independent of how the input field was generated. Thus, it can be linked to any other method.

INTRODUCTION

The heliostat field of solar power tower facilities [1, 2] can take up to 50% of the initial investment and up to 40% of energy loss at operation [3]. Thus, it is essential to optimize its design. The power that a field concentrates on its receiver is a valid optimization criterion, and it is considered herein and in [4, 5]. Another popular one is weighted efficiency [3, 6, 7], which is the ratio of the previous magnitude and the theoretical maximum without energy losses. Land consumption [8] and production costs [9] can be considered too. In fact, some works optimize several functions simultaneously: In [10], the objective function combines investment cost and energy produced. In [11], the authors compute Pareto fronts with the costs of energy and investment. Unfortunately, in general, the problems have numerous constrained variables [10]. Moreover, the objective functions are usually computationally expensive, multi-modal and without an exploitable structure [10]. There is also a considerable lack of details about optimized heliostat fields [12].

There are four main types of methods for designing heliostat fields [13]: i) pattern-based, ii) iterative, iii) continuous or free variable and iv) multi-step or hybrid. Pattern-based methods, which are one of the most popular options [10, 5], rely on forcing heliostats to follow geometrical patterns. Some existing patterns are radial-staggering [14], cornfield [15] and the recent biomimetic spiral [7]. In relation to iterative design methods, that in [8] has been widely studied due to its higher flexibility over patterns. It places heliostats, one after another, on the most promising position of a discrete grid defined over the ground. Although the same iterative work-flow is maintained in [10], there is no a grid of positions. The coordinates of every heliostat are defined on a continuous search space. Regarding free variable methods, [4, 16] design genetic algorithms whose individuals encapsulates whole heliostat fields. The coordinates of their heliostats are optimized in a continuous search space. The work in [5] falls into the same category, but a gradient-based optimizer is used. Finally, as multi-step strategies, DELSOL [13] considers different zones and adjusts radial-staggered patterns on them. The method proposed in [17] starts with a pattern-based field and improves it by locally perturbing the position of every heliostat.

As demonstrated in [17], the convergence of heliostat field optimizers might be suboptimal, and trying to improve their result through a different process can be advantageous. This work proposes a general post-optimizer that can be used to define multi-step design methods. It is independent of how the input field was generated. It does not require parameters either. The proposed method looks for wasted regions and tries to move heliostats to them. It aims to be faster and simpler than others such as that in [17] to allow its use with a negligible cost.

PROBLEM STATEMENT

Let H be the set of heliostats to deploy. They have a reflective surface of size $l \times w$, area A and diagonal $c = \sqrt{l^2 + w^2}$. The surface where they have to be deployed is considered flat. It is defined by a minimum and a maximum radius from the tower base, R_{min} and R_{max}, respectively, and a symmetric angular limit from the North direction, β. The origin of coordinates is the central point of the receiver tower. The position of every heliostat h is defined by the coordinates of its central point, x_h (East) and y_h (North), i.e., $h = (x_h, y_h)$. Figure. 1 depicts these ideas. It is necessary to optimize a vector of $|H|$ pairs of coordinates to design a heliostat field. The optimization problem can be defined as follows:

$$\begin{array}{ll} maximize_{(x_h,y_h)} & A \sum_{t \in T} I_t \left(\sum_{h \in H} \eta_h(t) \right) \\ subject\ to & R_{max} - \frac{c}{2} \geq \sqrt{x_h^2 + y_h^2} \geq R_{min} + \frac{c}{2}, \quad \forall h \\ & atan(|x_h|, y_h) \leq \left(\beta - asin\left(\frac{c}{2\sqrt{x_h^2+y_h^2}} \right) \right), \quad \forall h \\ & \sqrt{(x_h - x_j)^2 + (y_h - y_j)^2} \geq c, \quad \forall h \neq j \end{array} \tag{1}$$

where T is the set of time instants considered to evaluate candidate heliostat fields. I_t is the solar radiation density at instant t, and $\eta_h(t)$ is the optical efficiency of heliostat h at that instant. $\eta_h(t)$ depends on cosine, spillage, attenuation, reflectivity as well as shading and blocking losses, which is the most computationally expensive magnitude to compute [18, 7]. Any optimizer that solves Equation (1) must find the best pair of coordinates for each heliostat while also fulfilling the constraints. The first and second ones prevent trespassing the surface available to design the field. Finally, the third constraint avoids collisions among heliostats.

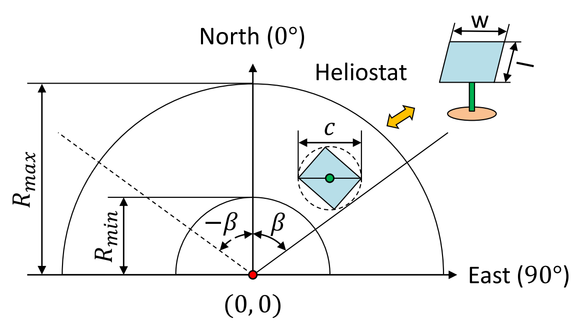

FIGURE 1. Definition of the problem region.

DESIGN OF THE METHOD

The proposed method consists of three consecutive stages which are explained below: i) Grid generation, ii) Grid cleaning and iii) Combinatorial resolution. It returns a variation of the input field. The new field must be ultimately evaluated with the objective function and accepted if it outperforms the input one.

Grid Generation

This step consists in generating a dense set of potential positions for heliostats on the available surface. They are arranged into concentric circular rows. Each row i has a certain radius from the center of the tower base, R_i, and an angular space to keep between its positions, $\Delta\Psi_i$. The radius of the first row is $R_{min} + c/2$ to respect the minimum one. Thus, the first position is $(R_{min} + c/2, 0)$ (radius from the tower base and azimuth from the North, respectively). The separation between consecutive positions in any row is set to c, i.e., the diagonal of the reflective surface of the

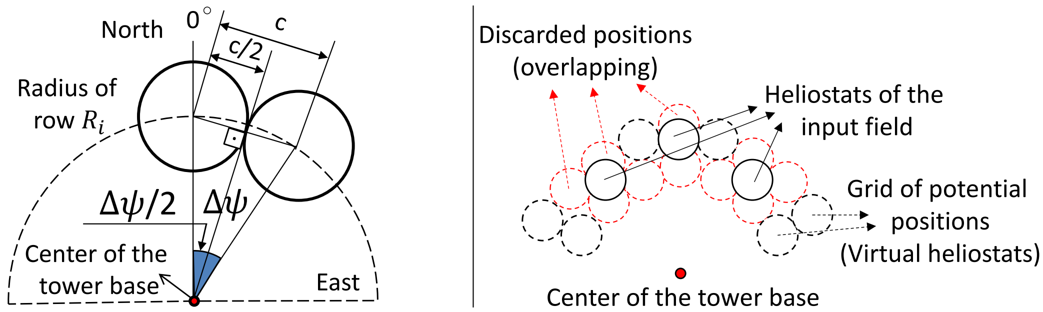

FIGURE 2. Grid: Distance to avoid overlapping at griding (left) and initial grid cleaning (right).

heliostats (see Figure 2 (left)). $\Delta\Psi_i$ can be hence calculated for row i according to Equation (2). By proceeding this way, if the positions are ultimately used to deploy real heliostats, they cannot collide. After computing $\Delta\Psi_i$, all the positions in row i are generated by advancing clockwise and adding their symmetric equivalent to the west side too. This is possible until reaching the angular limit β. Then, a new row is defined by adding c to the current radius and re-starting at 0° of azimuth. This process ends when any radius is greater than $R_{max} - c/2$ to avoid trespassing.

$$\Delta\Psi_i = 2\arcsin\left(\frac{c}{2R_i}\right) \tag{2}$$

Grid Cleaning

This step starts by removing those potential positions that cannot be selected because they are already used in the input field. To do so, it superimposes the previous grid of positions on the input field. Any position that overlaps a heliostat in that field is removed (see Figure 2 (right)). Thus, any remaining position or virtual heliostat could host a real one. This approach is useful to look for wasted regions and to shorten the list of potential positions. Next, the remaining positions are evaluated as an independent heliostat field to register their possible power contributions. Their cosine, spillage, reflectivity and atmospheric attenuation losses are considered. Shading and blocking is also computed but considering only that caused by the heliostats of the input field. By proceeding this way, the valuation of potential positions is expected to be more accurate. After that, the input field is also evaluated and recorded but without considering any virtual heliostat. Finally, each potential position with less estimated power contribution than the worst heliostat of the input field is removed from the grid. If the grid gets empty, the process ends without success.

Combinatorial Resolution

This step defines two vectors of heliostat positions, $E = (E_1, \ldots, E_H)$ and $G = (G_1, \ldots, G_K)$. E contains the position, i.e., the coordinates, of each heliostat of the input field. G consists of the coordinates of the remaining positions of the grid. Both vectors are first ordered descending by the power contribution of the heliostats at them (either virtual or real), which was recorded at the previous step. These ideas are depicted in Figure 3 (left), which omits the coordinates for simplicity. After that, the method replaces the least powerful position in E with the most powerful one in G. Next, it replaces the second least powerful position in E with the second most powerful one in G. The process is repeated with the third, fourth and so on while the power linked to the position in G is higher than that of the one in E. The field finally proposed by the method would be defined by vector E and the changes made on it, i.e., E'.

Figure 3 (right) shows a resolution example. For simplicity, only the power recorded when placing a heliostat at each position is shown, and their coordinates are omitted. As can be seen, the three worst positions in E would be replaced with the three best ones in G. Then, the potential power of the field would increase from 145 to 171 (kW for instance). Keeping the order of assignment is necessary to detect when to stop. In fact, in the example, it could be possible to replace more positions. If 20 in E were paired with 24 in G without altering the next two, the last 30 in E could be finally linked to 38 in G. Then, all the heliostats selected would have been improved in theory. However, the estimated power for that combination would be 165 instead of 171 kW, i.e., less than that of the solution shown. That said, as long as the positions to replace are the same as in a fully ordered execution, the resulting field is equivalent. For instance, moving 20, 26 and 29 in E to 30, 38 and 33 in G, respectively, would also result in a field of 171 kW.

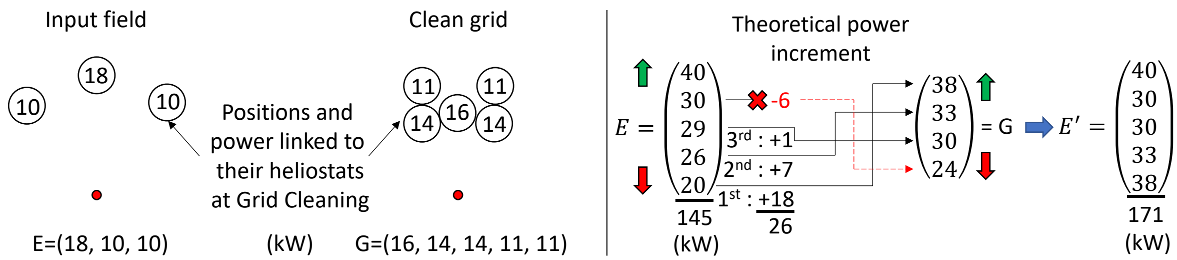

FIGURE 3. Graphical definition of vectors E and G (left) and example of the resolution step (right).

RESULTS AND FUTURE WORK

According to preliminary experimentation, the post-optimizer improved up to 1.2% the design-point performance of some fields of 300 heliostats obtained by the method described in [4]. The difference might seem small, but it is relevant considering the small room for improvement at design-point, and the numerical ranges in works such as [5, 7]. Besides, whereas the process in [4] takes hours, the present one took less than 20 seconds. Thus, it is like a cost-free add-on. As future work, the analysis will be extended to more types of input fields to confirm its effectiveness.

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