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A heuristic method for simultaneous tower and pattern-free field optimization on solar power systems

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ABSTRACT

A heuristic method for optimizing a solar power tower system is proposed, in which both heliostat field (heliostat locations and number) and the tower (tower height and receiver size) are simultaneously considered.

Maximizing the thermal energy collected per unit cost leads to a difficult optimization problem due to its characteristics: it has a nonconvex black-box objective function with computationally expensive evaluation and nonconvex constraints.

The proposed method sequentially optimizes the field layout for a given tower configuration and then, the tower design is optimized for the previously obtained field layout. A greedy-based heuristic algorithm is presented to address the heliostat location problem. This algorithm follows a pattern-free method. The only constraints to be considered are the field region and the nonconvex constraints (which allow heliostats to not collide).

The absence of a geometrical pattern to design the field and the simultaneous optimization of the field and the tower designs make this approach different from the existing ones. Our method is compared against other proposals in the literature of heliostat field optimization.

1. Introduction

Solar Power Tower (SPT) systems are known as one of the most promising technologies for producing solar electricity due to the high temperatures reached, resulting in high thermodynamic performances. For simplicity, we consider in this paper an SPT system to consist of two elements: a tower and a field of (hundreds or thousands) of heliostats. The study of other related problems, see Section 5, is beyond the scope of this paper.

In an SPT system direct solar irradiance is reflected by the heliostat field and concentrated onto a receiver placed at the top of the tower. In the receiver, this thermal energy at a high temperature is then transferred to the heat transfer fluid to produce electricity through a conventional thermodynamic cycle. The heliostat field is a group of mirrors having two-axis movement to reflect the direct light from the sun to the target point on the receiver aperture. The heliostat locations take into account the typical solar irradiance at the site.

The optimal design of an SPT system consists of determining the tower height, the shape and dimensions of the receiver aperture in the tower (*Tower Optimization*) and the location and number of the heliostats (*Field Optimization*) so as to optimize the annual thermal energy collected and the cost of the system. From the mathematical point of view, we want to simultaneously optimize several criteria. These objectives are in conflict to each other and they are usually aggregated into a single criterion, namely, the *thermal energy collected per unit cost*, see [24,31].

Three challenging issues are the dimensionality of the field optimization problem, with (a priori unknown) hundreds or thousands of variables, the nonconvex constraints related to the location of heliostats (which prevent the heliostats from colliding), and the evaluation of the objective function. This evaluation is implicitly defined by the subroutine, and due to the nature of the process, is not smooth, multimodal and has no apparent mathematical structure which can help to choose an appropriate optimization algorithm.

This optimization problem has great interest in the renewable energy literature, attracting researchers over the past thirty years. The problem continues being a very active research field, as can be appreciated in some reviews ([19,20,25,32,3]).

Fixed geometrical patterns are traditionally used to solve the *Field Optimization* problem. That is, the heliostat positions are

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given by some parameterized curves. The parameters are optimized in order to obtain a field layout. For instance, radially-staggered layouts are commonly assumed, originally proposed in [19], see also [13,30,33]. This pattern consists of concentric semicircumferences where the parameters indicate the separation between the circumferences and the angular distances between the heliostats located at the same circumference. The Spiral pattern is also used, where two parameters are optimized, see [21].

Radially staggered pattern has been so far the most popular SPT systems design. By the pattern itself, access is guaranteed to all heliostats in the field for cleaning or repairing work, since roads are naturally given. Although pattern-free fields do not define roads in their layout, (see e.g. the recently built Ivanpah system [6]), one may impose, as we do in this paper, heliostats to be sufficiently apart from each other, so that access to all heliostats in the field is possible. This would not be needed if new strategies for cleaning the heliostats were developed, see [1].

Although these geometric patterns strongly simplify the *Field Optimization* problem, they may not reach good results if, for instance, time asymmetric weather conditions or terrain constraints are involved, as pointed out in [25]. The adaptability of the pattern is very limited and dependent on the chosen geometry, usually field symmetry is induced by the pattern itself.

Fixed-pattern strategies consider the number of heliostats to be located not given in advance: an oversized field (i.e., a field with a sufficiently large number of heliostats), is built, and then those heliostats reflecting less solar energy into the receiver are sequentially removed while guaranteeing that a given receiver outlet thermal power is attained. This way, although the optimal parameters for the oversized field were obtained, there is a high risk that a strong distortion exists between the original and final fields.

We present a heliostats location procedure which will not force to follow a specific geometrical pattern, and, instead, will be a pattern-free optimization strategy. With our algorithm an initial oversized field is not needed, the final number of heliostats is found during the optimization process. A possible drawback is that road design and building may be more expensive. Contrarily, pattern-free fields are much more flexible and can be adapted (as will be shown in Section 4.3) to many geographical circumstances.

Most articles in the literature focus on the *Field Optimization* problem, see [13,26,30], or on the *Tower Optimization* separately, see [18]. References to simultaneous optimization of the *Field* and *Tower* are very scarce. [23,24] address the joint optimization by using a metaheuristic (genetic algorithm and simplex Nelder-Mead) improved by local searches (Powell algorithm), always under the assumption of a radially-staggered pattern for the field.

This paper presents a pattern-free procedure for the field layout optimization, and an optimization algorithm including the optimization of both the *Tower* and the *Field*.

The rest of the paper is organized as follows. In Section 2, we describe the main ingredients affecting the performance of the SPT system. In Section 3, our methodology to solve the problem is explained. In Section 4, we apply the optimization algorithms and analysis tools to a typical SPT design, and finally, in Section 5, our main results are summarized and some perspectives for further work are presented.

2. Problem statement

In this Section, the SPT system, the variables used in the optimization process and the constraints that have to be satisfied are described. Finally, the two criteria involved in the objective function (energy and cost) and the optimization problem are presented.

2.1. Decision variables

Two types of decision variables appear, some associated to the height of the tower and the receiver aperture, and the remaining ones associated to the heliostats locations.

We will assume that the receiver consists of a cylinder pointing to the North, as can be seen in Fig. 1 and is also explained in [3,12,32], among others. The front surface of the receiver, also known as the *aperture*, is especially important because it is here where strong radiative losses occur. For simplicity, only the two most relevant variables associated with the tower and the receiver design are considered, namely the *aperture size*, given by its radius r_a, and its height h in the tower.

In what concerns the heliostat field, the heliostats locations, given by the coordinates (x, y) of their centers, are the variables to be used. A heliostat is characterized by its geometry and its optical properties. All heliostats are assumed to be rectangular, to have the same dimensions and to be composed of rectangular facets.

From now on we will denote by Θ the variables related to the *Tower*, i.e. $\Theta = (r_a, h)$, and by $\mathcal{S}$ the finite set of coordinates of the centers of the heliostats that define the *Field*. The decision variables are Θ and S. Observe that the points of $\mathcal{S}$ belong to $\mathbb{R}^2$ and $\mathcal{S}$ can be viewed as a set of non-fixed cardinality. Consequently, we write in the sequel relations of the form $\mathcal{S} \subset \mathbb{R}^2$.

2.2. Constraints

Let $\Pi_t(\Theta, \mathcal{S})$ denote the receiver outlet thermal power at time t for an SPT system with parameters $(\Theta, \mathcal{S})$. Usually, when designing an SPT system, a fixed instant of time is used to size the system, as explained in [12,26,27]. This time instant is known in the literature as the *design point*, T_d. At T_d, a minimal power Π_0 has to be achieved, that is

$$\Pi_{T_d}(\Theta, \mathcal{S}) \geq \Pi_0. \tag{1}$$

Other constraints on the variables related to the receiver are determined by the operation scheme of the system, which is in turn influenced by technical and legal regulations, leading to a compact set $\boldsymbol{\Theta}$ as the feasible region for Θ. There exist minimum and maximum values, r_{min} and r_{max} respectively, for the aperture radius and a maximum value h_{max} for the tower height. The feasible region $\boldsymbol{\Theta}$ can be written as follows:

$$\boldsymbol{\Theta} = \{(r_a, h) : r_{min} \leq r_a \leq \min(h, r_{max}) \leq h_{max}\}. \tag{2}$$

Related to the heliostat field we have to consider different constraints. The heliostats must be located within a given region $\Omega \subset \mathbb{R}^2$ and they have to rotate freely avoiding collisions between

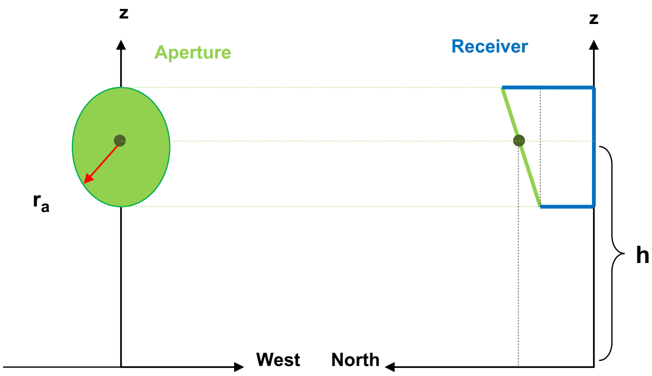

Fig. 1. Receiver with circular aperture.