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Field-Design Optimization with Triangular Heliostat Pods

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Abstract. In this paper the optimization of a heliostat field with triangular heliostat pods is addressed. The use of structures which allow the combination of several heliostats into a common pod system aims to reduce the high costs associated with the heliostat field and therefore reduces the Levelized Cost of Electricity value. A pattern-based algorithm and two pattern-free algorithms are adapted to handle the field layout problem with triangular heliostat pods. Under the Helio100 project in South Africa, a new small-scale Solar Power Tower plant has been recently constructed. The Helio100 plant has 20 triangular pods (each with 6 heliostats) whose positions follow a linear pattern. The obtained field layouts after optimization are compared against the reference field Helio100.

INTRODUCTION

Approximately 40% of the capital costs (CAPEX) of Solar Power Tower (SPT) systems lies in the heliostat field, however it is also here where the highest technology improvement opportunities reside. Heliostats are traditionally constructed with very large collector areas fixed to a single pedestal [8]. Significant work has been conducted on optimizing the shape, size and drive systems of heliostats to reduce the Levelized Cost of Electricity (LCOE) of the system, see [5]. It is out of the scope for this paper to present a complete discussion on heliostat cost reduction. However, a significantly related approach relies on the improvement of the foundations, for instance, using free standing heliostats also known as pod systems. Recent developments on heliostats which do not use conventional single foundations are: triangular pod [4], rectangular ganged heliostat [1] or trapezoidal pod [11]. The advantage of pod systems is that significant reduction in LCOE can be gained due to reduced ground and civil work and lower material costs due to lighter self-supporting structures [11].

Starting in the 70s heliostat field layout optimization is an area of ongoing research where multiple techniques have been studied each with varying degrees of accuracy and computational speed [9, 12]. However, since the pods have only been used relatively recently there is less development in optimization techniques to design heliostat pod fields.

This paper presents three optimization techniques developed to design heliostat fields with triangular heliostat pods. The field layouts obtained are compared against the Helio100 plant constructed in South Africa. The facility, consisting of 20 triangular pods, has been constructed under the Technology Innovation Agency (TIA) Helio100 project at the University of Stellenbosch and serves as a demonstration, testing and research facility of the triangular pod technology. As the number of pod is considered fixed, in this paper we focus on the heliostat pod field design. Future work will consider real cost figures to be included in the optimization process.

In the next section the triangular pod prototype used in Helio100 project, called Helio pod, is described. The performance of collected energy of the triangular prototype is analyzed and compared against individual heliostat fields. Then, the three optimization algorithms developed to design the heliostat field are explained. In the Results

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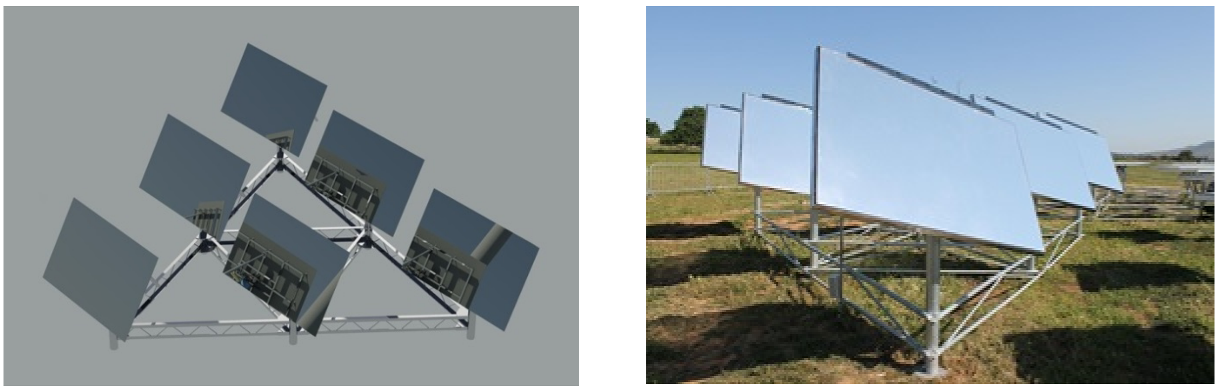
Section, the fields obtained with the different algorithms are presented and compared against the Helio100 facility. Finally, the conclusions of the paper are detailed.

TRIANGULAR HELIOSTAT POD

In [7] possible aspects of heliostat cost reduction are identified. For instance the heliostat size: smaller heliostats suffer from lower wind loading and therefore, require less structural material. Furthermore, larger number of heliostats immediately benefit from economies of scale. However, this also incurs higher foundation and wiring costs per m^2 of collector area. The Helio pod prototype is an equilateral triangular pod with six small-size heliostats: three in the vertices and three in the middle points, see Fig. 1. All the parameters of the prototype are detailed in Table 2 (Results Section).



(a) (b)

FIGURE 1. Heliostats positions in the Helio pod.

The Helio pod has been designed with no foundations and it is operated and powered wirelessly. It can be directly installed on uneven ground, eliminating the civil and site preparation costs associated with the field. In addition the pod has been designed for easy manufacture and assembly in order to reduce the high labor costs. The sides of the pod were capped at 6 m as this is the standard steel tube lengths readily available. Longer (or shorter) side lengths will require additional manufacturing, increasing the total plant CAPEX. Although, from Fig. 2 it can be seen that 6 m is not the optimal pod side length, the marginal increase in efficiency of 1% from 69% for a 6 m side length to 70% at optimal, may outweigh the reduction in manufacturing cost.

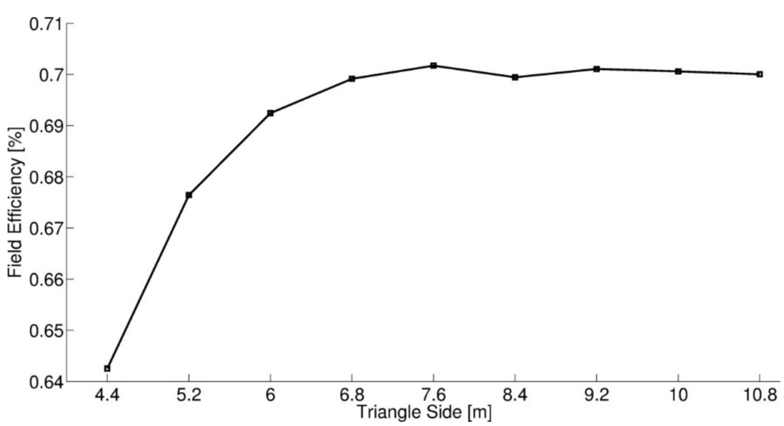


FIGURE 2. Field Efficiency for different pod sides.

The field efficiency achievement with individual heliostat fields is slightly higher than for triangular pod fields, see Fig. 3. However, the low reduction in efficiency will be compensated by the overall field cost reduction expected with pod systems (e.g. no foundations needed).

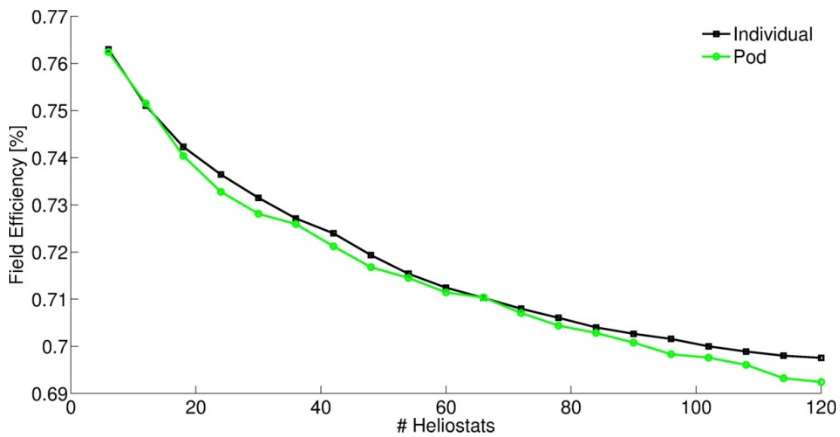


FIGURE 3. Efficiency of individual small-size heliostats vs Helio pods.

FIELD-DESIGN OPTIMIZATION

The field-design optimization is usually addressed in the literature with pattern-based strategies, commonly radial-staggered [12] and spiral [9]. In pattern-based strategies a pattern determines the possible heliostat positions and the parameters describing the geometry of the selected pattern are optimized. Pattern-free strategies have been recently studied to solve the standard field layout problem in which the heliostat positions are found during the optimization process without fixing any pattern, see [2, 10].

In this paper, a pattern-based and two pattern-free optimization algorithms are applied to design the field layout. The pattern-based algorithm considers the positions and rotation angles of the triangular pods given by the pattern parameters. However, in the pattern-free optimization approach, the triangular pod positions and rotation angles are not fixed in advance.

Regarding the pattern-free problem, the use of pod systems reduces the number of optimization variables. Instead of having (at least) two variables for each heliostat, six heliostats are grouped together in one single pod described only with three variables (x, y, α), where (x, y) denotes the coordinates of one vertex of the triangle and α the angle with respect to the vertical axis, see Fig. 4. Note that during the optimization process pods can rotate to find their optimal location in the field.

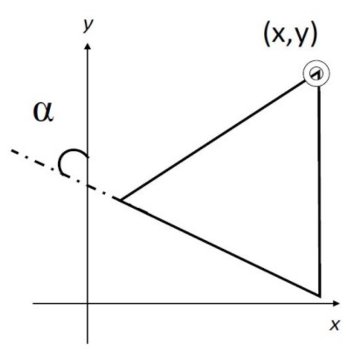


FIGURE 4. Pod optimization variables.

In order to obtain an operational field layout some constraints have to be incorporated into the optimization. Heliostats have to move freely in order to follow the sun at each time instant without collisions. Therefore, the clear-out circles enclosing the heliostats are incorporated to the problem through the following safety constraints: $\|(x_i, y_i) - (x_j, y_j)\| \leq d$, for each pair of heliostats $(x_i, y_i), (x_j, y_j)$ in the field. The safety distance d is given by the heliostat diagonal.

In the Helio100 project the number of pod systems was fixed to 20 which results in a total of 120 heliostats. For simplicity, it is assumed that the total cost of the heliostat field is independent on the pod positions selected. Therefore, in our approach if the number of pods is fixed the cost of the system is also fixed. The objective function considered is the annual thermal energy collected by the field, which in this case is equivalent to optimize the LCOE function. In the following the three different optimization algorithms are described.

Pattern-Based Algorithm

In the pattern-based algorithm the pods are placed in rows whose geometry is given by the pattern. The user provides the number of rows, the number of pod systems in each row and which pattern to use: ellipses (either with a common center point or a common center and focal point), parabolas (with a common focal point) or lines (parallel to the horizontal axis). The optimization parameters considered describe the different geometries of the selected pattern as well as the inter row and inter pod spacing, see Fig. 5. Then, the pods are located in alternating positions (main triangle vertex pointing towards and away from the tower) and the individual pod rotation angles are given by the slope of the obtained rows.

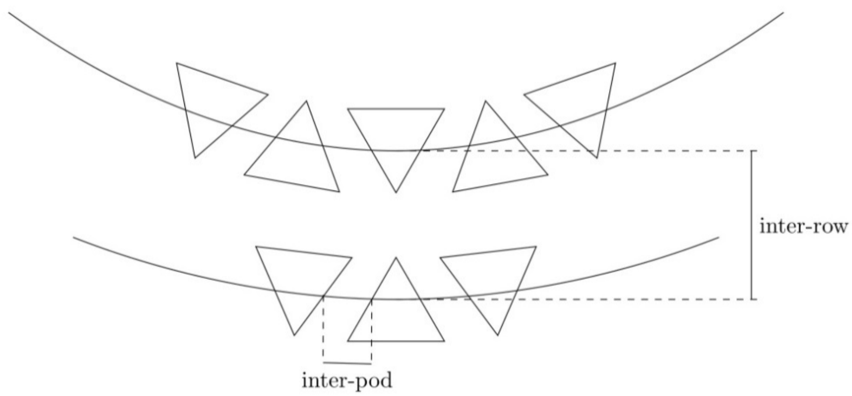


FIGURE 5. Pattern-Based scheme.

Having only few optimization parameters standard optimization methods for a nonlinear optimization, e.g. Nelder-Mead, can be used. This is in fact the main advantage of pattern-based algorithms from the computational viewpoint.

The pattern-based approach is designed to guarantee symmetry about the North-South direction (vertical axis). For this reason, in rows with an even number of pods, a gap appears in the middle of the row due to the symmetry requirement. This effect can be avoided by specifying only an odd number of heliostats per row, which reduces the number of possible configurations for a given total number of pod systems.

Genetic-Based Algorithm

The functionality of a genetic algorithm is inspired by the biological evolution. The algorithm starts with several configurations, each with randomly distributed heliostat pod systems on the field. Out of the best configurations (selection) new configurations are derived (recombination) and its properties slightly modified (mutation) until the objective function of the best configuration converges (termination).

We adapted the recombination and mutation rules such that it is tailored to the problem. This guarantees a fast convergence of the algorithm. First, two or more individuals are randomly selected by roulette-wheel method from the old population according to their fitness values. The properties of the selected configurations are combined according to the fitness value of their heliostats. Therefore the heliostat pods of all parent configurations are sorted in descending order according to this value. Successively the best pods are picked for the new configuration. If any selected heliostat pod causes a conflict, it is neglected and the next best pod is picked. In case that there are no more pods, the remaining ones are generated by random. Afterwards, the heliostat pods are mutated by locally changing their position. The algorithm terminates if a stop criterion is satisfied, e.g. convergence of the best configuration. See [10] for further details.

Greedy-Based Algorithm

The greedy-based algorithm proposed is a pattern-free heuristic algorithm which locates the pods one by one sequentially in the field. This algorithm has been adapted from [2], where it was proposed to design heliostat fields with single heliostats. Starting from an empty field, a new pod is added to the field at each step of the algorithm. For the location of the current pod, a local search is performed to find the position where the best objective value is achieved.

At step *k*, pod number *k* is located. The nonconvex constraints related with the *k-1* triangular pods already located are included into the optimization process to avoid possible collisions. Many local optima can appear due to the shading and blocking effects of the heliostats already located. In order to avoid these local optima a randomized multi-start strategy is applied where different local searches are performed starting from different random feasible solutions. The selection of the next pod position is determined according to the objective function value. As the number of pods is fixed in this problem, the algorithm stops after iteration *k=20*.

However, note that the same algorithm is completely meaningful with an a priori free total number of pods. In other words, for a prescribed LCOE, it makes sense to use this strategy to construct an admissible (optimal or suboptimal) field.

RESULTS

The parameters related with the selected small-size heliostat and Helio pod prototype are detailed in Table 1. Also, the remaining fixed parameters related with the location and the tower-receiver characteristics are given

TABLE 1. Parameter Specifications.

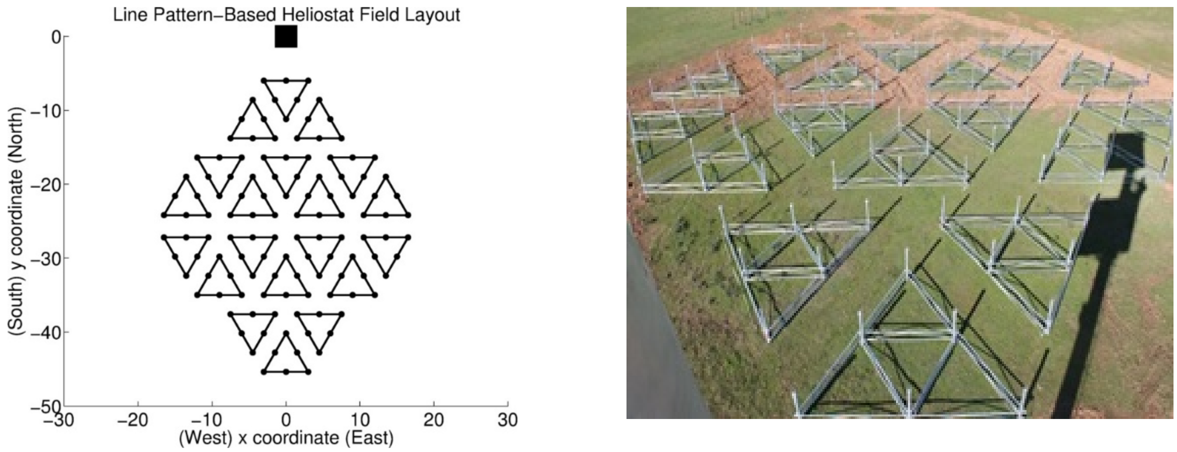
General		**Triangular Heliostat Pod**	
Site Location	South Africa	Triangle Side	6 m
Tower Latitude	33°51'13.40"S	Heliostat Width	1.83 m
Tower Longitude	18°49'29.03"E	Heliostat Height	1.22 m
Aperture Surface	1 m^2	Optical Height	1.5 m
Tower Height	12.20 m	# Helio pods	20
Field Slope	0º		

The annual field performance is computed using the algorithm described in [2] based on NSPOC procedure [3]. The simulation is based on the hourly performance for the 21st of every month considering clear sky conditions. Note that the annual value is calculated using a discretization over the year considering different time steps. Due to the complexity of the model, it seems very hard to measure in a rigorous way the error caused by such discretization. However, we can get an idea by checking how stable results are with respect to the used grids. For instance, if we consider 5, 9 or 13 different hours to compute the daily thermal energy, for different fixed days we obtain the results shown in Table 2. These results suggest that 2 or 3 decimal digits are acceptable and significant.

TABLE 2. Daily thermal energy

E (MWth)	**March**	**July**	**Nov.**
E_5	**0.050**35	**0.04**484	**0.056**75
E_9	**0.051**22	**0.04**040	**0.059**45
E_{13}	**0.049**65	**0.04**112	**0.060**26

The TIA Helio100 field layout and construction process are shown in Fig. 6. A linear pattern has been used for this demonstration plant due to the easy field assemble and placement.



(a) (b)

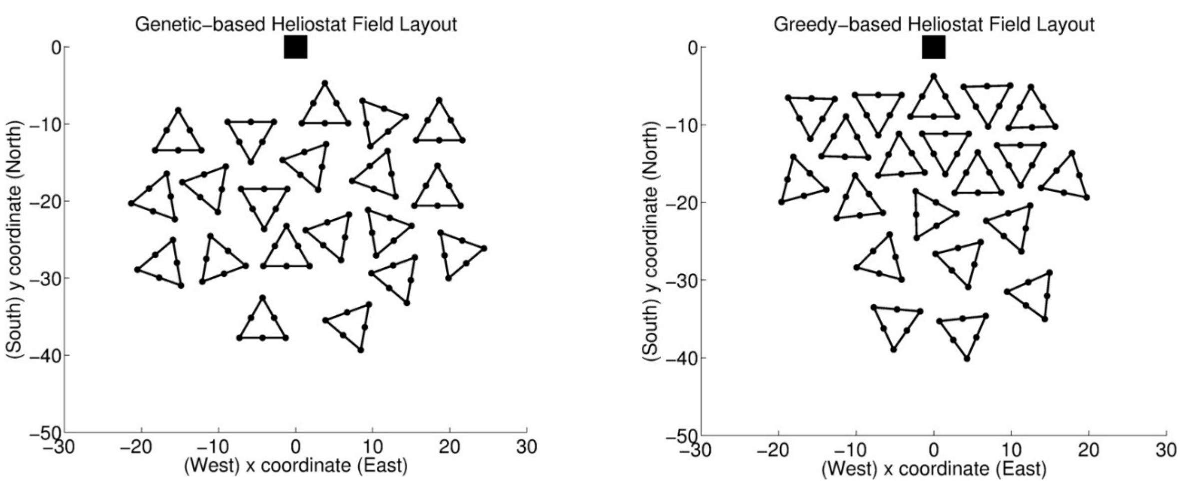
FIGURE 6. (a) Helio100 Layout (b) Helio100 under construction

The heliostat field layouts obtained with the three optimization algorithms are shown in Fig. 7-8. For the pattern-based approach only the ellipsoidal field is shown as this configuration gave the best results. Remember that, in our approach the number of pods is fixed and the cost of the system is also fixed. Therefore, minimizing the LCOE function or maximizing the field efficiency are equivalent to maximize the annual thermal energy collected by the field, which is the objective function considered in the optimization.

The results of the simulation of the obtained field layouts and the real Helio100 field are given in Table 3. All three optimization routines deliver solutions with similar field efficiency values when compared against the real Helio100 facility.

TABLE 3. Heliostat Fields Results

Fields	Field Efficiency (%)
Helio100	**66.64**
Pattern-Based Ellipsoidal	67.28
Genetic-Based	68.07
Greedy-Based	69.24



(a) (b)

FIGURE 7. (a) Genetic-Based. (b) Greedy-Based

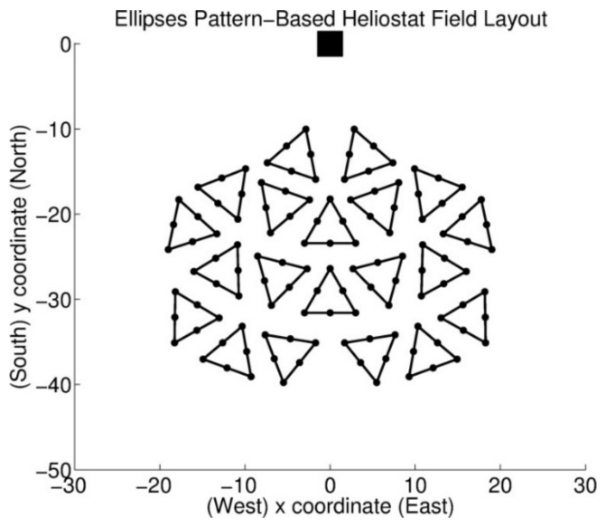


FIGURE 8. Pattern-based (Ellipsoidal)

The regular linear layout was used to construct the plant because it was felt that the irregular layouts of pattern-free strategies will require strict supervision when placing pods. The triangular pods were designed such that two unskilled laborers can assemble the entire field which also allows cost reduction. A sensitivity analysis was not performed on pod placement therefore there is no information on what will happen to the field efficiency if the pods are not placed precisely at the locations given by the optimized layouts. However, for large-scale pod fields, a *2%* of improvement over the field efficiency will be valuable to take into consideration pattern-free layouts.

Note that the asymmetrical measured irradiation data affect the final layout obtained, in some cases slightly deviated to the east. As can be seen in the obtained fields, both pattern-free algorithms are able to detect this asymmetrical behavior and locate more pods into the east field area obtaining an improvement over the field efficiency.

CONCLUSIONS

This paper studies the three different field-design optimization strategies for locating triangular pods. The Helio triangular pod and TIA Helio100 demonstration facility are used as prototype and reference field layout respectively. All three optimization routines deliver solutions with similar results when compared against the Helio100 field. The efficiency values of the three layouts vary from 67% to 69%. We show that for the presented complex optimization problem, new field layouts with triangular pods can be found improving the field efficiency and therefore improving the LCOE value. Furthermore, a larger improvement of the LCOE is expected due to the reduction on the heliostat costs when using pod systems.

Similar optimization techniques can be applied in more complicated situations: different pod shapes (e.g. rectangular ganged heliostats [1] or trapezoidal pods [11]), multi-tower solar systems, etc. In particular, the use of pattern-free algorithms is compatible with irregular fields which are able to adapt the layout to new innovative requirements improving at the same time the field efficiency.

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