Optimisation of Aiming Strategies in Solar Tower Power Plants

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Abstract. Inclement weather effects have a direct impact on the efficiency of a Solar Power Tower plant and have the potential to damage the receiver by flash heating. An optimised aiming strategy for the heliostat field mitigates the risk of receiver damage and maximises plant efficiency. A stochastic integer programming approach is applied to optimise the aiming strategy of the heliostat field, with uncertainty in the cloud location, size and density. The optimisation technique is demonstrated with a test case and results are presented for near real-time simulation of the optimal aiming strategy.

INTRODUCTION

Research into renewable energy sources has continued to increase in recent years, and in particular the research and application of solar energy systems. Concentrated Solar Power (CSP) is a method of solar energy collection, where the energy from the Sun is concentrated by a field of heliostats onto a central receiver. In Solar Power Tower (SPT) plants, this receiver is mounted atop a tower, and the resultant thermal load is used to drive a steam generator. This allows high temperatures to be achieved and is an increasingly investigated method into renewable energy production, see [1, 2, 3, 4, 5].

The SPT plant is usually formed of at least one central tower, with a field of heliostats located in front of the receiver side of the tower. These heliostats are able to rotate, in order to track the movement of the Sun and focus the light onto the receiver surface. The chosen aiming point for the heliostats on the receiver surface will have an effect on the production of energy, as well as an effect on the lifetime of the materials used in the receiver surface, due to thermal stresses. Therefore, the aiming strategy used by a SPT plant is of importance when seeking to achieve the optimal energy production, whilst minimising risk of damage to components.

Using a central aim point for all heliostats leads to a large heat flux at the centre of the receiver and large flux gradients towards the edge of the receiver, which can cause strong heat loads and can lead to damage over time and therefore costly repairs [6, 7, 8, 9, 10].

An uneven flux distribution across the receiver surface also lowers the efficiency of the energy transfer to the thermal fluid within the receiver [10, 11]. Therefore, maintaining an even distribution by using an optimal aiming strategy will increase the efficiency and allow for greater energy production [16].

Research has been conducted where more complex aiming strategies are considered for different receiver types [12, 13], as well as closed-loop feedback mechanisms to provoke changes in aiming strategy [14, 15]. Applications

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of alternate optimisation algorithms for the aiming strategy have also been exhibited [8, 9, 10, 16, 17] and a summary of optimisation techniques collected [18].

Optimisation strategies for SPT plants are typically performed using normal weather conditions, however inclement weather has been shown to have an effect on the productivity of a SPT plant, as well as on the lifespan of the receiver components, due to thermal fluctuations [19]. Research into weather and its affects on SPTs [20, 21, 22] has also been conducted, with a review of articles given in [23].

In this paper we will utilise the methodology in [16] to model the passage of clouds across a SPT, and optimise the aiming strategy implemented in order to protect the receiver from damage and to maximise energy produced.

The effect of a cloud on the production of a SPT plant can be described in terms of efficiency curves for the heliostats within the field. The efficiency of a heliostat field changes across time due to solar conditions, and the introduction of a cloud will produce a localised effect of efficiency loss. The characteristics of a cloud, such as size, location and density, determine the scale of efficiency loss and are naturally uncertain across time. Therefore we apply the methodology from [16] whilst considering uncertain cloud characteristics, represented by the efficiency curves of the heliostats within the field.

The distribution of reflected energy from the heliostats onto the receiver is assumed to be a Gaussian, as in [5, 16]. The distribution can be written in the form:

$$f_1(x, y, \Theta)\exp\left(\frac{-f_2(u, v, x, y)}{2f_3^2(t, x, y, \Theta)}\right)$$

Where the f_i with $i = 1,2,3$ are as follows:

$$f_1(x, y, \Theta) = \frac{f_4}{2\pi f_3^2(t,x,y,\Theta)\|\vec{w}\|^2} \qquad f_2(x, y, \Theta) = \frac{u^2+v^2}{2\|\vec{w}\|^2}\left[(1 + f_4^2) + \frac{|u|}{\sqrt{u^2+v^2}}(1 - f_4^2)\right]$$

$$f_3(t, x, y, \Theta) = \left[\mu_1^2 + \left(\frac{\mu_2(1 - f_{cos})}{4\|\vec{w}\|}\right)^2\right]^{1/2}$$

and, finally,

$$f_4(x, y) = \begin{cases} 0, & if \cos\beta \le 0 \\ \frac{\vec{w}.\vec{p}}{\|w\|}, & otherwise, \end{cases}$$

In these definitions, it is assumed that the heliostat is at (x, y) and aims at (u, v), and $\vec{w}$ is the vector from the heliostat to the receiver. The cosine efficiency, f_{cos}, is given by:

$$f_{cos}(t, x, y, \Theta) = \sqrt{\frac{1}{2} + \frac{\vec{w}.\vec{v}}{2\|\vec{w}\|}}$$

where $\vec{v}$ is the solar vector with $\|\vec{v}\| = 1$.

The cosine efficiency is a number between 0 and 1; f_4 is equal to $\cos\beta$, where β is the angle between the vector from heliostat to receiver and the vector normal to the receiver.

The fraction of reflected energy reaching the receiver, known as the *spillage efficiency*, can be found by integrating this distribution across the area of the receiver surface,

$$f_{sp}(x, y, \Theta) = f_1(x, y, \Theta)\iint_S exp\left(\frac{-f_2(u, v, x, y)}{2f_3^2(x, y, \Theta)}\right)dudv$$

where *S* denotes the aperture area.

Converting this to polar coordinates with $u = \rho\cos\varphi$ and $v = \rho\sin\varphi$, gives:

$$f_{sp}(x,y,\Theta) = f_1(x,y,\Theta)\int_0^{2\pi}\int_0^{r} exp\left(\frac{-\widetilde{f_2}(\rho,\varphi,x,y)}{2f_3^2(x,y,\Theta)}\right)\rho d\rho d\varphi$$

where *r* is the radius of the circular receiver and $\widetilde{f_2}(\rho,\varphi,x,y) \equiv f_2(\rho\cos\varphi, \rho\sin\varphi, x, y)$.

The spillage efficiency, $f_{sp}(x,y,\Theta)$, is thus found by means of an exact integral over ρ and then a numerical approximation over φ; see [24, 25] for more information.

OPTIMISATION

A linear integer programming technique is applied in order to optimise the aiming strategy of the heliostat field, as used in [16].

Let $\boldsymbol{A}$ be the set of aiming points on the receiver surface and let $\boldsymbol{H}$ be the set of heliostats aiming at the points in $\boldsymbol{A}$. Let us define an Integer Linear Programming optimisation procedure for any fixed time instant, $\boldsymbol{t}$.

For $\boldsymbol{h} \in \boldsymbol{H}, \boldsymbol{a} \in \boldsymbol{A}$, set $\boldsymbol{z_{ha}}$ to the Boolean variable defined as:

$$\boldsymbol{z_{ha}} = \begin{cases} \boldsymbol{1, if\ heliostat\ h\ is\ allocated\ to\ aiming\ point\ a} \\ \boldsymbol{0, otherwise.} \end{cases}$$

The reflected radiation pattern $\boldsymbol{r_{ha}^b}$ is the radiation point value at aiming point $\boldsymbol{b}$ received from heliostat $\boldsymbol{h}$ aiming at aiming point $\boldsymbol{a}$. The total integrated radiation, $\boldsymbol{R_{ha}}$, is the total radiation received across the receiver from heliostat $\boldsymbol{h}$ aiming at aiming point $\boldsymbol{a}$.

We therefore look to maximise the total incident energy on the receiver:

$$\boldsymbol{Maximise}\sum_{\boldsymbol{a,h}}\boldsymbol{R_{ha}z_{ha}}.$$

We constrain this objective function by requiring that no heliostat may be looking at more than one aiming point on the receiver, but may be stowed in case of high winds or potential damage to the receiver or mirror.

This gives the constraint:

$$\sum_{\boldsymbol{h\epsilon H}}\boldsymbol{z_{ha}} \leq \boldsymbol{1} \quad \forall\ \boldsymbol{a\ \epsilon\ A}.$$

We also constrain the received energy at the aiming points:

$$\boldsymbol{C_*} \leq \sum_{\substack{\boldsymbol{h\epsilon H} \\ \boldsymbol{a\epsilon A}}}\boldsymbol{r_{ha}^b z_{ha}} \leq \boldsymbol{C^*} \quad \forall\ \boldsymbol{b\ \epsilon\ A}.$$

where $\boldsymbol{C^*}$ is a fixed maximum energy and $\boldsymbol{C_*}$ is a fixed minimum energy. These constraints prevent the receiver being subject to excessive temperatures (which could cause permanent damage) and also ensure that a minimum amount of energy is being collected at each aiming point.

In order to approximate a uniform distribution of energy across the receiver, we will look to also constrain the range of energy received between any two aiming points by imposing

$$\max_{a}\left(\sum_{\substack{h\epsilon H\\ a\epsilon A}} r^{i}_{ha} z_{ha}\right) - \min_{a}\left(\sum_{\substack{h\epsilon H\\ a\epsilon A}} r^{i}_{ha} z_{ha}\right) \leq \tau,$$

Where τ is a given constant.

This can also be written in the form

$$\max_{a}\left(\sum_{\substack{h\epsilon H\\ a\epsilon A}} r^{i}_{ha} z_{ha}\right) \leq \tau + \min_{a}\left(\sum_{\substack{h\epsilon H\\ a\epsilon A}} r^{i}_{ha} z_{ha}\right)$$

which is equivalent to the following set of linear constraints:

$$\sum_{\substack{h\epsilon H\\ a\epsilon A}} r^{i}_{ha} z_{ha} \leq \tau + \sum_{\substack{h\epsilon H\\ a\epsilon A}} r^{j}_{ha} z_{ha} \quad \forall\, i, j\, \epsilon\, A, with\ i \neq j$$

The optimisation problem to be solved at each time instant *t* can then be summarised as follows:

$$Maximise \sum_{a,h} R_{ha} z_{ha}.$$

Subject to:

$$\sum_{h\epsilon H} z_{ha} \leq 1 \quad \forall\, a\, \epsilon\, A,$$

$$C_{*} \leq \sum_{\substack{h\epsilon H\\ a\epsilon A}} r^{b}_{ha} z_{ha} \leq C^{*} \quad \forall\, b\, \epsilon\, A,$$

$$\sum_{\substack{h\epsilon H\\ a\epsilon A}} r^{i}_{ha} z_{ha} \leq \tau + \sum_{\substack{h\epsilon H\\ a\epsilon A}} r^{j}_{ha} z_{ha} \quad \forall\, i, j\, \epsilon\, A, with\ i \neq j$$

$$z_{ha} \in \{0, 1\} \ \forall\, h\, \epsilon\, H, \forall a\, \epsilon\, A$$

The uncertainty of the cloud location in the heliostat field can be considered as a stochastic programming problem, where we will assume a set of possible scenarios *S*, where each scenario represents a possible set of characteristics for the cloud.

This method implies that we have knowledge of the clouds characteristics in terms of a probability distribution. The probability for each scenario could be generated from historical data for the geographical location of the SPT or from weather tracking technology, but for demonstration purposes a uniform distribution will be applied here.

The optimisation problem can then be considered as:

$$\max \sum_{s\in S} p(s) \sum_{\substack{h\in H\\ a\in A}} R^{s}_{ha} Z_{ha}$$

where $p(s)$ is the probability distribution of each scenario.

The constraints then become:

$$\sum_{h \epsilon H} z_{ha} \leq 1 \quad \forall\, a \,\epsilon\, A,$$

$$C_* \leq \sum_{\substack{h \epsilon H \\ a \epsilon A}} p(s) r_{ha}^{is} z_{ha} \leq C^* \quad \forall\, i \,\epsilon\, A, \forall\, s \,\epsilon\, S$$

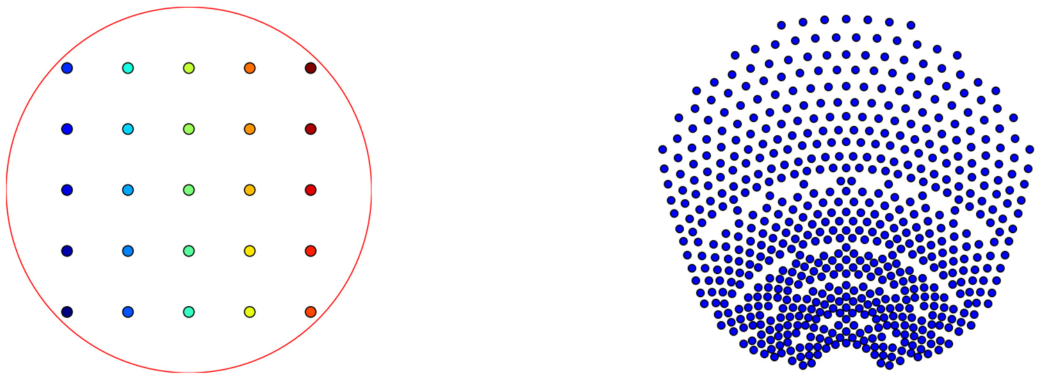
$$\sum_{\substack{h \epsilon H \\ a \epsilon A}} p(s) r_{ha}^{is} z_{ha} \leq \tau + \sum_{\substack{h \epsilon H \\ a \epsilon A}} p(s) r_{ha}^{js} z_{ha} \quad \forall\, i, j \,\epsilon\, A, \forall\, s \,\epsilon\, S \text{ with } i \neq j$$

$$z_{ha} \in \{0, 1\} \;\; \forall\, h \,\epsilon\, H, \forall a \,\epsilon\, A$$

Optimising this problem then gives us the aiming strategy that is best when considering the uncertainty of cloud characteristics.

RESULTS

The presented optimisation problem is applied to the PS10 SPT in Sanlucar la Mayor, Seville [26] as in [16], where a grid of aim points on the receiver surface is defined, as shown in FIGURE 1a, and the locations of the heliostats within the field are shown in FIGURE 1b. The uncertainty of the cloud parameters have been modelled in using a uniform distribution, considering 5 possible scenarios.



(a) (b)

FIGURE 1. (a): Aiming point layout on receiver. (b): PS10 Heliostat field layout

A cloud is modelled, as shown in FIGURE 2, over a portion of the heliostat field. The location, size and density of the cloud is uncertain, and this uncertainty is considered as a uniform distribution, where each variable can differ by 10% of a known value, which would be taken from current weather condition knowledge in practise but is demonstrated here with set values.

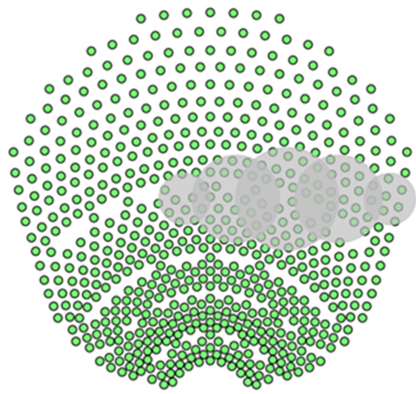
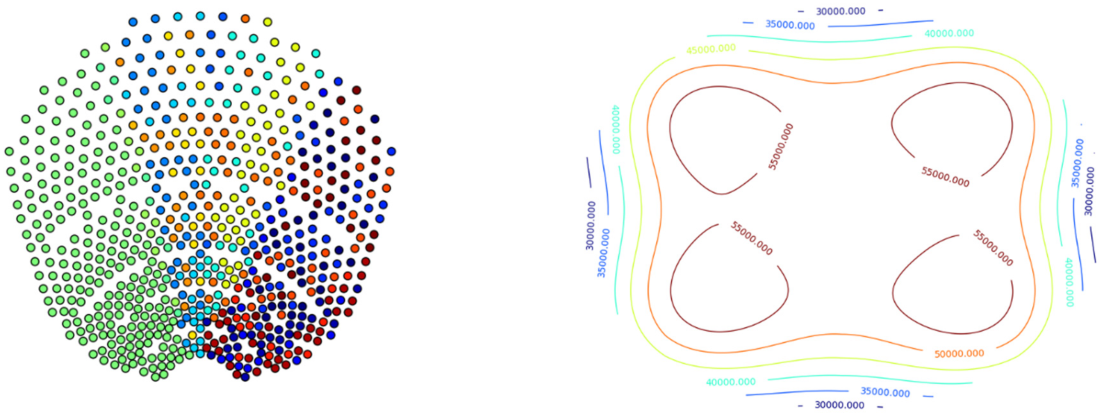


FIGURE 2. Example of cloud implementation

FIGURE 3 shows the application of the optimisation procedure detailed in this paper to the PS10 SPT plant for the first solar hour of a day, with clear skies. The aiming strategy result, as shown in Figure 3a by colour coding in accordance with Figure 1a, has maximized the flux reaching the receiver, whilst maintaining a homogenous distribution, shown in Figure3b. It can be seen from this result, that due to the time point being considered, the East side of the field (left) is concentrated on the center of the receiver, whilst the West side of the field focuses towards the edge. This can be explained by the cosine angle of the reflected light, where larger values cause the standard distribution to increase, and thereby increase spillage of light by the affected heliostats. Any heliostat with a large cosine value then has a tendency to aim towards the center of the receiver, in order to minimise the amount of energy lost to spillage.

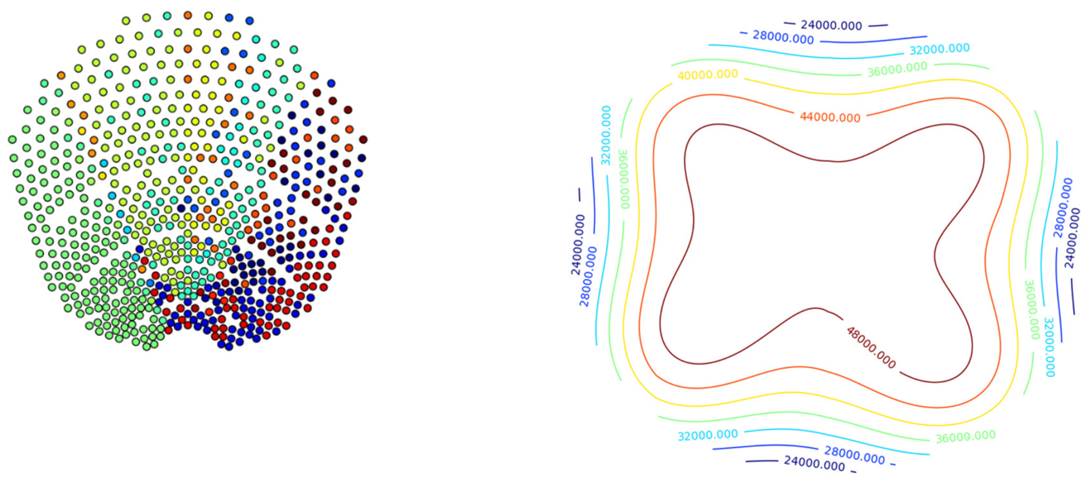
FIGURE 4 shows the optimal aiming strategy and energy distribution on the receiver surface for the same time point, with uncertain cloud characteristics based upon the cloud shown in FIGURE 2. Comparing Figures 3a and 4a, we can see that the intrusion of a cloud over the heliostat field changes the resultant optimal aiming strategy found by the procedure. In this case, we see that fewer heliostats aim towards the center of the receiver, and instead adopt aiming points towards the edge. This difference is caused by the constraint within the optimisation procedure to maintain a homogenous flux distribution across the receiver surface.

The optimal aiming strategy for the heliostat field changes with a cloud implemented, but does not exhibit a specific pattern based upon the cloud location. This is expected, as the allocation of aiming points is primarily affected by the cosine angle of the incident radiation, and less by the magnitude of radiation. Therefore the results show that in order to maintain the constraints of homogeneity on the receiver surface, the overall aiming strategy must change, not only the heliostats covered by the cloud.



(a) (b)

FIGURE 3. (a) Optimal aiming strategy. (b) Energy distribution on receiver surface



(a) (b)

FIGURE 4. (a) Optimal aiming strategy with coud uncertainty. (b) Energy distribution on receiver surface

CONCLUSIONS

The effect of uncertainty in cloud location, size and density on the optimal aiming strategy for a SPT plant heliostat field has been investigated. The method has been demonstrated for a time point at the PS10 SPT plant and shows how the efficiency of the plant can be maximised when there is local inclement weather.

A stochastic linear integer programming technique has been applied with short time limits, which provide near-optimal solutions in near real-time. It is expected that increasing computational power and providing the solver with an initial heuristic solution could further increase the speed of the program.

The method presented is directly extendible to include more scenario possibilities and a different probability distribution for their occurrence. These factors could be determined by considering historical weather data for the region of interest, as well as the inclusion of weather predicting technology such as satellite data and cloud detecting cameras.

The optimisation method used in this research intends to find a near-optimal solution that is solved within short timescales. It was found that solutions sufficiently close the optimal solution can be found with a simulation time of 30s, allowing this method to be implemented in real time with local weather predictions for a SPT plant.

Depending on the location of the SPT plant, other types of inclement weather may be typical, such as rain, snow and sand storms. The method implemented in this article may be extended to account for such weather conditions, and demonstrate their effect on the efficiency of a SPT plant.

An extension to this problem is to consider an extra constraint on the difference between the energy of each heliostat at the current time point, against the energy of each scenario. This will look to prevent flash heating due to heliostat movement. This will utilise the current aiming solution of the SPT plant to optimise the uncertainty problem and produce the optimal aiming strategy for the next time step.

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