High-Concentration Wide-Angle Tracking Integration with Stacked Lens Arrays

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Abstract. Tracking-integration can reduce or eliminate the need for external solar tracking in CPV (concentrator photovoltaics). Previous research has shown how tracking-integrated systems can achieve high concentration ratios, wide tracking ranges, and compatibility with low-cost high-volume manufacturing methods. However, to our knowledge, no existing concept has demonstrated high performance in all of these objectives at the same time. We show how a numerical optimization-based design method can be used to develop high-performance tracking-integrated configurations. We then present a configuration maintaining an approximately 5000x geometric concentration ratio across a two-axis ±60° tracking range, while also being compatible with low-cost manufacturing processes. By significantly increasing the achievable concentration ratio of low-cost tracking integrated systems, these systems may improve the competitiveness for concentrator photovoltaics. This can also lead to new applications such as high efficiency rooftop-mountable or vehicle-mountable CPV.

INTRODUCTION

Concentrator photovoltaics (CPV) promises improved efficiency compared to flat-panel Silicon photovoltaics [1], but this requires highly accurate solar tracking. Solar tracking is usually implemented using an external dual-axis tracking system, which adds to the bulk and cost of the installation. The large mechanical size can also make these trackers unsuitable for small-scale installations such as rooftop or vehicle-mountable CPV.

Tracking-integrated concentrator-schemes have been proposed as a way to mitigate this problem by reducing or removing the need for external solar trackers [2]. Kotsidas et al. proposed a system where an array of solar cells is moved relative to a stationary lens array in order to track the sun [3], and Hallas et al. proposed a similar system where an array of waveguide coupling features are moved relative to a stationary lens array [4]. Duerr et al. proposed a system where a pair of lens arrays are moved relative to each other to concentrate sunlight onto a moving lens array [5]. Price et al. proposed a system where a catadioptric optical stack creates a very flat image plane, and solar tracking is implementing by moving an array of microcells in this image plane [6].

In this work, we present an optimization-based design method for designing tracking-integrated CPV systems, and use this method to combine the novel catadioptric stack proposed by Price et al. with the idea of relative motion between lens arrays as proposed by Duerr et al. These new configurations achieve concentration ratios on the order of 5000x across a ±60° tracking range.

DESIGN METHOD

A tracking-integrated CPV concentrator should concentrate incident solar radiation with (1) the highest possible efficiency, (2) across the largest possible tracking range, and (3) onto the smallest possible surface of a PV cell. The design of a tracking-integrated CPV concentrator can therefore be considered a multi-objective optimization problem where the goal is to find a design that optimizes these three objectives.

We have chosen a design method based on numerical optimization. The objective function is scalarized using a sum scalarization of the efficiency and concentration ratio objectives:

$$\min f(x) = \sum_{i=1}^{m}(w_1 \frac{1}{\eta_i(x)} + w_2 \left(r_i(x)\right)^2 \quad (1)$$

$$\text{such that } g_j(x) \leq 0, \quad (2)$$

where $\eta_i(x)$ is the simulated optical efficiency for a grid of rays with incidence angle number i and optical system described by the parameters x. $r_i(x)$ is the RMS radius of the rays in field number i relative to the position of the PV cell for this angle of incidence. w_1 and w_2 are relative hand-tuned weights applied to optical efficiency and RMS radius. $g_j(x)$ is a set of constraints ensuring manufacturability of the design.

A set of constraints were selected as shown in Table 1. These constraints were chosen as example values in order to demonstrate how manufacturing requirements can be taken into account in the optimization process. When choosing a manufacturing method, these constraints should be updated to match the requirements of the specific process. All lenses were assumed to be made from PMMA as an example of an injection-moldable thermoplastic with good optical properties, and reflective lens arrays were assumed to be silver coated. We have chosen a fixed two-axis tracking range of ±60° for the optimization.

TABLE 1. Constraints used when optimizing the different CPV configurations. The dimensions of the system are scalable with the arbitrary scaling factor k.

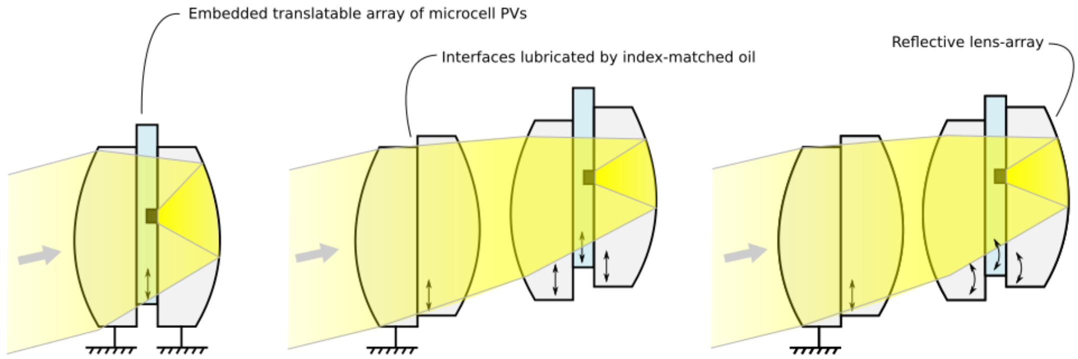
Parameter	Value
Semi-diameter of lenses	$1.0 \cdot k$
Minimum thickness at thinnest point of lens	$0.4 \cdot k$
Maximum thickness at thickest point of lens	$2.5 \cdot k$
Minimum air gap between lenses	$0.05 \cdot k$
Maximum air gap between lenses	$4 \cdot k$
Minimum radius of curvature on the lens	$0.5 \cdot k$
Maximum aspect ratio of a single surface	0.5

A custom-built three-dimensional sequential ray-tracer was used to simulate the optical system, as reported in a previous publication [7]. The ray-tracer takes into account reflection losses and chromatic aberration in the PMMA lens arrays. The material is assumed to be non-absorptive, because absorption losses depend on system dimensions which were not fixed in this work. The surface profile is aspheric and rotationally symmetric, and modelled as an even polynomial with 4 terms. The lenses were assumed to be hexagonally packed in a lens array.

The numerical optimization problem was solved using memetic optimization, a class of optimization algorithms that combine evolutionary algorithms and their ability to search a large design space for an approximate global minimum, with the ability of local gradient-based algorithms to quickly and accurately identify a local minimum. We implemented a memetic optimization algorithm based on Qin et al.'s local search chains [8]. The differential evolution solver from SciPy [9] was extended to evolve the population using local search chains based on SciPy's SLSQP optimization algorithm in parallel to the differential evolution algorithm.

Three different configurations were optimized:

- **Simple catadioptric**: A catadioptric stack with an embedded translatable array of microcell PV, as conceptually illustrated in Fig. 1a and first proposed by Price et al. [6]
- **Flat tracking trajectory**: A catadioptric stack similar to *simple catadioptric*, but all lens arrays are allowed to move laterally relative to each other, and an additional pair of lens arrays are added to the front, as conceptually illustrated in Fig. 1b.
- **Curved tracking trajectory**: A catadioptric stack similar to *flat tracking trajectory*, but the lens arrays are allowed to follow a curved tracking trajectory at the air gap between the two pairs of lens arrays as illustrated in Fig. 1c.

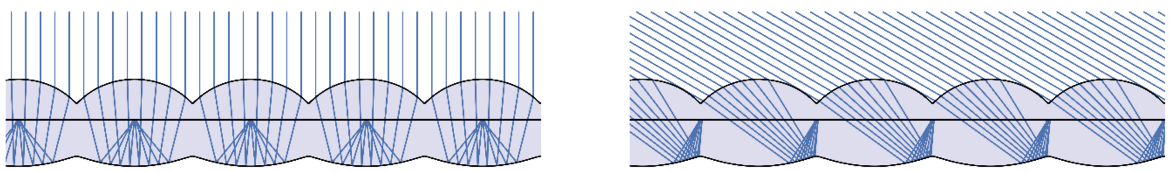


(a) (b) (c)

FIGURE 1. Conceptual illustration of the three different CPV-configurations that were optimized: Simple catadioptric (a), flat tracking trajectory (b), and curved tracking trajectory (c). In each configuration, the lens stacks are assumed to be arranged in a hexagonally packed lens array.

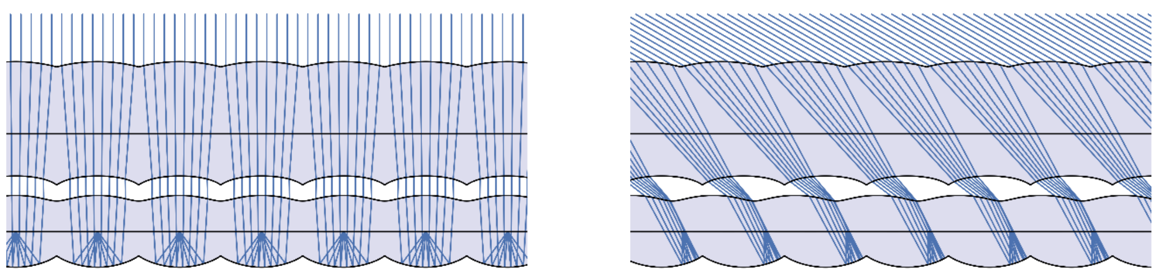
OPTIMIZATION RESULTS

Figure 2-4 show ray-traced drawings of the optimized CPV-designs after 9000 iterations of differential evolution.



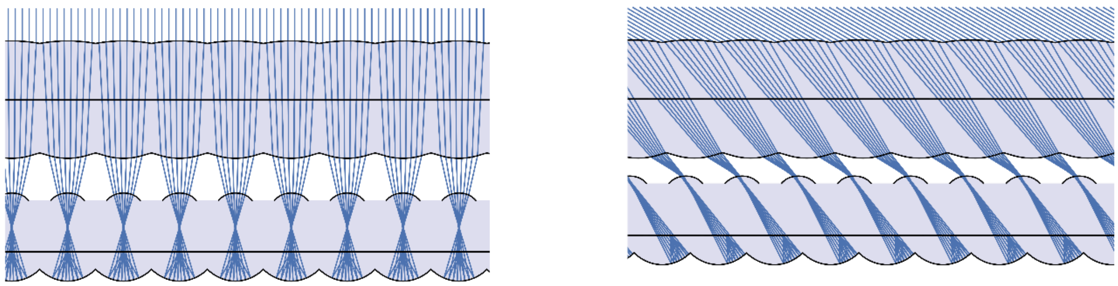
(a) (b)

FIGURE 2. Optimized simple catadioptric CPV-system at 0° (a), and 60° (b) angle of incidence.



(a) (b)

FIGURE 3. Optimized CPV-system with flat tracking trajectory at 0° (a), and 60° (b) angle of incidence.



(a) (b)

FIGURE 4. Optimized CPV-system with curved tracking trajectory at 0° (a), and 60° (b) angle of incidence.

A more comprehensive Monte-Carlo simulation was performed on the optimized systems, quantifying optical efficiency and geometric concentration ratio as a function of angle of incidence. We define optical efficiency $\eta = \frac{P_{in}}{P_{out}}$ where P_{in} is total energy in the rays entering the system for a specific angle of incidence, and P_{out} is the energy in the rays arriving on the receiver plane. We define geometric concentration ratio as $C_{geo} = \frac{A_{in}}{A_{out}}$ where A_{in} is the hexagonal area of a lenslet, and A_{out} is defined as the smallest area of a circular receiver intercepting 90% of the transmitted energy for the given angle of incidence. This definition allows quantifying how the concentrating abilities of the system varies with angle of incidence. In a physical implementation, a fixed receiver size A_{out} would be chosen.

For each angle of incidence, 100 000 rays were sampled with random wavelengths according to the AM1.5D solar spectrum, random directions within the 0.27° divergence half-angle of sunlight, and random positions within the hexagonal aperture of the first lens. The results from this Monte-Carlo simulation are shown in Fig. 5.

The simulated performance of the *simple catadioptric* configuration gives a geometric concentration ratio >400x and optical efficiency >90%. This is comparable to the results published by Price et al [6], and the small variations are mainly because our work assumes a circular receiver when estimating concentration ratio.

The geometric concentration ratio is increased from approximately 400x to approximately 2000x when adding an additional pair of lens arrays to the system in the configuration shown in Fig. 1b. The concentration ratio is further increased to approximately 5000x if the lens arrays are allowed to follow a curved tracking trajectory as illustrated in Fig. 1c. The improved concentration ratio comes at the cost of reduced optical efficiency due to reflection losses, but these reflection losses can possibly be reduced without significant added cost using anti-reflective coatings or anti-reflective surface nanostructures [10].

The improved concentration ratio also introduces additional mechanical complexity with several lens arrays moving relative to each other. However, the translation of the different lens arrays is constrained to be proportional to each other so that they can share the same mechanical actuators, and the increased complexity might be justified by the significant improvement to concentration ratio. The designs are compatible with high-volume manufacturing techniques, such as injection molding or hot embossing by being relatively thin and made from commonly available thermoplastics such as PMMA.

The reported concentration ratios are very high, and much higher than in conventional CPV systems. We believe that the very high simulated concentration ratio is explained by a combination of factors. First, the concentration happens inside a dielectric, which inherently increases the thermodynamic limit to concentration by a factor n^2 where n is the refractive index of the dielectric. Second, the largest contributor to optical power in the system is the reflective lens array, which does not suffer for chromatic aberration unlike refractive lenses. Third, the system is assumed to be able to track the sun exactly, with an acceptance angle just large enough to fit the angular extent of the solar disc. This final assumption is made because each module can track the sun individually using a closed control loop, eliminating tracking errors from mounting the module to an external tracer, as well as tracking errors due to flexing of this external tracker.

Manufacturing tolerances are not taken into account in these simulations. It is likely that this will limit somewhat the ratio achieved in a physical implementation. The reported concentration ratios may also be too high for a PV cell to handle. However, we believe that this work demonstrates how it is possible to design tracking-integrated optical systems where optical aberrations are not the limiting factor to system performance, and that it can motivate a further search towards tracking-integrated configurations with an optimal trade-off between performance and complexity.

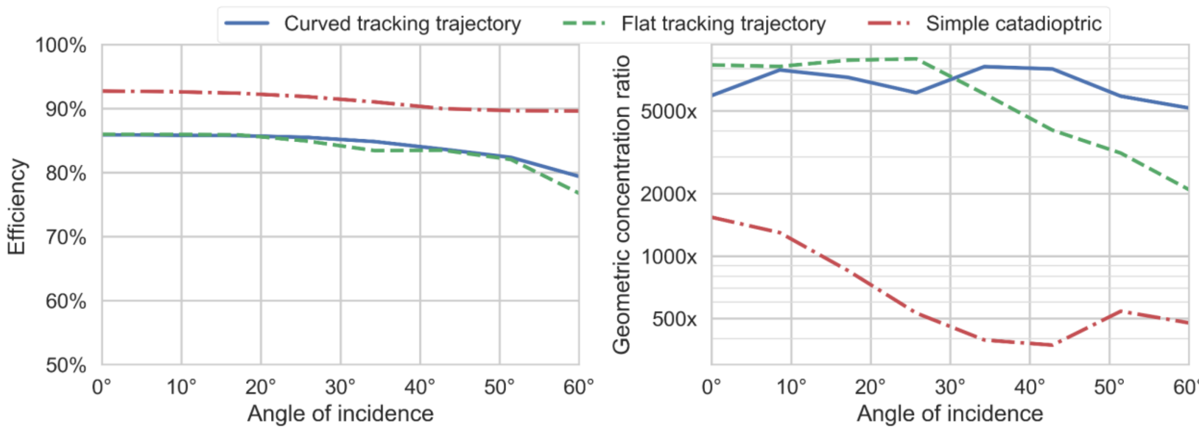


FIGURE 5. Simulated optical efficiency and geometric concentration ratio across tracking range for the optimized CPV configurations. The performance is simulated using Monte Carlo ray-tracking, taking into account reflection losses, chromatic aberration in the PMMA lens arrays, and the angular divergence of sunlight. The material is assumed to be non-absorptive.

CONCLUSIONS

We have presented an optimization-based design method for tracking-integrated CPV concentrator, and demonstrated how this method can be used to develop new and improved concentrators. Using this design method, we demonstrated new configurations for tracking-integrated CPV concentrators with improved optical performance, including a concentrating achieving a geometric concentration ratio of 5000x across a two-axis ±60° tracking range.

By significantly increasing the achievable concentration ratio of low-cost tracking integrated systems, these systems may improve the competitiveness for concentrator photovoltaics, and can also motivate the further search for new and promising concentrator configurations. The improved performance might enable new applications such as high efficiency rooftop-mountable or vehicle-mountable CPV. The presented design method can take into account the requirements of a specific application and manufacturing method, and can therefore be used to develop tailored CPV solutions optimized for specific use-cases and applications.

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