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SolarPILOT: A power tower solar field layout and characterization tool

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ABSTRACT

This paper develops and demonstrates a new Solar Power tower Integrated Layout and Optimization Tool (SolarPILOT). The tool uses the analytical flux image Hermite series approximation originally implemented in the DELSOL3 software developed by Sandia National Laboratory in the early 1980s. By applying the analytical model to individual heliostat images rather than large groups or zones of heliostats, SolarPILOT can characterize a wide variety of heliostat field layouts. The individual heliostat modeling approach increases computational expense in comparison with DELSOL3, so SolarPILOT implements a number of improvements to the analytical approximation method to improve model accuracy and computational efficiency. This paper discusses several of these methods, including dynamic heliostat grouping to reduce the expense of intercept factor evaluation, approximation of annual productivity with a subset of time steps throughout the year, polygon clipping to accurately calculate inter-heliostat shadowing and blocking, receiver and tower geometry optimization, and a trigonometric image transformation technique that ensures model accuracy for small heliostats. SolarPILOT also integrates a Monte-Carlo ray tracing engine (SolTrace), providing improved receiver optical modeling capability, a user-friendly front end for geometry definition, and side-by-side validation of the analytical algorithms.

1. Introduction

Power tower systems (also known as “central receiver systems”) are optically complex, using thousands of individually tracking heliostats to reflect sunlight onto a stationary receiver throughout the day and the year. The angular acceptance window for the reflected image from a heliostat is typically very small, requiring tracking precision with an error distribution standard deviation on the order of 1 mrad or less. In addition, receiver operation typically requires that the incident flux density be maintained below a maximum value, and heliostat images must be strategically placed on the receiver to achieve a workable distribution (Zavoico, 2001; Reilly and Kolb, 2001; Pacheco et al., 2002) that extends the receiver material lifetime and minimizes optical interception losses. The redirection of sunlight by the heliostat field is also subject to a series of losses that depend on the heliostat's position relative to the receiver, the position and orientation of neighboring heliostats, the position and apparent shape of the solar disc, the particulate content in the atmosphere, the geometry of the heliostat, optical errors in the heliostat, and the heliostat field operation strategy. Many of these losses are dynamic and must be modeled over a range of conditions in order to adequately characterize the likely performance of a concentrating solar power (CSP) plant (Wagner, 2008). Consequently, computer software has been used to generate solar field geometry and characterize its performance since the late 1970s (Dellin, 1979; Leary and Hankins, 1979; Walzel et al., 1977; Lipps and Vant-Hull, 1978).

The history of available software programs extending from first-generation tools through current solutions is well documented (Ho, 2008; Garcia et al., 2008). A number of programs have been developed to support the various stages of analysis that are necessary to characterize system performance. Tools such as the University of Houston Codes (UHC - also known as the RCELL suite) (Lipps and Vant-Hull, 1978), DELSOL3 (Kistler, 1986), TieSOL (Izygon et al., 2011), and HFLCAL (Kiera, 1986) can generate solar field geometry programmatically. Other programs such as MIRVAL (Leary and Hankins, 1979), HELIOS (Vittitoe and Biggs, 1981), STRAL (Belhomme et al., 2009), Tonatiuh (Blanco et al., 2005), and SolTrace (Wendelin, 2003) are capable of detailed field characterization but are not designed to quickly generate and optimize solar field geometry. (DLR has developed an extension for MIRVAL that facilitates automated field layout (Garcia et al., 2008).) Finally, given a particular geometry, several codes are capable of characterizing the annual performance of tower systems, including Solergy (Stoddard et al., 1987), System Advisor Model (SAM) (Blair et al., 2018), and the TRNSYS STEC library (European Commission, 2005). These capabilities are summarized in Table 1.

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Table 1
Summary of power tower modeling software capabilities, including generation of heliostat layouts, characterization of optical performance, prediction of annual plant electricity production, and maintenance status of the code.

Software	Layout	Char.	Plant	Maintained	Reference
UHC/RCELL	✓	✓		✓	Lipps and Vant-Hull (1978)
DELSOL3	✓	✓	✓		Kistler (1986)
TieSOL	✓	✓		✓	Izygon et al. (2011)
HFLCAL	✓	✓			Kiera (1986)
MIRVAL		✓			Leary and Hankins (1979)
HELIOS		✓			Vittitoe and Biggs (1981)
STRAL		✓			Belhomme et al. (2009)
Tonatiuh		✓		✓	Blanco et al. (2005)
SolTrace		✓		✓	Wendelin (2003)
Solergy			✓		Stoddard et al. (1987)
SAM			✓	✓	Blair et al. (2018)
TRNSYS STEC			✓		European Commission (2005)

Because these various tools emphasize different aspects of power tower solar field design or characterization, each must be used deliberately within the scope of the problem that it addresses.

The work described in this paper contributes to existing literature in several ways, namely, by presenting a methodology and software tool that: (i) implements the Hermite series analytical flux density model on individual heliostats, (ii) likewise implements the SolTrace Monte-Carlo ray tracing engine alongside the analytical model to provide more accurate optical characterization, (iii) provides several novel mechanisms for reducing computational expense while maintaining accuracy, (iv) improves model accuracy for systems with small heliostats, (v) is publicly and freely available as open-source software, (vi) allows optimization of a range of system design parameters, and (vii) provides plotting and scripting functionality. The primary scientific value and novelty of this work lies in the aggregation of these items.

1.1. Modeling approaches

The aforementioned tools characterize optical performance using one of two general approaches: analytical (or semi-analytical) approximation or Monte-Carlo ray-tracing (MCRT). The basis for analytical methods lies in modeling a reflected image with a closed-form density function. The reflected image density function describes the intensity of light (flux) as a function of position on a projection plane. Under the theoretical conditions that incident flux on the reflector is perfectly collimated, that the reflector geometry is perfectly parabolic, and that the projection plane contains the focal point of the reflector, the reflected image is infinitely small and of infinite intensity. In practice, however, various sources of reflection error cause the image to assume the form of a distribution. Most simply, an image can be approximated using a Gauss-normal distribution with standard deviation defined in one or two dimensions.

Multiple physical effects can introduce reflected image error. For example, light from the sun is not perfectly collimated but instead is described by a probabilistic distribution of incident angles. Reflector surface defects, tracking error, and imperfect or non-ideal focusing of the reflector can also affect the reflected image. As these sources of error increase, the reflected image size also tends to increase. One approach for modeling multiple error factors is to simply convolve the various error sources as independent normal distributions into a single normal distribution described by a standard deviation in each dimension. This approach limits the shapes of the reflected images that can be modeled, but may be appropriate for heliostats with certain optical properties. A more nuanced approach utilizes the truncated Hermite polynomial series to describe the image shape in two dimensions (Walzel et al., 1977; Dellin, 1979), originally developed by the University of Houston. This method accommodates non-normal sun shape distributions and can accurately represent flux patterns for flat, focused, or canted heliostats at a variety of tracking angles. This method is the basis for DELSOL3 and the University of Houston Codes (UHC), which are related to RCELL. The primary advantages of this approach are its computational efficiency in comparison with ray-tracing methods, flexibility in describing complex flux shapes with continuous functions using relatively few expansion coefficients, and its corresponding ability to accurately determine intercepted power on the receiver using integration by quadrature.

One limitation of the Hermite method is that directional information is not preserved in the analytical approach. This makes analysis of multiple reflections or beam-spread within a cavity receiver non-trivial (Feierabend, 2010; Teichel, 2011). Furthermore, unlike MCRT, shadowing and blocking must be handled independently of flux image calculations, and accounting for partial shadowing or blocking exclusions in the final image shape is not straightforward.

The MCRT approach is widely used in optical analysis as it offers easy implementation, flexibility in the geometry that can be modeled, preservation of directional information through multiple reflections, and a clear physical analog. Codes such as SolTrace, MIRVAL, and Tonatiuh offer solutions for power tower modeling that can account for the various error sources and shapes, and can characterize non-ideal reflector surfaces as obtained by high-resolution surface slope measurements (e.g., VSHOT Jones et al., 1996). The primary disadvantage of MCRT approaches is their relatively long run times. This is especially true for power tower heliostat fields in which ray intersections are possible over a large number of geometrical entities and many rays are required to obtain convergence. However, Izygon et al. (2011) and others have developed a program that utilizes graphical processing units (GPUs) to provide enhanced parallelization that greatly reduces run time (Izygon et al., 2011) but requires specific graphics processing hardware.

With these considerations in mind, the Hermite analytical approach has traditionally been used in optimization tools for which many model instance runs are required to determine an optimal system configuration. For example, the DELSOL3 code was implemented in System Advisor Model (Wagner et al., 2009) and was capable of first generating a near-optimal solar field layout, tower height, and receiver size, then characterizing the solar field efficiency and receiver flux profile for 96 solar positions in fewer than ten seconds using a standard laptop computer. In comparison, SolTrace was used to evaluate a power tower system with 5000 heliostats using 1×10^6 rays on a laptop computer with Intel® Core i7 and four parallel threads. This run required thirteen seconds and yielded a peak flux uncertainty of 1.1%. By integrating the analytical and MCRT engines, SolarPILOT provides rapid layout capabilities with more flexible MCRT characterization options.

2. Tool description

SolarPILOT provides layout, characterization, parametric simulation, plotting, and optimization capabilities via a graphical user interface (Fig. 1). Limited functionality is, at the time of this writing, available through a C++ application programming interface (API). SolarPILOT has been integrated into SAM via the API, and now serves as the power tower characterization engine. An important aspect of SolarPILOT is the integration of both analytical and raytrace methods in the software. The remainder of this paper is organized as follows: first, a brief overview of the analytical methodology is given along with the details of several enhancements, then integration of the raytrace engine is described, and lastly, the section discusses an optimization methodology that considers a large set of design parameters.

2.1. Analytical methods

SolarPILOT extends the Hermite method implemented in DELSOL3 by applying the optical model to individual heliostats to simulate