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artist: A Python Package for AI-Enhanced Differentiable Raytracing in Solar Tower Power Plants

Marlene Busch [1], **Kaleb Phipps** [2,3], **Daniel Maldonado Quinto** [1], **Marie Weiel** [2,3], **Robert Pitz-Paal** [1,4], **Markus Götz** [2,3], **and Max Pargmann** [1]

1 German Aerospace Center (DLR), Institute of Solar Research, Germany **2** Karlsruhe Institute of Technology (KIT), Scientific Computing Center (SCC), Germany **3** Helmholtz AI, Karlsruhe, Germany **4** RWTH Aachen University, Chair of Solar Technology

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Software

- Review
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Summary

artistis a software package for concentrating solar power (CSP) plant digital twins. Solar tower power plants use an array of mirrors (heliostats), to reflect and concentrate sunlight onto a small area called the receiver. This process generates heat energy which is either used directly in industrial processes or to produce electricity. Efficient power plant operation is complex and differentiable digital twins can play an important role in enabling data-driven optimization and control. This Python package, artist, implements a fully differentiable digital twin for solar tower power plants, allowing for high-performance, memory-efficient optimization and parameter learning of the plant's components. At its core, the differentiable ray tracer simulates how light interacts with the three-dimensional scene, including environmental conditions, enabling gradient-based optimization from predicted flux distributions. By including differentiable models of all power plant components - including Non-Uniform Rational B-Splines (NURBS) surface models - artist can be used for highly accurate surface reconstruction, kinematic reconstruction, and aim point optimization. To ensure scalability, artist features native GPU acceleration, data-parallel processing, support for distributed computation, and is designed for portability across multiple hardware stacks.

Statement of Need

Concentrating solar power is a sustainable and renewable alternative to fossil fuels and nuclear energy, providing an environmentally friendly solution to meet the globally rising demand for energy (Zhu et al., 2023). The absorbed thermal power in a solar tower can be converted into electricity or high-temperature heat for industrial processes. The economic performance of solar tower power plants has yet to reach its full potential, as operational costs remain high due to mechanical imperfections, real-time control requirements and dynamic weather conditions (Carballo et al., 2025). Digital twins with advanced simulation techniques, as well as precise behavior analysis and prediction capabilities are essential for establishing fully autonomous power plant operation and a consequential reduction in costs (Huang et al., 2021). While solar tower power plants may vary in their individual architectural details, their digital twins consistently rely on ray tracing. Conventional ray tracers (Ahlbrink et al., 2012), (Wendelin et al., 2018), (Cardoso et al., 2018) achieve good results in simulating power plant behavior. However, they can only use ray tracing to make predictions based on supplied data and their current model. From a machine learning perspective, these ray tracers are confined to forward computations, and therefore they often require large amounts of data to function accurately. artist addresses this limitation with its differentiable implementation of the ray tracer and all connecting modules. The differentiability significantly improves the data requirements for CSP digital twins and also enables additional applications, including heliostat field layout

optimization and solar tower design optimizations. The underlying concepts of `artist` are based on previous publications, which have demonstrated the potential of increasing solar tower power plant efficiency (Pargmann et al., 2024). `artist`'s modular architecture, built on abstraction and inheritance, enables its application across diverse solar tower power plant designs. Users can incorporate specific design details and define custom power plant behavior to be used in combination with shared differentiable algorithms for alignment, ray tracing, heliostat surface reconstruction, and kinematic reconstruction already defined in `artist`. This software is designed for researchers, power plant operators, developers within the CSP community or anyone else interested in the field. `artist` includes data loaders compatible with various data sources, including the open-access CSP database PAINT (Phipps et al., 2025), for users who do not have direct access to an operational power plant. Overall, the accessibility of the data, the modularity of the software, and its adherence to the FAIR principles for research software (Barker et al., 2022) aim to strengthen community engagement and collaboration for further research advancements.

Features

The main features of `artist` are shown in Figure 1. To create digital twins of solar tower power plants in `artist`, users are asked to provide HDF5-files containing data about the physical layout of the power plant. The HDF5 scenarios can be generated by `artist` from various data sources. `artist` unpacks these files to initiate the simulation process by aligning heliostats and performing ray tracing to predict flux density distributions. This combination of alignment and ray tracing is used iteratively in the optimization tasks for reconstructing real-world mirror surfaces and the kinematic and for subsequently optimizing the heliostat aim points. The optimized parameters, can be used directly as input to a power plant control software. To efficiently handle heliostat surfaces, `artist` contains a fully differentiable, parallelized NURBS implementation.

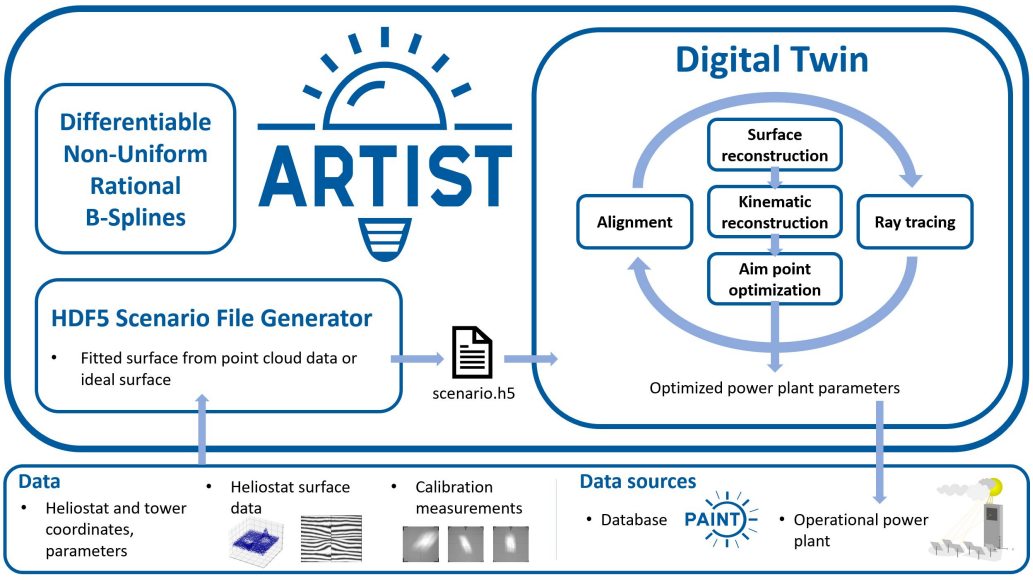

Figure 1: Features of `artist`, the AI-enhanced differentiable Ray Tracer for Irradiation Prediction in Solar Tower Digital Twins.

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