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Blobmodel: A Python package for generating superpositions of pulses in one and two dimensions

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Summary

`blobmodel` is a Python library for generating synthetic data that mimics the behavior of moving pulses in a turbulent environment. It creates controlled datasets where the true motion of each pulse is known, allowing researchers to gain further understanding on the statistical outputs of such systems as well as to test and improve analysis and tracking algorithms. While originally developed for studying turbulence in fusion experiments, `blobmodel` can be applied to any field where turbulence leads to the generation of structures propagating in one or two dimensions. The software is open source, easy to use, and designed to support reproducible research.

Statement of need

Understanding and analyzing the motion of structures in turbulent systems is crucial in many areas of research, including plasma physics (D'Ippolito et al., 2011), fluid dynamics (Fiedler, 1988), and atmospheric science (Nosov et al., 2009).

More widely, the study of the statistical characteristics resulting from the superposition of uncorrelated propagating pulses is of importance in fields such as astrophysical plasmas (Veltri, 1999), detection rates of interplanetary dust (Kočiščák, S. et al., 2023), $1/f$ noise in self-organized critical systems (Bak et al., 1988), and shot noise in electronics (Lowen & Teich, 1990).

In experimental studies, imaging diagnostics are often used to capture the evolution of these structures (Zweben et al., 2017), but extracting reliable velocity information from such data remains challenging (Offeddu et al., 2023). Many existing analysis methods rely on assumptions about the underlying dynamics and must be tested against known reference data to ensure accuracy.

Several stochastic models have been developed describing a point process resulting from the superposition of uncorrelated structures with random arrival times (Garcia et al., 2016); or propagating in one (Losada et al., 2023) or two (F. Militello et al., 2018) spatial dimensions. In the simplest cases, it is possible to derive analytical expressions for different statistical quantities such as probability density functions, autocorrelation functions, power spectral densities and spatial dependence of the mean or other higher-order moments (Garcia et al., 2016; Losada et al., 2023; F. Militello & Omotani, 2016). More general scenarios require numerical tools (Losada, Paikina, et al., 2024), and synthetic realizations of the model.

`blobmodel` addresses this need by providing a framework for generating synthetic datasets resulting from a superposition of uncorrelated pulses (Losada & Garcia, 2025; F. Militello et al., 2018):

$$\Phi(x, y, t) = \sum_{k=1}^{K} a_k \varphi\left(\frac{x - v_k(t - t_k)}{\ell_{x,k}}, \frac{(y - y_k) - w_k(t - t_k)}{\ell_{y,k}}\right),$$

where:

- a_k represents the initial pulse amplitude.
- v_k and w_k are the horizontal and vertical velocity components, respectively.
- t_k is the pulse arrival time at the position $x = 0$, $y = y_k$.
- y_k is the pulse vertical position at time $t = t_k$.
- $\ell_{x,k}$ and $\ell_{y,k}$ are the horizontal and vertical pulse sizes, respectively.
- φ is an unspecified pulse shape.

All these parameters, except for the pulse shape φ are assumed to be random variables. Additionally, each pulse may be tilted on an angle given by an additional random variable θ_k with respect to its centre.

The framework allows an explicit definition of all relevant process parameters, including:

- All pulse parameters if defined as degenerate random variables.
- All distribution functions of the pulse parameters otherwise.
- Optionally, a drainage term $\tau_{\parallel}$ that models an exponential decay in the pulse amplitude through an additional factor $e^{-\frac{t-t_k}{\tau_{\parallel}}}$ in the pulse evolution.
- Spatial and temporal resolution.
- Degree of pulse overlap by setting different ratios of number of pulses to signal length and domain size.
- Total duration of the process.

This allows researchers to systematically test and benchmark tracking algorithms and velocity estimation techniques in a controlled setting. Originally developed for studying turbulence-driven transport in fusion plasma experiments, blobmodel is applicable to any system where turbulence leads to the formation of moving structures in one or two-dimensional space. By offering an open-source and easily accessible tool, blobmodel supports the development and validation of analysis methods used in experimental and computational research.

To the authors' knowledge, no other packages exist which provide a comprehensive, open-source framework for generating synthetic datasets of uncorrelated, propagating pulses in one or two spatial dimensions, with fully customizable statistical distributions for pulse parameters and explicit control over spatial and temporal resolution, pulse overlap, and drainage effects, as implemented in `blobmodel`.

For more details visit blobmodel's documentation.

The package has been used to generate synthetic data to study and compare the robustness of velocity estimation techniques on coarse-grained imaging data (Losada, Helgeland, et al., 2024).

Additionally, theoretically predicted radial profiles from stochastic modelling (Garcia et al., 2016; F. Militello & Omotani, 2016) agree with those obtained with `blobmodel`.

Implementation details

The evolution of the pulses is discretized by the `Blob` class in a three dimensional grid (two space and one time dimensions) according to the above formula. The discretization grid is provided by the `Geometry` and the superposition of all pulses is performed by the `Model` class, which also contains functions for the model initialization. The generation of pulses with pulse parameters following user-specified distribution functions is performed by the `BlobFactory`.

Since the simulation domain has finite spatial extent, pulses may originate or extend beyond its boundaries. If a pulse has a non-bound shape, such as a Gaussian, its tails can still contribute to the superposition inside the domain. However, in long simulations, most pulses will exist outside the domain for the majority of the time, making it computationally inefficient to account for all of them. To improve efficiency, a `speed_up` flag has been added to `Model.make_realization`. When enabled, the model ignores pulses whose contribution within the domain falls below a user-defined `error` threshold. This allows for significant computational savings while maintaining accuracy in the simulation.

Periodicity in the vertical direction is an optional feature. It is implemented by replicating each pulse at vertical positions $y_b \pm L_y$, where y_b is the pulse's original position and L_y is the vertical size of the simulation domain. This ensures that blobs crossing the upper or lower boundaries are correctly wrapped around, maintaining continuity in the periodic direction.

This package is fully compatible with `xarray` (Hoyer & Hamman, 2017), with all outputs provided as `xarray` datasets for easy handling and analysis.

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