# Data Driven Fluid Simulations Using Regression Forests

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Dynamic Mode Decomposition



**DOYLE KANE**

**Real-time Rendering of Data-driven Fluid Simulations with Style Transfer**

Springer Nature

The approximation of natural phenomena such as liquid simulations in computer graphics requires complex methods that are computationally expensive. Despite recent advances in this field, the gap in realism between a simulated liquid and reality remains considerable. This disparity that separates us from the desired realism requires numerical models whose complexity continues to grow. The ultimate goal is to provide users the capacity and tools to manipulate these liquid simulation models to obtain acceptable realism. In the last decade, several approaches have been revisited to simplify and to allow more flexible models. In this dissertation by articles, we present three projects whose contributions support the improvement and flexibility of generating liquid simulations for computer graphics. First, we introduce a hybrid approach allowing us to separately process the volume of non-apparent liquid (i.e., in-depth) and a band of surface particles using the Smoothed Particle Hydrodynamics (SPH) method. We revisit the particle band approach, but this time newly applied to the SPH method, which offers a higher level of realism. Then, as a second project, we propose an approach to improve the level of detail of splashing liquids. By upsampling an existing liquid simulation, our approach is capable of generating realistic splash details through ballistic dynamics. In addition, we propose a wave simulation method to reproduce the interactions between the generated splashes and the quasi-static portions of the existing liquid simulation. Finally, the third project introduces an approach to enhance the apparent resolution of liquids through machine learning. We propose a learning architecture inspired by optical flows by which we generate a correspondence between the displacement of the particles of liquid simulations at different resolutions (i.e., low and high resolutions). Our training model allows high-resolution features to be encoded using pre-computed deformations between two liquids at different resolutions and convolution operations based on the neighborhood of the particles. Analysis Supported SPH Fluid Simulation CRC Press This book provides an introduction, overview, and specific examples of computational fluid dynamics and their applications in the water, wastewater, and stormwater industry. *Micro- and Nanoscale Fluid Mechanics* CRC Press This textbook explores both the theoretical foundation of the Finite Volume Method (FVM) and its applications in Computational Fluid Dynamics (CFD). Readers will discover a thorough explanation of the FVM numerics and algorithms used for the simulation of incompressible and compressible fluid flows, along with a detailed examination of the components needed for the development of a collocated unstructured pressure-based CFD solver. Two particular CFD codes are explored. The first is uFVM, a three-dimensional unstructured pressure-based finite volume academic CFD code, implemented within Matlab. The second is OpenFOAM®, an open source framework used in the development of a range of CFD programs for the simulation of industrial scale flow problems. With over 220 figures, numerous examples and more than one hundred exercise on FVM numerics, programming, and applications, this textbook is suitable for use in an introductory course on the FVM, in an advanced course on numerics, and as a reference for CFD programmers and researchers.

**Automatically Distributing and Load Balancing Graphical Fluid Simulations**

Springer Science & Business Media

Fluid flows are encountered in our daily life as well as in engineering industries. Identifying the temporal and spatial distribution of fluid dynamic properties is essential in analyzing the processes related to flows. These properties, such as velocity, turbulence, temperature, pressure, and concentration, play important roles in mass transfer, heat transfer, reaction rate, and force analysis. However, obtaining the analytical solution of these fluid property distributions is technically difficult or impossible. With the technique of finite difference methods or finite element methods, attaining numerical solutions from the partial differential equations of mass, momentum, and energy have become achievable. Therefore, computational fluid dynamics (CFD) has emerged and been widely applied in various fields. This book collects the recent studies that have applied the CFD technique in analyzing several representative processes covering mechanical engineering, chemical engineering, environmental engineering, and thermal engineering. *Parallel, Data-Driven Simulation and Visualization of the Heart* Cambridge University Press A practical introduction, the second edition of Fluid Simulation for Computer Graphics shows you how to animate fully three-dimensional incompressible flow. It covers all the aspects of fluid simulation, from the mathematics and algorithms to implementation, while making revisions and updates to reflect changes in the field since the first edition. Highlights of the Second Edition New chapters on level sets and vortex methods Emphasizes hybrid particle–voxel methods, now the industry standard approach Covers the latest algorithms and techniques, including: fluid surface reconstruction from particles; accurate, viscous free surfaces for buckling, coiling, and rotating liquids; and enhanced turbulence for smoke animation Adds new discussions on meshing, particles, and vortex methods The book changes the order of topics as they appeared in the first edition to make more sense when reading the first time through. It also contains several updates by distilling author Robert Bridson's experience in the visual effects industry to highlight the most important points in fluid simulation. It gives you an understanding of how the components of fluid simulation work as well as the tools for creating your own animations.

*Adaptive Fluid Simulation Using a Linear Octree Structure* Springer Nature

An Eulerian approach to fluid flow provides an efficient, stable paradigm for realistic fluid simulation. However, its traditional reliance on a fixed-resolution grid is not ideal for simulations that simultaneously exhibit both large and small-scale fluid phenomena. Octree-based fluid simulation approaches have provided the needed adaptivity, but the inherent weakness of a pointer-based tree structure has limited their effectiveness. We present a linear octree structure that provides a significant runtime speedup using these octree-based simulation algorithms. As memory prices continue to decline, we leverage additional memory when compared to traditional octree structures to provide this improvement. In addition to reducing the level of indirection in the data, because our linear octree is stored contiguously in memory as a simple C array rather than a recursive set of pointers, we provide a more cache-friendly data layout than a traditional octree. In our testing, our approach yielded run-times that were 1.5 to nearly 5 times faster than the same simulations running on a traditional octree implementation.

**Deep Learning for Fluid Simulation and Animation**

Springer Data-driven Analysis and Modeling of Turbulent Flows explains methods for the analysis of large fields of data, and uncovering models and model improvements from numerical or experimental data on turbulence. Turbulence simulations generate large data sets, and the extraction of useful information from these data fields is an important and challenging task. Statistical learning and machine learning have provided many ways of helping, and this book explains how to use such methods for extracting, treating, and optimizing data to improve predictive turbulence models. These include methods such as POD, SPOD and DMD, for the extraction of modes peculiar to the data, as well as several reduced order models. This resource is essential reading for those developing turbulence models, performing turbulence simulations or interpreting turbulence simulation results.

*Data Analysis for Direct Numerical Simulations of Turbulent Combustion*

Springer

This book presents methodologies for analysing large data sets produced by the direct numerical simulation (DNS) of turbulence and combustion. It describes the development of models that can be used to analyse large eddy simulations, and highlights both the most common techniques and newly emerging ones. The chapters, written by internationally respected experts, invite readers to consider DNS of turbulence and combustion from a formal, data-driven standpoint, rather than one led by experience and intuition. This perspective allows readers to recognise the shortcomings of existing models, with the ultimate goal of quantifying and reducing model-based uncertainty. In addition, recent advances in machine learning and statistical inferences offer new insights on the interpretation of DNS data. The book will especially benefit graduate-level students and researchers in mechanical and aerospace engineering, e.g. those with an interest in general fluid mechanics, applied mathematics, and the environmental and atmospheric sciences.

**On the Data-driven Reduced Order Modelling in Fluid Dynamics**

Springer Nature

Data-driven dynamical systems is a burgeoning field?it connects how measurements of nonlinear dynamical systems and/or complex systems can be used with well-established methods in dynamical systems theory. This is a critically important new direction because the governing equations of many problems under consideration by practitioners in various scientific fields are not typically known. Thus, using data alone to help derive, in an optimal sense, the best dynamical system representation of a given application allows for important new insights. The recently developed dynamic mode decomposition (DMD) is an innovative tool for integrating data with dynamical systems theory. The DMD has deep connections with traditional dynamical systems theory and many recent innovations in compressed sensing and machine learning. Dynamic Mode Decompositio n: Data-Driven Modeling of Complex Systems, the first book to address the DMD algorithm, presents a pedagogical and comprehensiv e approach to all aspects of DMD currently developed or under development; blends theoretical development, example codes, and applications to showcase the theory and its many innovations and uses; highlights the numerous innovations around the DMD algorithm and demonstrates its efficacy using example

problems from engineering and the physical and biological sciences; and provides extensive MATLAB code, data for intuitive examples of key methods, and graphical presentations.
*Turbulence*
Cambridge University Press
This is the first book dedicated to data-driven methods for fluid dynamics, with applications in analysis, modeling, control, and closures.
*Guide to Dynamic Simulations of Rigid Bodies and Particle Systems*
Elsevier
This textbook presents a modern account of turbulence, one of the greatest challenges in physics. The state-of-the-art is put into historical perspective five centuries after the first studies of Leonardo and half a century after the first attempt by A. N. Kolmogorov to predict the properties of flow at very high Reynolds numbers. Such 'fully developed turbulence' is ubiquitous in both cosmical and natural environments, in engineering applications and in everyday life. The intended readership for the book ranges from first-year graduate students in mathematics, physics, astrophysics, geosciences and engineering, to professional scientists and engineers. Elementary presentations of dynamical systems ideas,

of probabilistic methods (including the theory of large deviations) and of fractal geometry make this a self-contained textbook.
Deep Data-driven Modeling and Control of High-dimensional Nonlinear Systems SIAM
This book introduces the techniques needed to produce realistic simulations and animations of particle and rigid-body systems. The text focuses on both the theoretical and practical aspects of developing and implementing physically based dynamic-simulation engines. Each chapter examines numerous algorithms, describing their design and analysis in an accessible manner, without sacrificing depth of coverage or mathematical rigor. Features: examines the problem of computing an hierarchical representation of the geometric description of each simulated object, as well as the simulated world; discusses the use of discrete and continuous collision detection to handle thin or fast-moving objects; describes the computational techniques needed for determining all impulsive and contact forces between bodies with multiple simultaneous collisions and

contacts; presents techniques that can be used to dynamically simulate articulated rigid bodies; concludes each chapter with exercises.

**Computational Methods for Fluid Dynamics**

Springer Nature

This book gathers the latest advances, innovations, and applications in the field of computational engineering, as presented by leading international researchers and engineers at the 26th International Conference on Computational & Experimental Engineering and Sciences (ICCES), held in Phuket, Thailand on January 6-10, 2021. ICCES covers all aspects of applied sciences and engineering: theoretical, analytical, computational, and experimental studies and solutions of problems in the physical, chemical, biological, mechanical, electrical, and mathematical sciences. As such, the book discusses highly diverse topics, including composites; bioengineering & biomechanics; geotechnical engineering; offshore & arctic engineering; multi-scale & multi-physics fluid engineering; structural integrity & longevity; materials design & simulation; and computer modeling methods in engineering. The

contributions, which were selected by means of a rigorous international peer-review process, highlight numerous exciting ideas that will spur novel research directions and foster multidisciplinary collaborations.
Computational Fluid Dynamics Cambridge University Press
Fluid solvers that provide accurate and fast fluid simulations are of great importance in many scientific and engineering disciplines. Conventional numerical solvers based on the Eulerian description of the flow provide highly accurate solutions to the Navier-Stokes equations. However, there is typically a significant amount of computational effort is required to execute such Eulerian simulations. On the other hand, fluid solvers built on the Lagrangian description of the flow are more appealing in terms of its vicinity to the true physics, since it treats the actual fluid particles as the primary computational elements. A particular group of Lagrangian particle methods based on vorticity, instead of velocity, as the primary flow variable, delivers velocity field solutions, which are always divergence-free. These vortex

methods have an inherent advantage that the particles need to be present only in the regions where vorticity exists, and therefore fewer fluid particles are required to execute simulations as compared to their counterparts with velocity-based formulations. Recently, deep learning solutions for fluid dynamics problems by the application of artificial neural networks has become more prominent. Neural networks encode the information about the governing laws of fluid dynamics in its parameters using the knowledge extracted from data samples during training. The aim of this work is to use deep learning to learn fluid dynamics with Lagrangian vortex particles as the primary flow representation. Solution strategies to train and evaluate the neural networks for predicting Lagrangian vortex particle dynamics for different flow scenarios are presented throughout this work. Conceptualization and implementation of an approach to model interaction between vortex particles based on the Taylor series expansion of the velocity form the core of this work. We demonstrate that our trained neural networks produce fluid simulations with reasonable accuracy for different flow scenarios while respecting appropriate constraints pertaining to fluid dynamics.

**Example-Based Fluid Simulation**

BoD – Books on Demand

This book presents methodologies for analysing large data sets produced by the direct numerical simulation (DNS) of turbulence and combustion. It describes the development of models that can be used to analyse large eddy simulations, and highlights both the most common techniques and newly emerging ones. The chapters, written by internationally respected experts, invite readers to consider DNS of turbulence and combustion from a formal, data-driven standpoint, rather than one led by experience and intuition. This perspective allows readers to recognise the shortcomings of existing models, with the ultimate goal of quantifying and reducing model-based uncertainty. In addition, recent advances in machine learning and statistical inferences offer new insights on the interpretation of DNS data. The book will especially benefit graduate-level students and researchers in mechanical and aerospace engineering, e.g. those with an interest in general fluid mechanics, applied mathematics, and the environmental and atmospheric sciences.

**Modeling in Engineering Using Innovative Numerical Methods for Solids and Fluids**

Academic Press

A pioneer in the fields of statistics and probability theory, Richard von Mises (1883–1953) made notable advances in boundary-layer-flow theory and airfoil design. This text on compressible flow, unfinished upon his sudden death, was subsequently completed in accordance with his plans, and von Mises' first three chapters were augmented with a survey of the theory of steady plane flow. Suitable as a text for advanced undergraduate and graduate students — as well as a reference for professionals — Mathematical Theory of Compressible Fluid Flow examines the fundamentals of high-speed flows, with detailed considerations of general theorems, conservation equations, waves, shocks, and nonisentropic flows. In this, the final work of his distinguished career, von Mises summarizes his extensive knowledge of a central branch of fluid mechanics.

Characteristically, he pays particular attention to the basics, both conceptual and mathematical. The novel concept of a specifying equation clarifies the role of thermodynamics in the mechanics of compressible fluids. The general theory of characteristics receives a remarkably complete and simple treatment, with detailed applications, and the theory of shocks as asymptotic phenomena appears within the context of rational mechanics. *Determining Unknown Boundary Conditions in Fluid-Thermal Systems Using the Dynamic Data Driven Application Systems Methodology* CRC Press Distributing graphical fluid simulations across many machines enables faster and more detailed simulations. However, distributing these simulations efficiently is challenging. First, it requires writing efficient distributed simulation code. Graphical fluid simulations use many diverse, novel and optimized data structures. Existing production libraries contain code developed over decades. It is important to leave low level control over simulation data structures to applications, in order to support these different data structures and existing libraries. Second, even with well written code, it is necessary to distribute work evenly in order to run the simulation efficiently. Fluid simulations exhibit spatial and temporal variation in fluid distribution and computational load. This makes distributing work evenly difficult. Optimal decision making requires knowing future computational load, but computing this state automatically for an arbitrary simulation requires running the simulation itself. As a result, many simulations use a manually specified partitioning, a heuristic, or a reactive approach based on the current load. This dissertation shows that using coarse grained geometric descriptions about data and computations, it is possible for a system to automatically distribute such simulations efficiently by addressing these two challenges. It presents a four layer data model that allows a high level framework to automatically distribute grid-based and hybrid simulations over application owned data structures, and proposes a new approach, speculative load balancing to automatically distribute work evenly. The four layer data model supports complex data structures by providing a simple, geometric abstraction to the simulation author and library. It uses geometric information to translate between geometric views and disjoint system views for efficiently analyzing and enforcing dependencies, and to assemble complex application objects containing data in the format that the simulation library expects from underlying system objects. Speculative load balancing runs the same sequence of computations over a lower resolution grid to estimate future load, and uses these estimates to distribute work evenly. The lower resolution simulation runs orders of magnitude faster and adds negligible execution time overhead. Experimental results show that speculative load balancing outperforms traditional ways of distributing work. The Finite Volume Method in Computational Fluid Dynamics Courier Corporation Second, we model liquid-liquid microflow systems. We employ a state-of-the-art algorithm in computational fluid dynamics

(CFD) simulations to study flow patterns, extraction, and mass transport in biphasic microreactors. The convective and diffusive contributions to the mass transfer of different flow patterns are analyzed. Moreover, we build a machine learning model to predict the flow patterns accurately and identify critical features for design.

**Fluid Simulation for Computer Graphics**

Cambridge University Press Accurately predicting the behaviour of multiphase flows is a problem of immense industrial and scientific interest. Modern computers can now study the dynamics in great detail and these simulations yield unprecedente d insight. This book provides a comprehensiv e introduction to direct numerical simulations of multiphase flows for researchers and graduate students. After a brief overview of the context and history the authors review the governing equations. A particular emphasis is placed on the 'one-fluid' formulation where a single set of equations is used to describe the entire flow field and interface terms are included as singularity distributions. Several applications

are discussed, showing how direct numerical simulations have helped researchers advance both our understanding and our ability to make predictions. The final chapter gives an overview of recent studies of flows with relatively complex physics, such as mass transfer and chemical reactions, solidification and boiling, and includes extensive references to current work.
Mathematical Theory of Compressible Fluid Flow Cambridge University Press
In this translation of the German edition, the authors provide insight into the numerical simulation of fluid flow. Using a simple numerical method as an expository example, the individual steps of scientific computing are presented: the derivation of the mathematical model; the discretization of the model equations; the development of algorithms; parallelization; and visualization of the computed data. In addition to the treatment of the basic equations for modeling laminar, transient flow of viscous, incompressibl e fluids - the Navier-Stokes equations - the authors look at the simulation of free surface flows; energy and chemical transport; and turbulence. Readers are enabled to write their

own flow simulation program from scratch. The variety of applications is shown in several simulation results, including 92 black-and-white and 18 color illustrations. After reading this book, readers should be able to understand more enhanced algorithms of computational fluid dynamics and apply their new knowledge to other scientific fields.

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