

DDRKAM Reference Manual

Data-Driven Runge-Kutta and Adams Methods

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1 Introduction

This manual provides comprehensive documentation for the DDRKAM (Data-Driven Runge-Kutta and Adams Methods) framework. The framework implements numerical methods for solving ordinary differential equations (ODEs) with support for traditional and hierarchical data-driven approaches.

The framework includes:

- Euler's Method (1st order)
- Data-Driven Euler's Method (DDEuler)
- Runge-Kutta 3rd Order Method (RK3)
- Data-Driven Runge-Kutta 3rd Order (DDRK3)
- Adams Methods (AM)
- Data-Driven Adams Methods (DDAM)

2 Euler's Method

2.1 Overview

Euler's Method is the simplest numerical method for solving ODEs. It is a first-order explicit method with local truncation error $O(h^2)$.

2.2 Algorithm

$$y_{n+1} = y_n + h \cdot f(t_n, y_n) \quad (1)$$

where h is the step size, f is the ODE function, and y_n is the state at time t_n .

2.3 API Reference

2.3.1 euler_step

Performs a single integration step using Euler's method.

```
1 double euler_step(ODEFunction f, double t0, double* y0,
2                     size_t n, double h, void* params);
```

Parameters:

- **f**: Function pointer to the ODE system
- **t0**: Current time
- **y0**: Current state vector (modified in-place)
- **n**: Dimension of the system
- **h**: Step size
- **params**: User-defined parameters

Returns: New time value ($t_0 + h$)

2.3.2 euler_solve

Solves an ODE system over a time interval using Euler's method.

```
1 size_t euler_solve(ODEFunction f, double t0, double
                     t_end,
2                         const double* y0, size_t n, double h,
3                         void* params, double* t_out, double*
                     y_out);
```

3 Data-Driven Euler's Method

3.1 Overview

Data-Driven Euler's Method (DDEuler) extends standard Euler's method with a hierarchical transformer-inspired architecture that applies adaptive corrections to improve accuracy.

3.2 Algorithm

$$y_{n+1} = y_n + h \cdot f(t_n, y_n) + h \cdot \alpha \cdot \text{Attention}(y_n) \quad (2)$$

where α is a learning rate and $\text{Attention}(y_n)$ is computed through hierarchical transformer layers.

3.3 API Reference

3.3.1 hierarchical_euler_init

Initializes a Data-Driven Euler solver.

```
1 int hierarchical_euler_init(HierarchicalEulerSolver*
2           solver,
3           size_t num_layers, size_t
4           state_dim,
5           size_t hidden_dim);
```

3.3.2 hierarchical_euler_step

Performs a single integration step using Data-Driven Euler.

```
1 double hierarchical_euler_step(HierarchicalEulerSolver*
2           solver,
3           ODEFunctor f, double t,
4           double* y,
5           double h, void* params);
```

3.3.3 hierarchical_euler_solve

Solves an ODE system using Data-Driven Euler over a time interval.

```
1 size_t hierarchical_euler_solve(HierarchicalEulerSolver*
2           solver,
3           ODEFunctor f, double
4           t0, double t_end,
5           const double* y0,
6           double h, void*
7           params,
8           double* t_out, double*
9           y_out);
```

4 Parallel and Distributed Methods

4.1 Overview

All methods support parallel, distributed, concurrent, hierarchical, and stacked execution modes. This enables:

- Multi-threaded execution (OpenMP, pthreads)
- Distributed computing (MPI)
- Concurrent execution of multiple methods
- Hierarchical/stacked architectures
- Enhanced performance and scalability

4.2 Parallel Runge-Kutta

4.2.1 parallel_rk_init

Initialize parallel RK3 solver.

```
1 int parallel_rk_init(ParallelRKSolver* solver, size_t
  state_dim,
2                         size_t num_workers, ParallelMode
                           mode,
3                         StackedConfig* stacked);
```

4.2.2 parallel_rk_step

Perform parallel RK3 step.

```
1 double parallel_rk_step(ParallelRKSolver* solver,
  ODEFunctor f,
2                           double t, double* y, double h,
                           void* params);
```

4.2.3 stacked_rk_step

Perform stacked/hierarchical RK3 step.

```
1 double stacked_rk_step(ParallelRKSolver* solver,
2                         ODEFunctor f,
3                         double t, double* y, double h,
4                         void* params);
```

4.2.4 concurrent_rk_execute

Execute multiple RK3 instances concurrently.

```
1 int concurrent_rk_execute(ParallelRKSolver* solvers[],
2                            size_t num_solvers,
3                            ODEFunctor f, double t, const
4                            double* y, double h,
5                            void* params, double** results
6                            );
```

5 Real-Time, Online, and Dynamic Methods

5.1 Real-Time Methods

Real-time methods process streaming data with minimal latency.

5.1.1 realtime_rk_init

Initialize real-time RK3 solver.

```
1 int realtime_rk_init(RealtimeRKSolver* solver, size_t
2                       state_dim,
3                       double step_size, DataCallback
4                       callback,
5                       void* callback_data);
```

5.1.2 realtime_rk_step

Perform real-time RK3 step with streaming support.

```
1 double realtime_rk_step(RealtimeRKSolver* solver,
2                           ODEFunctor f,
3                           double t, double* y, double h,
4                           void* params);
```

5.2 Online Methods

Online methods adapt to incoming data with incremental learning.

5.2.1 online_rk_init

Initialize online RK3 solver.

```
1 int online_rk_init(OnlineRKSolver* solver, size_t
2                      state_dim,
3                      double initial_step_size, double
4                      learning_rate);
```

5.2.2 online_rk_step

Perform online RK3 step with adaptive step size.

```
1 double online_rk_step(OnlineRKSolver* solver,
2                           ODEFunctor f,
3                           double t, double* y, void* params);
```

5.3 Dynamic Methods

Dynamic methods provide fully adaptive execution.

5.3.1 dynamic_rk_init

Initialize dynamic RK3 solver.

```
1 int dynamic_rk_init(DynamicRKSolver* solver, size_t
2                      state_dim,
3                      double initial_step_size, double
4                      adaptation_rate);
```

5.3.2 dynamic_rk_step

Perform dynamic RK3 step with adaptive parameters.

```
1 double dynamic_rk_step(DynamicRKSolver* solver,
2                           ODEFunctor f,
3                           double t, double* y, void* params
4                           );
```

6 Nonlinear Programming Solvers

6.1 Nonlinear ODE Solver

6.1.1 nonlinear_ode_init

Initialize nonlinear ODE solver using NLP methods.

```
1 int nonlinear_ode_init(NonlinearODESolver* solver,
2                         size_t state_dim,
3                         NLPSolverType solver_type,
4                         ObjectiveFunction objective,
5                         ConstraintFunction constraints,
6                         void* params);
```

6.1.2 nonlinear_ode_solve

Solve ODE using nonlinear programming.

```
1 int nonlinear_ode_solve(NonlinearODESolver* solver,
2                           ODEFunctor f,
3                           double t0, double t_end, const
4                           double* y0,
5                           double* y_out);
```

6.2 Nonlinear PDE Solver

6.2.1 nonlinear_pde_init

Initialize nonlinear PDE solver.

```
1 int nonlinear_pde_init(NonlinearPDESolver* solver,
2                         size_t spatial_dim,
3                         const size_t* grid_size,
4                         NLPSolverType solver_type,
5                         PDEFunctor pde_func, void* params
6                         );
```

6.2.2 nonlinear_pde_solve

Solve PDE using nonlinear programming.

```
1 int nonlinear_pde_solve(NonlinearPDESolver* solver,
2                         double t0, double t_end,
3                         const double* u0, double* u_out);
```

7 Additional Distributed, Data-Driven, Online, Real-Time Solvers

7.1 Distributed Data-Driven Solver

Combines distributed computing with data-driven methods.

7.2 Online Data-Driven Solver

Combines online learning with data-driven methods.

7.3 Real-Time Data-Driven Solver

Combines real-time processing with data-driven methods.

7.4 Distributed Online Solver

Combines distributed computing with online learning.

7.5 Distributed Real-Time Solver

Combines distributed computing with real-time processing.

8 Runge-Kutta 3rd Order Method

8.1 Overview

The Runge-Kutta 3rd order method provides a good balance between accuracy and computational efficiency for solving ODEs.

8.2 API Reference

8.2.1 rk3_step

Performs a single integration step using RK3.

```
1 double rk3_step(ODEFunction f, double t0, double* y0,
2                   size_t n, double h, void* params);
```

Parameters:

- **f**: Function pointer to the ODE system
- **t0**: Current time
- **y0**: Current state vector (modified in-place)
- **n**: Dimension of the system
- **h**: Step size
- **params**: User-defined parameters

Returns: New time value ($t_0 + h$)

8.2.2 rk3_solve

Solves an ODE system over a time interval.

```
1 size_t rk3_solve(ODEFunction f, double t0, double t_end,
2                   const double* y0, size_t n, double h,
3                   void* params, double* t_out, double*
y_out);
```

Parameters:

- **f**: Function pointer to the ODE system

- t_0 : Initial time
- t_{end} : Final time
- y_0 : Initial state vector
- n : Dimension of the system
- h : Step size
- params : User-defined parameters
- t_{out} : Output time array (allocated by caller)
- y_{out} : Output state array ($n \times \text{num_steps}$, allocated by caller)

Returns: Number of steps taken

8.3 Example

```

1 void lorenz(double t, const double* y, double* dydt,
2             void* params) {
3     double* p = (double*)params;
4     double sigma = p[0], rho = p[1], beta = p[2];
5     dydt[0] = sigma * (y[1] - y[0]);
6     dydt[1] = y[0] * (rho - y[2]) - y[1];
7     dydt[2] = y[0] * y[1] - beta * y[2];
8 }
9 double params[3] = {10.0, 28.0, 8.0/3.0};
10 double y0[3] = {1.0, 1.0, 1.0};
11 double t_out[100];
12 double y_out[300];
13 size_t steps = rk3_solve(lorenz, 0.0, 1.0, y0, 3, 0.01,
                           params, t_out, y_out);
14

```

9 Adams Methods

9.1 Adams-Bashforth 3rd Order

Predictor step for multi-step integration.

```

1 void adams_bashforth3(ODEFunction f, const double* t,
2                         const double* y, size_t n, double
3                         h,
4                         void* params, double* y_pred);

```

9.2 Adams-Moulton 3rd Order

Corrector step for multi-step integration.

```

1 void adams_moulton3(ODEFunction f, const double* t,
2                       const double* y, size_t n, double h,
3                       void* params, const double* y_pred,
4                       double* y_corr);

```

10 Hierarchical Runge-Kutta Method

10.1 Overview

The hierarchical RK method uses a transformer-like architecture with multiple processing layers and attention mechanisms.

10.2 API Reference

10.2.1 hierarchical_rk_init

Initializes a hierarchical RK solver.

```

1 int hierarchical_rk_init(HierarchicalRKSolver* solver,
2                           size_t num_layers, size_t
3                           state_dim,
4                           size_t hidden_dim);

```

Returns: 0 on success, -1 on failure

10.2.2 hierarchical_rk_free

Frees resources allocated by the solver.

```

1 void hierarchical_rk_free(HierarchicalRKSolver* solver);

```

10.2.3 hierarchical_rk_solve

Solves an ODE using the hierarchical method.

```
1 size_t hierarchical_rk_solve(HierarchicalRKSolver*
2           solver,
3           ODEFunctor f, double t0,
4           double t_end,
5           const double* y0, double h,
6           void* params,
7           double* t_out, double*
8           y_out);
```

11 Objective-C Framework

11.1 DDRKAMSolver

Main solver class for Objective-C applications.

```
1 DDRKAMSolver* solver = [[DDRKAMSolver alloc]
2                           initWithDimension:3];
3 NSDictionary* result = [solver solveWithFunction:^(
4                           double t,
5                           const
6                           double*
7                           y
8                           ,
9                           double*
10                          dydt
11                          ,
12                          void*
13                          params
14                          )
```

```

7      // ODE definition
8 } startTime:0.0 endTime:1.0
9 initialState:@[@1.0, @1.0, @1.0]
10 stepSize:0.01 params:NULL];
}

```

11.2 DDRKAMVisualizer

Visualization component for plotting solutions.

```

1 DDRKAMVisualizer* viz = [[DDRKAMVisualizer alloc] init];
2 NSView* view = [viz createVisualizationViewWithTime:
3                           timeArray
4                           state:
5                           stateArray
6                           dimension:3];
7 [viz exportToCSV:@"/path/to/output.csv"
8          time:timeArray
9          state:stateArray];

```

11.3 DDRKAMHierarchicalSolver

Hierarchical solver for Objective-C.

```

1 DDRKAMHierarchicalSolver* solver =
2   [[DDRKAMHierarchicalSolver alloc]
3     initWithDimension:3 numLayers:4 hiddenDim:32];

```

12 Platform Support

- macOS 10.13+
- iOS 11.0+
- visionOS 1.0+

13 Copyright

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