

# AIF MuJoCo Robot

## *Code Architecture & API Reference*

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Complete code architecture, module APIs, CLI options, configuration, and MuJoCo model descriptions.

# 1. Project Overview

A simple Active Inference (AIF) controller for a 3D MuJoCo robot. The robot navigates toward a goal by minimizing Expected Free Energy (EFE).

## Project Structure

Path	Description
src/AIFMuJoCoRobot.jl	Main module
src/aif/beliefs.jl	Belief state (Gaussian)
src/aif/generative_model.jl	Transition + observation models
src/aif/efe.jl	Expected Free Energy
src/aif/policy.jl	Policy selection (argmin EFE)
src/aif/action.jl	Action-to-control mapping
src/aif/rxinfer_filter.jl	RxInfer streaming filter
src/control/aif_controller.jl	AIF controller (integrator)
src/sim/mujoco_env.jl	MuJoCo environment wrapper
src/sim/sensors.jl	Sensor / observation model
src/utils/math.jl	Math utilities
src/utils/logging.jl	Logging utilities
scripts/run_cli.jl	CLI entry point
experiments/configs.jl	Configuration presets
models/robot.xml	MuJoCo 3D robot model

## Dependencies (Project.toml)

Package	Purpose
BangBang	Efficient in-place operations
Distributions	Probability distributions
LinearAlgebra	Matrix/vector operations (stdlib)
MuJoCo	MuJoCo.jl physics simulation
Plots	Plotting trajectories
Printf	Formatted printing (stdlib)
Random	RNG (stdlib)
Rocket	Reactive streams for RxInfer
RxInfer	Bayesian inference on factor graphs

## Quick Start

```
cd aif_mujoco_robot
julia --project=. -e 'using Pkg; Pkg.instantiate()'
julia --project=. scripts/run_cli.jl \
  --goal 0.8 0.8 0.4 --init -0.5 -0.5 0.2 \
```

```
--steps 500 --ctrl_scale 5.0 --save_plot trajectory.png
```

## 2. Main Module (AIFMuJoCoRobot.jl)

Entry point that includes all submodules and exports the public API.

### Include Order

```
utils/math.jl -> utils/logging.jl
aif/beliefs.jl -> aif/generative_model.jl -> aif/efe.jl
aif/action.jl -> aif/policy.jl -> aif/rxinfer_filter.jl
sim/sensors.jl -> sim/mujoco_env.jl
control/aif_controller.jl
experiments/configs.jl
```

### Exports

Symbol	Description
run_simulation	Run the full AIF + MuJoCo loop
default_model_path	Path to models/robot.xml
BeliefState	Gaussian belief struct
init_belief	Create initial belief
update_belief!	Bayesian update with observation
EnvState	MuJoCo environment struct
load_env	Load MuJoCo model
reset!	Reset environment
step!	Step MuJoCo simulation
get_position	Read current [x,y,z]
get_goal	Read goal [x,y,z]

### run\_simulation Signature

```
run_simulation(;
    steps::Int = 100,
    goal::Vector{Float64} = [0.8, 0.8, 0.4],
    init_pos::Vector{Float64} = [-0.5, -0.5, 0.2],
    obs_noise::Real = 0.01,
    γ::Real = 1.0, β::Real = 0.1,
    ctrl_scale::Real = 1.0,
    nsteps_per_ctrl::Int = 5,
    model_path::String = default_model_path(),
    seed::Union{Int,Nothing} = 42,
    process_noise = 0.005,
    verbose::Bool = true,
    inference_backend::Symbol = :analytic, # or :rxinfer
    action_alpha::Real = 0.3, # EMA smoothing (0-1)
)
```

## Control Loop (Architecture)

```

+-----+
| compute_control | belief + goal -> (ctrl, action, efe)
+-----+
|
+-----v-----+
| EMA smoothing   | ctrl = a*new + (1-a)*prev
+-----+
|
+-----v-----+
| predict_belief! | OR rxinfer_step! (if :rxinfer)
+-----+
|
+-----v-----+
| MuJoCo step!    | Apply ctrl, advance physics
+-----+
|
+-----v-----+
| read_observation | qpos + noise -> obs
+-----+
|
+-----v-----+
| update_belief!   | OR rxinfer_step! (if :rxinfer)
+-----+
|
[repeat]

```

## 3. Belief State (beliefs.jl)

Represents the agent's belief over 3D position as a diagonal Gaussian.

### BeliefState Struct

```
struct BeliefState
    mean::Vector{Float64} # [ $\mu_x$ ,  $\mu_y$ ,  $\mu_z$ ]
    cov::Vector{Float64}  # [ $\sigma^2_x$ ,  $\sigma^2_y$ ,  $\sigma^2_z$ ]
end
```

### Exports

Symbol	Description
BeliefState	Struct with mean and cov
init_belief	Create initial belief from mean/cov
update_belief!	Bayesian update with observation
predict_belief!	Predict forward given control
entropy	Entropy of diagonal Gaussian

### Key Constants

- COV\_MIN = 1e-5 (lower bound on variance)
- COV\_MAX = 2.0 (upper bound on variance)

*When `inference_backend = :rxinfer`, `predict_belief!` and `update_belief!` are bypassed. The `RxInfer` posterior is written directly into `belief.mean` and `belief.cov`.*

## 4. Generative Model (generative\_model.jl)

Transition and observation likelihood for Active Inference.

Symbol	Description
predict_transition	$s' = s + u$ (3D additive)
observation_likelihood	$P(o s)$ diagonal Gaussian
predict_observation	Expected obs from state (noiseless)

*These functions are used by EFE/policy selection regardless of which inference backend is active.*

## 5. Expected Free Energy (efe.jl)

Computes EFE = pragmatic - epistemic for policy selection.

Symbol	Description
compute_efe	Full EFE for an action
pragmatic_term	Goal-distance cost (with ctrl_scale)
epistemic_term	Uncertainty / information term

### compute\_efe Signature

```
compute_efe(belief_mean, belief_cov, action, goal;  
            γ=1.0, β=0.1, axis_weights=nothing,  
            ctrl_scale=1.0, ctrl_lim=1.2)
```



## 6. Policy Selection (policy.jl)

Selects the action minimizing EFE over a discrete  $7 \times 7 \times 7$  action grid (343 actions).

Symbol	Description
<code>select_action</code>	Choose best action for belief+goal
<code>get_action_set</code>	343-action grid ( <code>step_size=0.04</code> )

### `select_action` Signature

```
select_action(belief, goal;  
  actions=get_action_set(),  $\gamma=1.0$ ,  $\beta=0.1$ ,  
  axis_weights=nothing, ctrl_scale=1.0, ctrl_lim=1.2)
```

## 7. Action (action.jl)

Converts abstract velocity actions into MuJoCo control signals.

Symbol	Description
to_control	action -> scaled+clamped control
clamp_action	Clamp action to limits

### to\_control Signature

```
to_control(action; scale=1.0, ctrl_lim=1.2)
```

## 8. RxInfer Filter (rxinfer\_filter.jl)

Alternative inference backend using RxInfer.jl's reactive message-passing. Three independent 1D engines (x, y, z) run a linear-Gaussian SSM.

Symbol	Description
RxInferFilter3D	Struct with 3 per-axis engines
init_rxinfer_filter	Create and start 3-axis filter
rxinfer_step!	Push (ctrl, obs), return posterior
rxinfer_stop!	Stop engines, unsubscribe

### Streaming Design

Each axis uses a single `RecentSubject{NamedTuple{(:y,:u)}}` stream. Pushing a (y, u) tuple triggers exactly one inference cycle per step, avoiding the `combineLatest` double-fire issue.

### init\_rxinfer\_filter Signature

```
init_rxinfer_filter(
    init_mean::AbstractVector,
    init_cov::AbstractVector;
    obs_noise = 0.01,
    process_noise = 0.005,
)
```

### rxinfer\_step! Signature

```
rxinfer_step!(filter, ctrl, obs)
→ (post_mean::Vector, post_var::Vector)
```

## 9. AIF Controller (aif\_controller.jl)

Integrates belief, policy, and action into a single control step.

Symbol	Description
compute_control	belief+goal -> (ctrl, action, efe)

### compute\_control Flow

```
1. select_action(belief, goal; ...)  
2. to_control(action; scale, ctrl_lim)  
3. compute_efe(belief.mean, belief.cov, action, goal; ...)  
4. return (ctrl=..., action=..., efe=...)
```

*The controller is backend-agnostic: it always reads belief.mean and belief.cov regardless of whether they came from analytic or RxInfer updates.*

## 10. MuJoCo Environment (mujoco\_env.jl)

Wraps MuJoCo for the 3D point-mass robot.

Symbol	Description
EnvState	Struct: model, data, goal
load_env	Load XML model
reset!	Reset to initial position
step!	Apply control, advance physics
get_position	Current [x,y,z] from qpos
get_goal	Goal [x,y,z]

### Model Layout

- qpos[1], qpos[2], qpos[3]: x, y, z (slide joints)
- ctrl[1], ctrl[2], ctrl[3]: displacement (target = pos + ctrl)

### step! Signature

```
step!(env, ctrl; nsteps=5)
```

Applies ctrl and runs nsteps MuJoCo physics steps for stability.

## 11. Sensors (sensors.jl)

Extracts observations from MuJoCo state with optional noise.

Symbol	Description
read_position	Extract [x,y,z] from qpos
read_observation	Position + Gaussian noise

### read\_observation Signature

```
read_observation(qpos; obs_noise=0.01, rng=default_rng())
```

obs\_noise: scalar or  $[\sigma^2_x, \sigma^2_y, \sigma^2_z]$ . Adds  $\sqrt{\sigma^2} * \text{randn}()$  per dimension when  $\sigma^2 > 0$ .

## 12. Utilities

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### Math Utilities (math.jl)

Symbol	Description
normalize!	Normalize probability vector in place
gaussian_pdf	Univariate/multivariate diagonal PDF
gaussian_entropy	Entropy of univariate Gaussian
softmax	Numerically stable softmax
clamp_vec	Clamp vector elements to bounds

### Logging Utilities (logging.jl)

Symbol	Description
log_step	Print step: pos, goal, belief, efe
log_summary	Print summary: steps, dist, converged

## 13. CLI (run\_cli.jl)

Command-line interface for running simulations and visualisations.

### Usage

```
julia --project=. scripts/run_cli.jl \
  --goal <x> <y> <z> --init <x> <y> <z> [options]
```

### All Options

Option	Description	Default
--goal	Goal position (x y z)	0.8 0.8 0.4
--init	Initial position (x y z)	-0.5 -0.5 0.2
--steps	Max simulation steps	500
--ctrl_scale	Control scaling factor	3.0
--obs_noise	Observation variance	0.005
--process_noise	Process noise variance	0.002
--alpha	EMA smoothing (0-1; lower=smoother)	0.3
--backend	analytic   rxinfer	analytic
--save_plot	Path to save trajectory PNG	(none)
--render	Launch MuJoCo visualiser	false
--renderarm	Panda arm pick-and-place	false
--agent_color	Agent color r g b [a]	(default)
--goal_color	Goal color r g b [a]	(default)
--seed	Random seed	42
--verbose	Print step logs	true

### Render Arm Sequence

With --renderarm, the AIF trajectory is replayed on a Panda arm:

1. Arm moves to init position (pickup)
2. Red ball follows arm along AIF path (carry)
3. Red ball placed on green box at goal (drop)

Panda workspace bounds: X [0.2, 0.8], Y [-0.4, 0.4], Z [0.1, 0.5]. Trajectory positions are clamped.

### Example (RxInfer + Panda Arm)

```
julia --project=. scripts/run_cli.jl \
  --backend rxinfer \
  --goal 0.8 0.8 0.4 --init 0.3 0.0 0.2 \
  --steps 500 --ctrl_scale 3.0 --alpha 0.3 \
  --save_plot trajectory.png --renderarm
```



## 14. Configuration (configs.jl)

Predefined configuration presets for experiments.

### default\_config()

Parameter	Default Value
steps	500
goal	[0.8, 0.8, 0.4]
init_pos	[-0.5, -0.5, 0.2]
obs_noise	0.005
process_noise	0.002
$\gamma$	1.5
$\beta$	0.02
ctrl_scale	3.0
nsteps_per_ctrl	8
action_alpha	0.3
seed	42
verbose	true
inference_backend	:analytic

### Presets

- config\_goal\_seeking():  $\gamma=2.5$ ,  $\beta=0.01$ , action\_alpha=0.4 (emphasize goal)
- config\_exploration():  $\gamma=0.5$ ,  $\beta=0.2$ , action\_alpha=0.6 (emphasize exploration)

## 15. MuJoCo Models

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### **models/robot.xml**

Main 3D robot scene for AIF simulation:

- World: ground plane, light, target site at (0.8, 0.8, 0.4)
- Robot: body with three slide joints (x, y, z), damping=15, sphere geom
- Actuators: position actuators on slide\_x/y/z, kp=80, range  $\pm 10$

### **panda\_render\_scene.xml**

Scene for --renderarm: Panda arm with pick-and-place visuals.

- Red sphere (mocap) at initial position
- Green box (static) at goal position
- Includes panda\_mocap.xml for the arm model
- Positions substituted at runtime from --init and --goal