

2025-11-01

E001: Project Overview

Welcome to DIP-SMC-PSO

Part 1 · Duration: 25-30 minutes

Beginner-Friendly Visual Study Guide

⌚ **Learning Objective:** Understand the DIP-SMC-PSO project structure and how seven different controllers work together with simulation, optimization, and monitoring components

What Is This Project?

The Challenge

💡 Key Concept

Imagine balancing **two broomsticks** connected end-to-end on your hand while moving left and right. Now add:

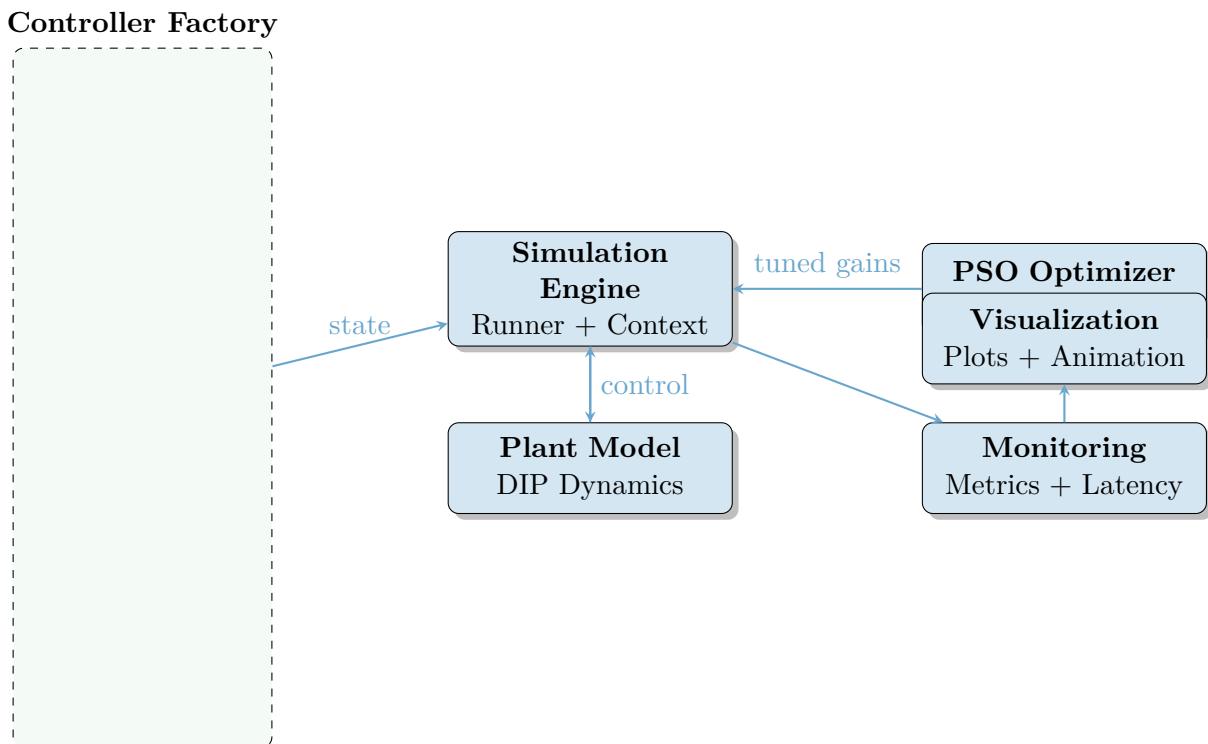
- You're **blindfolded**
- Random **wind** is blowing
- You're on a **moving platform**
- You must respond every **1-10 milliseconds**

Real-World Applications

⌚ This isn't just academic - it's the same math that powers:

- **SpaceX rocket landings** (Falcon 9 boosters)
- **Humanoid robots** (Boston Dynamics)
- **Self-balancing vehicles** (Segway, scooters)
- **Construction cranes** (load stabilization)
- **Satellite orientation** (aerospace attitude control)

System Architecture: The Seven Brains



Controllers by Sophistication

✓ **Classical SMC** - The baseline (1970s theory, 200 lines)

✓ **Super-Twisting** - Smooth operator (2nd-order, ABS brakes analogy)

⌚ **Adaptive Controllers** - Self-tuning intelligence:

- Adaptive SMC (real-time gain adjustment)

- Hybrid Adaptive STA (21.4% improvement)

- Conditional Hybrid (safety-aware switching)

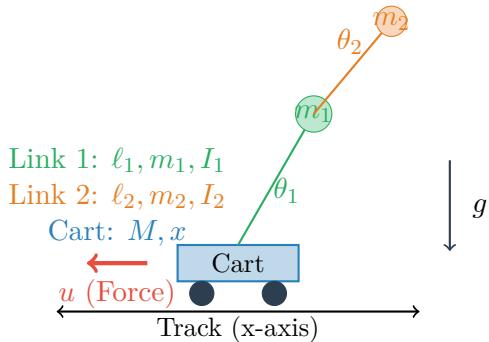
✓ **Swing-Up SMC** - Energy-based (starts from hanging position)

⚗️ **MPC (Experimental)** - Model Predictive Control (constraint handling)

💡 **Pro Tip**

All controllers use the **same interface**, so you can swap them with a single configuration change!

The Physics: Double Inverted Pendulum



Why Is This Hard?

⚠ Common Pitfall

Underactuated System: ONE control (cart force) manages THREE states (cart position, angle 1, angle 2)

Unstable Equilibrium: Like balancing a pencil on its tip - tiny errors cause collapse

Nonlinear Dynamics: Sine/cosine functions couple the pendulum angles

💡 Key Concept

Fast Response Required:

Control algorithm decides every 1-10ms = 100-1000 times per second.

Blink and you've missed 300 control cycles!

Three Levels of Reality: Plant Models

☰ Model Comparison

	Model	When to Use
Simplified DIP		Initial testing, PSO prototyping Small angles ($< 5^\circ$)
Full Nonlinear		Final validation, research papers Complete equations
Low-Rank DIP		Monte Carlo (1000 runs) Sensitivity analysis

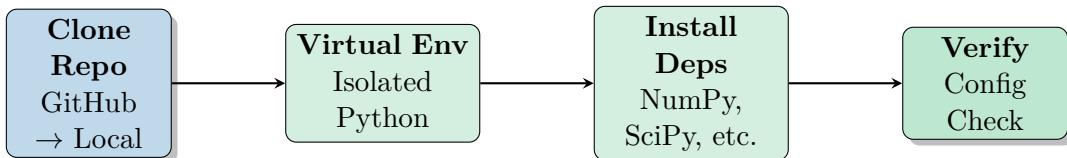
leftrightarrow Example

Video Game Analogy:

- Simplified = Low graphics settings (fast, rough)
- Full Nonlinear = Ultra settings (slow, beautiful)
- Low-Rank = Balanced settings (optimized)

From Installation to Research Paper

Phase 1: Lab Setup (15 minutes)



Phase 2: First Experiments (30 minutes)

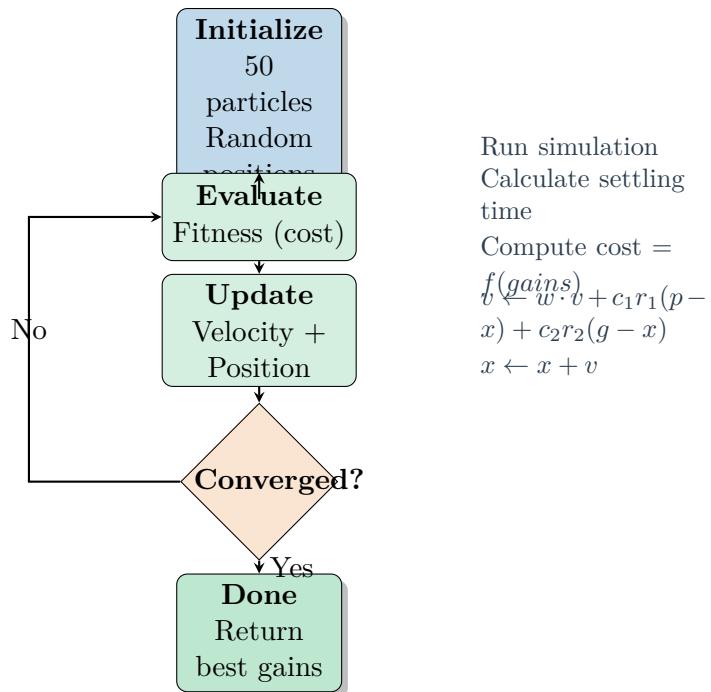
enumiClassical SMC: Baseline performance

- 0. enumiSuper-Twisting: Notice smoother control?
- 0. enumiAdaptive SMC: Watch gains adjust in real-time

What to Look For:

- ⚡ Settling time (how fast?)
- ⚡ Overshoot (swings too far?)
- ⚡ Control effort (energy usage)
- ⚡ Chattering (high-freq oscillations)

Phase 3: Intelligent Tuning (2-4 hours)



Pro Tip

PSO Performance: Achieved 6-21% improvement across all seven controllers. In research at this level, those percentage points can make or break a hardware deployment!

Phases 4-5: Research-Grade Work

☰ Quick Summary

Benchmarking (1-2 days): Test all 7 controllers, multiple scenarios, disturbances

Research (weeks-months): Lyapunov proofs, uncertainty analysis, paper writing

Current Status: Submission-ready paper (v2.1) with 14 figures, 11 completed tasks

Quick Reference: Common Operations

Running Simulations

```
lstnumberSuper-Twisting Algorithm python simulate.py -ctrl stasmc --plot
lstnumberAdaptive SMC python simulate.py -ctrl adaptivesmc --plot
```

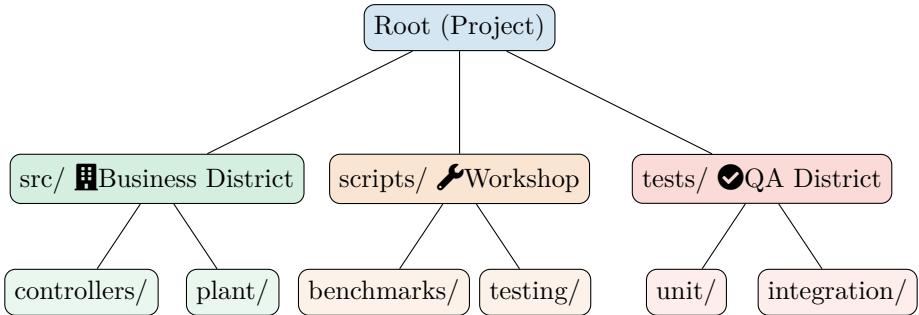
PSO Optimization

```
lstnumberLoad optimized gains python simulate.py -load gains.json -plot
```

Testing & Validation

```
lstnumberSpecific controller tests python -m pytest tests/testcontrollers/testclassicalsmc.py -v
lstnumberCoverage report python -m pytest tests/ -cov=src -cov-report=html
```

Directory Structure: Zoning Laws



Key Technologies

Core Scientific Stack:

- NumPy (array operations)
- SciPy (ODE integrators)
- Matplotlib (visualization)

Optimization:

- PySwarms (PSO algorithm)
- Optuna (Bayesian alternative)

Quality Assurance:

- pytest (250+ tests)
- Hypothesis (property-based)
- 90% test coverage

Configuration:

- Pydantic (type-safe YAML)
- PyYAML (file parsing)

Project Metrics

Status Dashboard

- Test Coverage:** 89.7% overall, 94% controllers (exceeds 85%/95% targets)
- Performance:** 1-10s single sim, 2-4hrs PSO, 30s for 100 sims (vectorized)
- Codebase:** 150+ Python files, 25,000+ lines, 250+ test cases
- Research:** 1 submission-ready paper (v2.1), 14 figures, 11 completed tasks

Design Principles

- 💡 **Modularity:** One job per component
- ⚡ **Type Safety:** Hints everywhere
- ☰ **Configuration-First:** No magic numbers

- ⌚ **Reproducibility:** Seeded RNGs
- ⚠ **Testability:** Every module tested

What's Next?

💡 Key Concept

E002: Control Theory Fundamentals - Lyapunov stability, sliding mode theory, why SpaceX rockets don't tip over

E003: Plant Models & Dynamics - Lagrangian mechanics, Coriolis forces, complete physics

E004-E029: Advanced Topics - PSO deep dive, benchmarks, Lyapunov proofs, research paper walkthrough

Learning Resources

- 🔗 GitHub Repository
- ☰ Documentation: [docs/](#) directory
- ☰ Sliding Mode Control: Utkin, Guldner, Shi (2009)
- ☰ Nonlinear Control: Khalil (2002)
- ☰ PSO: Kennedy & Eberhart (1995)

From Broomsticks to Rockets

Every successful SpaceX landing uses control theory similar to what we're building here.
That's the power of understanding fundamentals.