

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**

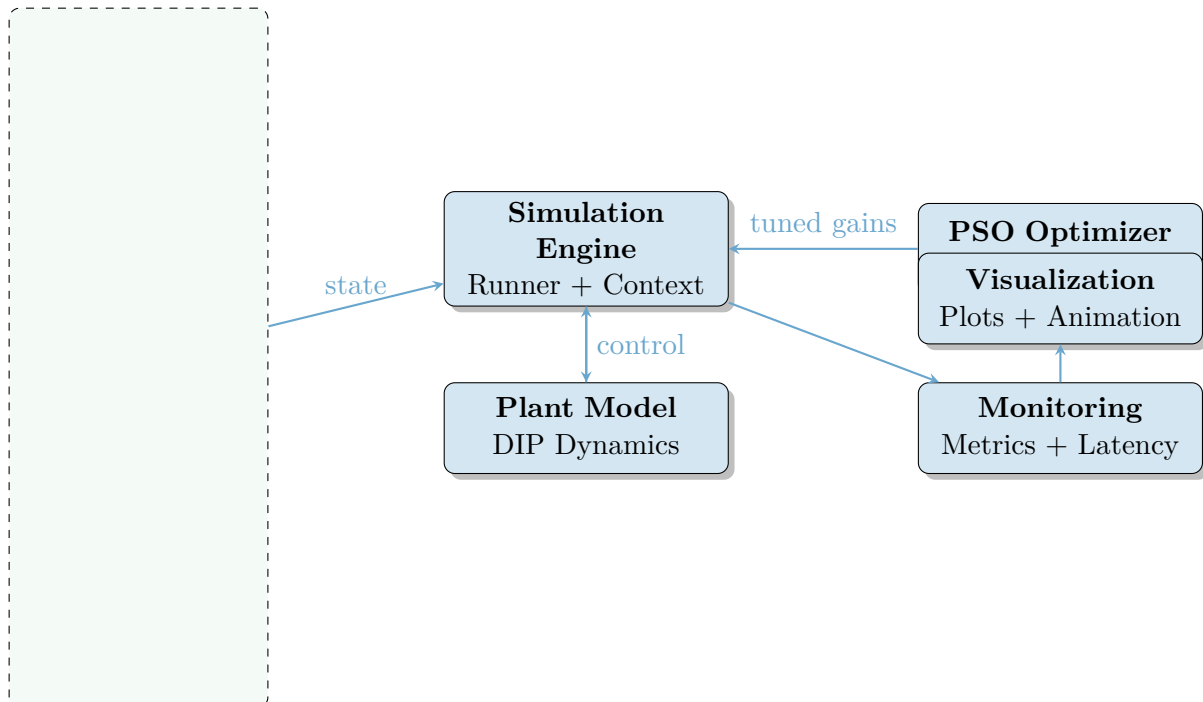
### Real-World Applications

🎯 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

#### Controller Factory



### 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)

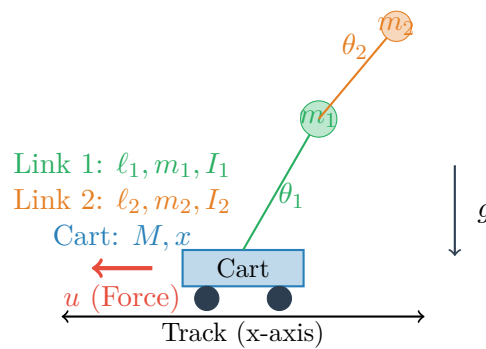
✔ **Swing-Up SMC** - Energy-based (starts from hanging position)

🧪 **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

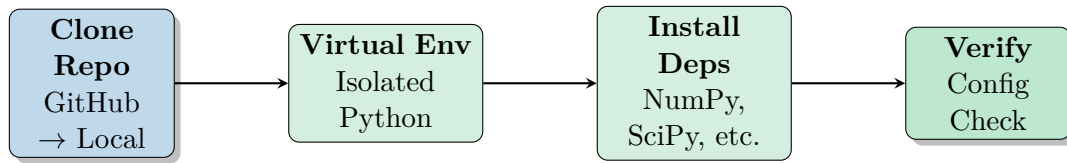
#### 🔗 Example

##### 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)



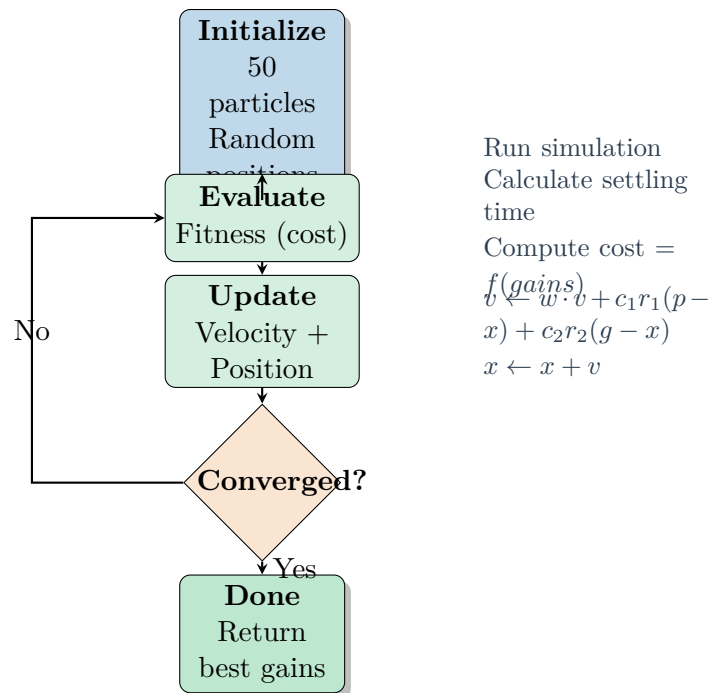
### Phase 2: First Experiments (30 minutes)

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

What to Look For:

- 0. 🎯 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
```

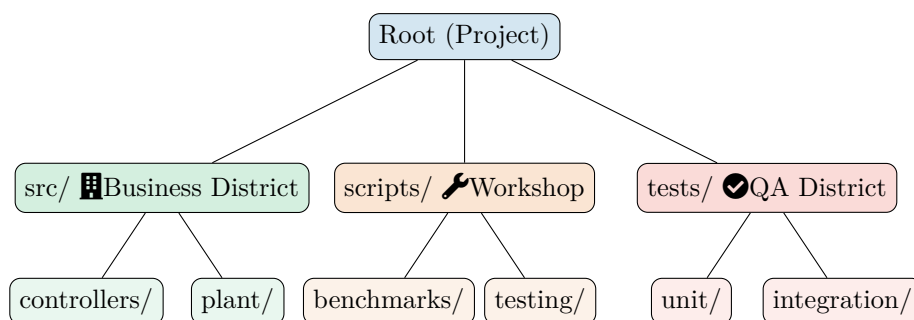
### PSO Optimization

```
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.