2025-11-01

E006: Analysis and Visualization Tools

From Gigabytes of Data to Publication Figures

Part 2 · Duration: 15-20 minutes

Beginner-Friendly Visual Study Guide

Learning Objective: Understand performance metrics, statistical validation (Monte Carlo, bootstrap), and visualization techniques for controller analysis

The Visualization Challenge

Key Concept

The Curation Problem: 2,400 simulations → 105 MB JSON → 15 MB HDF5 → **14 publication figures (7 MB)**

From gigabytes of computation to 7 MB of publication-ready insights

Each figure passed 15-item quality checklist, survived peer review, tells complete story

Three Challenges

Common Pitfall

enumi**Choosing representation**: Time series vs phase portraits vs frequency domain vs distributions

0. enumi**Avoiding misleading scales**: Y-axis at zero? Log vs linear?

0. enumi**Managing complexity**: 6 states + control + metrics + disturbances = overwhelming

Visualization is editorial - choices change interpretation!

Four Primary Performance Metrics

Controller Performance Metrics

0. enumi**Settling Time ($t_{\mathbf{settle}}$)**: How long until equilibrium?
   Min time where $|\theta_1| < \epsilon$ AND $|\theta_2| < \epsilon$ for all future t
0. enumi**Overshoot**: How far past equilibrium before settling?
   Overshoot $= \max(\theta) - \theta_{\text{desired}}$
0. enumi**Energy Consumption**: Total control effort
   $E = \int_0^T u^2 \, dt$ (lower is better)
0. enumi**Chattering Frequency**: High-frequency oscillations (via FFT)
   Sum of energy above 10 Hz cutoff (screech vs hum)

Why These Four?

Key Concept

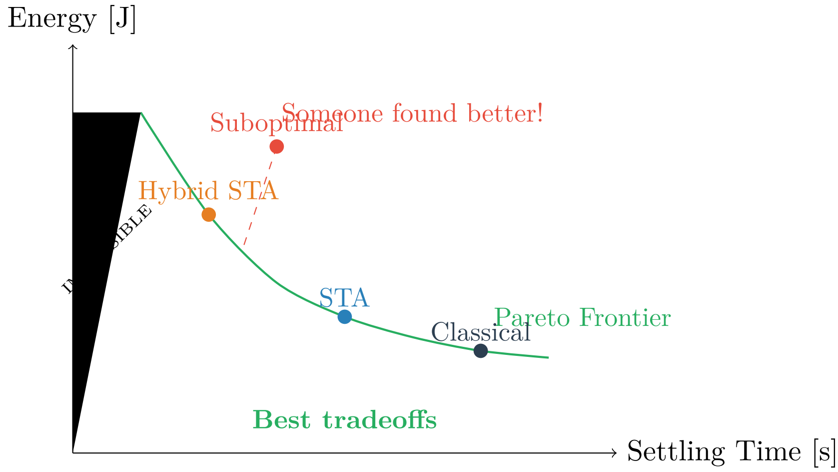
They capture **tradeoffs**:

0. Fast settling is good, BUT uses massive energy (wear out actuators!)

- Low chattering is good, BUT loses tracking accuracy (boundary layer smoothing)

A good controller balances all four!

Pareto Frontier: The "No Free Lunch" Line



Example

Interpretation:

- ON the frontier: Optimized (choose speed vs energy preference)
- BELOW frontier: Suboptimal (dominated by others)
- ABOVE frontier: Impossible (physics won't allow)

Figure 14 result: Hybrid Adaptive STA dominates the frontier!

Statistical Analysis: Monte Carlo & Bootstrap

Key Concept

Don't trust one simulation! Run 100 trials with randomized:

- Initial conditions
- Sensor noise
- Parameter uncertainty

Result: Distributions, not single numbers

Bootstrap: Shuffling the Deck

Example

The Card Shuffling Analogy:
You ran 100 real experiments (settling times). But maybe you got lucky?
Bootstrap asks: "What if you ran the experiment again tomorrow?"
Method:

enumiTake your 100 results (names in a hat)

0. enumiDraw 100 names randomly WITH REPLACEMENT (same name can appear multiple times)
0. enumiCreate "virtual" set of 100 results
0. enumiRepeat 10,000 times

Result: 10,000 "what-if" experiments simulated using only today's data!

Confidence Intervals

Bootstrap Confidence Interval

Classical SMC Example:

0. Mean settling time: 2.47 seconds

- Standard deviation: 0.08 seconds
- 95% confidence interval: [2.45, 2.55] seconds (via bootstrap)

Interpretation: If you ran 100 more trials, 95% chance the mean falls in [2.45, 2.55]

Why Bootstrap vs Standard Error?

Standard Error Formula (Stat 101):

- Assumes normal distribution (bell curve)
- Fast to compute
- ⚠ WRONG for skewed data!

Bootstrap (Modern stats):

- No distribution assumptions
- Handles skewed data (outliers!)
- Computationally intensive

Common Pitfall

Performance metrics are NOT normally distributed!
Settling time is skewed: Most trials settle at 2.5s, but outliers take 4-5s when hitting unlucky initial conditions.
Bootstrap handles real-world messiness correctly.

Comparing Controllers: Hypothesis Testing

Statistical Tests

Welch's t-test (2 controllers):

- Classical SMC: mean 2.5s
- STA-SMC: mean 2.1s
- p-value $< 0.001 \Rightarrow$ Less than 0.1% chance difference is random
- **Conclusion:** STA is significantly faster!

ANOVA (all 7 controllers):

- Tests whether ANY controller differs
- If significant $\Rightarrow$ pairwise comparisons with Bonferroni correction
- **Result:** Hybrid Adaptive STA ranks 1st, STA 2nd, Adaptive 3rd, Classical 4th

Effect Size: Practical Importance

Key Concept

Cohen's d: How many standard deviations apart are the means?

- $d = 0.2$ - Small effect
- $d = 0.5$ - Medium effect
- $d = 0.8$ - Large effect

Classical vs Hybrid Adaptive STA: $d = 2.5$ (HUGE effect!)
Not just statistically significant, but **practically important**

Real-Time Animation: DIPAnimator

Usage:

```
lstnumberanimator = DIPAnimator(
lstnumber     dt=0.01,
lstnumber     show_traces=True
lstnumber)
lstnumber
lstnumberwhile t < duration:
lstnumber     # Simulation step
lstnumber     animator.update(state)
lstnumber
lstnumberanimator.save('sim.mp4', fps=30)
```

Features:

- 30 FPS rendering
- Trajectory traces (pendulum tip path)
- Export to video (MP4)
- Visual debugging

Pro Tip

Tight spiral: Quick stabilization
Loops: Oscillations
Explosion: Controller failure

Chattering Analysis: Frequency Domain

Key Concept

Chattering = High-frequency oscillations
Sound analogy:

- Below 10 Hz: HUM (deep, steady rumble) - natural system response
- Above 10 Hz: SCREECH (high-pitched whine) - chattering waste

Measure: FFT (Fast Fourier Transform) → Power spectral density → Sum energy above 10 Hz

FFT Analysis Results

Chattering by Controller

Controller	Energy >10 Hz	Sound
Classical (no boundary)	45%	Loud screech
Classical ($\phi = 0.05$ rad)	8%	Faint whine
STA-SMC	2%	Nearly silent
Hybrid Adaptive STA	1.5%	Silent (best!)

Example

Physical Interpretation:
Pendulum natural frequency ≈ 5 Hz (hum of system responding)
Control should be below 10 Hz (matching natural rhythm)
Above 10 Hz = chattering (actuator screaming, but pendulum can't respond!)

Visualization Types

Time Series:

- State evolution over time
- Control signal trajectory
- Performance metrics

Phase Portraits:

- Position vs velocity

- Sliding surface behavior
- Reaching → Sliding → Chattering

Frequency Domain:

- FFT power spectral density
- Chattering quantification
- Hum vs screech analysis

Statistical Distributions:

- Histograms of metrics
- Box plots (median, quartiles)
- Violin plots (distribution shape)

Comparative:

- Bar charts (7 controllers)
- Pareto frontiers (tradeoffs)
- Heatmaps (parameter sensitivity)

Animation:

- Real-time pendulum motion
- Trajectory traces
- Video export (30 FPS)

The 14 Publication Figures

Key Concept

From hundreds of exploratory plots to 14 publication-ready figures
Each figure:

- Passed 15-item quality checklist
- Survived peer review by co-authors
- Tells complete story on its own
- Publication-ready formatting

Figure Categories

14-Figure Breakdown

System Architecture (2 figures):

- System diagram (7 controllers + plant + optimizer)
- DIP physical schematic

Performance Comparison (5 figures):

- Settling time bar chart (all 7 controllers)
- Energy consumption comparison
- Chattering frequency analysis (FFT)
- Time series overlay (Classical vs STA vs Hybrid)
- Phase portrait comparison

Optimization Results (4 figures):

- PSO convergence curves (cost vs iteration)
- Parameter sensitivity heatmap
- Pareto frontier (speed vs energy)
- Monte Carlo distributions (100 trials per controller)

Statistical Validation (3 figures):

- Bootstrap confidence intervals
- Effect size comparisons (Cohen's d)
- ANOVA results with pairwise tests

Quality Checklist (15 Items)

Quick Summary

Technical Accuracy:

enumiAxes labeled with units

0. enumiLegends clear and complete
0. enumiError bars/confidence intervals shown
0. enumiStatistical significance indicated

Visual Design:

0. enumiColorblind-friendly palette
0. enumiHigh-resolution (300 DPI for print)
0. enumiConsistent fonts/sizes
0. enumiNo clutter or overlapping text

Storytelling:

0. enumiCaption explains key insight
0. enumiFigure stands alone (no external context needed)
0. enumiComparison is fair (same scales, conditions)
0. enumiConclusion is obvious from visual inspection

Quick Reference: Visualization Workflow

Performance Metrics

`lstnumbermetrics = compute`$_metrics(times, states, controls, settling_threshold = 0.01) Returns :$
$settling_time, overshoot, energy, chattering_freq$

Statistical Analysis

`lstnumbermean, ci`$_lower, ci_upper = bootstrap_ci(data, n_bootstrap = 10000, alpha = 0.05)95$

Chattering Analysis

`lstnumberfreqs, psd = compute`$_psd(control_signal, dt) chattering = chattering_metric(freqs, psd, cutoff =$
$10) Energy above 10Hz cutoff$

Key Takeaways

Key Concept

Visualization is compression without loss of meaning:

0. 2,400 simulations → 14 figures (gigabytes → 7 MB)
- Each figure tells complete story

- Statistical rigor: Monte Carlo, bootstrap, hypothesis testing
- Practical insights: Pareto frontiers, effect sizes

Tools:

- DIPAnimator: Real-time visualization (30 FPS)
- FFT: Chattering quantification (hum vs screech)
- Bootstrap: Confidence intervals without assumptions
- Pareto frontier: Tradeoff visualization

What's Next?

Key Concept

E007: Testing & Quality Assurance - 250+ tests, coverage targets, property-based testing
Remember: Visualization reveals truth when done correctly. 14 figures distilled from gigabytes of data!