RESEARCH EVIDENCE / OCTOBER 2026

FARO vs PID ORACLE PHYSICAL R6 BENCHMARK

A deliberately PID-privileged physical comparison on RISC-V hardware. Practical parity in generalization; FARO advantage under degradation.

3 / 3	**5 / 6**	**5.08%**	**0.155%**
GENERALIZATION PROFILES WON BY EACH CONTROLLER	DEGRADATION PROFILES WON BY FARO	LOWER AGGREGATE DEGRADATION IAE FOR FARO	GENERALIZATION IAE DIFFERENCE; PRACTICAL PARITY

TESTS INCLUDED

1 / R6 generalization - 2 / R6 degradation - 3 / physical calibration and finite-bank PID Oracle selection

Prepared from the complete physical R6 record. No exclusions. No retries. PID Oracle gains frozen before scored execution.

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01 / EXECUTIVE RESULT

Parity in generalization. FARO advantage under degradation.

The two families answer different control questions and are reported separately. The protocol does not pool them into a single global winner.

35	70	22,512	225,120
PHYSICAL PAIRS COMPLETED	CONTROLLER RUNS	CONTROL DECISIONS	RAW ADC SAMPLES

Family	FARO aggregate IAE	PID Oracle aggregate IAE	Profile split	Interpretation
Generalization	183,590.04	183,305.64	3 - 3	PID Oracle lower by 0.155%; practical parity, not robust superiority.
Degradation	20,714.04	21,793.68	FARO 5 - 1	FARO lower by 5.080%; coherent advantage across primary and secondary metrics.

Why generalization is called practical parity

The IAE difference is only 284.40 count-seconds across six profiles. Profiles split 3-3, the descriptive sign result is p=1.0, and FARO recorded lower terminal RMSE and lower actuator variation.

Why degradation is a FARO result

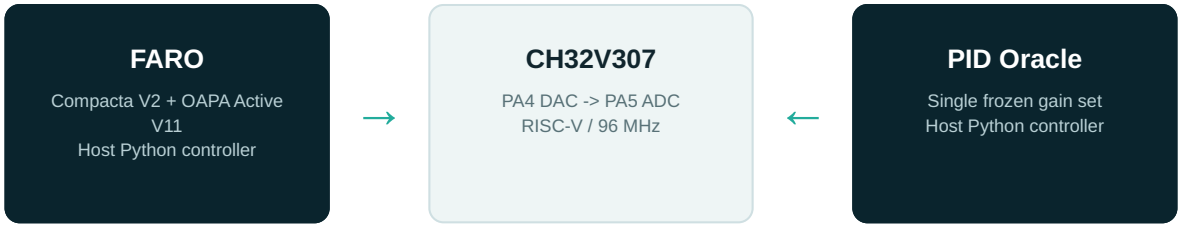
FARO reduced aggregate IAE by 1,079.64 count-seconds, won five of six profiles, reduced terminal RMSE by 60.49%, and reduced total DAC variation by 58.82%.

NO GLOBAL WINNER IS CERTIFIED. Generalization and degradation remain separate families. The evidence supports practical parity in one and a FARO advantage in the other.

02 / PHYSICAL BOUNDARY AND PROTOCOL

A physical loop, two host controllers, one declared metric.

Both controllers operated the same CH32V307VCT6 physical DAC-ADC loop. Controller code executed on the host; the MCU provided the measured physical boundary.



Preparation

4,416 physical decisions per controller across 23 jobs. OAPA was updated between preparation jobs, then frozen before scored profiles.

Evaluation

Six generalization profiles and six degradation profiles. Identical references, limits, order, chronology and ADC acquisition.

Primary metric

Nominal IAE = 0.12 x sum of absolute error using the raw post-action ADC median. Lower aggregate IAE wins each family.

Protocol property	Declared implementation
Attempts	One attempt per job; no local retry.
Selection	Every completed pair counts exactly once; timing warnings cannot remove or replace a result.
Acquisition	Five raw ADC samples before and five after every decision; raw UART bytes retained.
Transport boundary	OAPA model preserved; u_abs/current_y synchronized to DAC 2048 and transient history cleared at each run.
Retuning during scoring	None. OAPA model and PID gains were frozen before the 12 scored profiles.

PHYSICAL GATE PASS. Structural parity 30/30, ADC/DAC initialization PASS, electrical mismatches 8 / 0 / 14 counts against a 128-count limit, bridge gate PASS.

03 / PID ORACLE DEFINITION

The comparator was deliberately privileged.

The PID was not the fixed R6 baseline. It was selected before scoring from a finite preregistered search using physical calibration, exact future profiles and prior knowledge of the IAE objective.

1

Physical characterization

17 DAC levels in ascending and descending order, 240 ms settling at each level.

2

Finite-bank search

1,350 coarse combinations, deterministic local refinement, 2,001 unique nominal candidates.

3

Robust screening

40 candidates evaluated on nominal, ascending and descending plant variants.

4

Freeze before scoring

One gain set selected for both families and frozen before PREP_01.

Selected gains

Kp	Ki	Kd	Tf	Tt
0.50	3.15	0.12	0.12	0.12

Calibration quality

Center medians: 2048 / 2048 / 2048 / 2048 / 2048. Maximum directional hysteresis: 1 count. Maximum within-observation span: 18 counts.

- PID search used physical calibration.
- PID search knew IAE was the primary metric.
- Single gain set used for both families.
- PID search knew the 12 future R6 profiles.
- FARO did not receive the Oracle calibration.
- No retuning after physical scored results began.

INTERPRETATION LIMIT. “PID Oracle” means the best comparator found inside the declared finite bank and deterministic refinement. It is not the universal mathematical optimum. Information was intentionally asymmetric in PID's favor.

04 / TEST 1 - GENERALIZATION

Practical parity: 3 profiles each, 0.155% aggregate difference.

PID Oracle recorded the lower predeclared aggregate IAE by 284.40 count-seconds. The effect is small, the profile split is even, and secondary metrics favor FARO.

183,590.04	183,305.64	3 / 3	0.155%
FARO AGGREGATE IAE	PID ORACLE AGGREGATE IAE	PROFILES SPLIT EVENLY	SYMMETRIC DIFFERENCE

Profile	FARO IAE	PID Oracle IAE	Lower IAE	FARO symmetric advantage
G1_UP	22,917.00	22,936.08	FARO	+0.083%
G1_DOWN	22,849.08	22,827.36	PID ORACLE	-0.095%
G2_UP	31,522.68	31,537.68	FARO	+0.048%
G2_DOWN	31,656.60	31,473.12	PID ORACLE	-0.581%
G3_UP	37,263.36	37,321.32	FARO	+0.155%
G3_DOWN	37,381.32	37,210.08	PID ORACLE	-0.459%

Primary-metric reading

PID Oracle is the exact numerical IAE winner for this family. Because the difference is 0.155%, profiles split 3-3 and no formal significance is claimed, the engineering interpretation is practical parity.

Secondary-metric reading

FARO reduced terminal RMSE by 15.54% and total DAC variation by 3.18% relative to the PID Oracle.

Symmetric FARO advantage = 200 x (PID IAE - FARO IAE) / (PID IAE + FARO IAE). Positive values favor FARO; negative values favor PID Oracle.

05 / TEST 2 - DEGRADATION

FARO lower IAE in five of six degraded profiles.

Under sensor bias, quantization and actuator constraints, FARO recorded lower aggregate IAE, lower terminal error and substantially lower actuator movement.

20,714.04	21,793.68	5 / 6	5.08%
FARO AGGREGATE IAE	PID ORACLE AGGREGATE IAE	PROFILES WON BY FARO	LOWER AGGREGATE IAE

Profile	FARO IAE	PID Oracle IAE	Lower IAE	FARO symmetric advantage
D1_HIGH	4,559.16	4,862.40	FARO	+6.437%
D1_LOW	4,459.08	4,783.32	FARO	+7.016%
D2_HIGH	3,064.80	3,451.32	FARO	+11.864%
D2_LOW	3,133.68	3,146.16	FARO	+0.397%
D3_HIGH	2,707.20	2,809.92	FARO	+3.724%
D3_LOW	2,790.12	2,740.56	PID ORACLE	-1.792%

Primary result

FARO reduced aggregate IAE by 1,079.64 count-seconds and won D1_HIGH, D1_LOW, D2_HIGH, D2_LOW and D3_HIGH. PID Oracle won D3_LOW.

Effect coherence

The primary result is supported by 60.49% lower terminal RMSE and 58.82% lower total DAC variation.

BOUND ON THE CLAIM. Five of six profiles and a 5.08% aggregate effect are technically coherent, but six profiles are not enough for a broad formal significance claim. The result remains bounded to this physical R6 family.

06 / SECONDARY PERFORMANCE

FARO used less actuator movement and finished closer to target.

IAE remained the predeclared primary metric. Terminal RMSE and DAC variation are reported separately as supporting engineering measures.

Generalization

Mean tail RMSE



Total DAC variation



Reading

FARO's terminal RMSE was 15.54% lower and its actuator variation 3.18% lower, despite the PID Oracle's 0.155% aggregate IAE edge.

Degradation

Mean tail RMSE



Total DAC variation



Reading

FARO's terminal RMSE was 60.49% lower and its actuator variation 58.82% lower. The degradation result is not an IAE-only artifact.

CONTROL QUALITY, NOT JUST ACTIVITY. FARO's lower DAC variation was accompanied by lower terminal RMSE in both families. In degradation, it also coincided with lower aggregate IAE.

07 / AUDIT AND SOURCE IDENTITY

Complete counting, declared privileges, traceable artifacts.

The audit verified the full battery structure and absence of post-hoc exclusions. It did not perform a full independent controller replay.

PASS	0	0	8
STRUCTURAL AUDIT	EXCLUDED ATTEMPTS	RETRIES	TIMING-WARNING PAIRS; ALL COUNTED

Artifact	Identity
Runner	`95b9b1ac62641741c16d5df571e89a1e3b0f7b0380223b0bcdf9f4a48251f69f`
R3 dependency	`149af811461f578daaaaea034b292aa58c7eccb98d1698db7b721a2ae1130474`
Canonical R6 dependency	`651cab4df388bcf33ea47030e7e2e473e7864898eb580f07bc6d86c5db114968`
OAPA installer	`936ea3bb128e3b0a526d30aaf8f16ca2637329d3530a982b8c13714172c477d0`
OAPA wing	`23b4ff1d9f24d763f396154c609b22aa90a9dfbff79c16722af459a69e62d4c2`
Firmware source set	`eef70f8b609e88aa3cba6ac3adc6612f9a99223eec61fdcb5d8ba1d8485e9ce6`

What the audit confirms

35 pairs, 70 runs, 22,512 decisions, 225,120 samples, all completed pairs counted, no excluded attempts, no retries, and physical execution on the declared RISC-V boundary.

What remains outside this audit

The audit record declares full_controller_replay=false. Independent reproduction of every controller decision remains a separate verification step.

NOT THIRD-PARTY VALIDATION. The record is internally traceable and structurally audited. It does not replace independent external replication or application-specific qualification.

08 / INTERPRETATION AND NEXT EVIDENCE

A stronger comparator, a bounded conclusion.

This benchmark moves beyond a fixed PID baseline by granting the PID search physical calibration, future-profile knowledge and knowledge of the scoring metric.

SUPPORTED BY THIS TEST

FARO can perform at practical parity with a deliberately privileged PID Oracle in R6 generalization while using lower terminal error and lower actuator variation.

SUPPORTED BY THIS TEST

FARO outperformed the same PID Oracle under R6 degradation, with 5.08% lower aggregate IAE, five of six profile wins, lower terminal RMSE and lower actuator movement.

NOT SUPPORTED

Universal superiority over every PID, every tuning procedure, every plant or every industrial application.

NOT YET SUPPORTED

Adaptation to a physically mutating RC plant, continuous retuning inside the 120 ms loop, or independent third-party replication.

In a complete physical RISC-V R6 battery with no exclusions or retries, FARO reached practical parity with a deliberately PID-privileged Oracle in generalization - three profiles each and a 0.155% aggregate IAE difference - and outperformed it under degradation, with 5.08% lower aggregate IAE, five of six profile wins, lower terminal error and 58.82% less actuator variation.

Next benchmark stage

Physical mutant-plant RC testing, preserving the same truth-first rules: one attempt, every complete result counted, no exclusions, no retries, symmetric controller state and predeclared interpretation.

Publication status

Non-confidential technical evidence. The PID Oracle advantage and all methodological limits must remain visible in any public or investor-facing use.

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