Resonant Control

Real-Time Dissonance Feedback as a General Optimization Primitive

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Abstract

We introduce *Resonant Control*, an engineering pattern for optimization in which a global objective (or constraint violation field) is mapped to an *auditory* signal, and the solver is biased to "tune" toward consonance. We motivate the approach using protein folding as a canonical rugged, partially observed search problem and define a concrete sonification protocol that maps structure and constraint signals to pitch, detuning, and roughness. We present the *Marco Polo* algorithm: (Marco) attribute dissonance to the worst local contributor; (Polo) apply a targeted perturbation to reduce that contributor under a fixed compute budget. This draft is intentionally claim-hygienic: it specifies protocol, ablations, and falsifiers, but does not assert performance improvements without logged benchmark runs. The intended contribution is a reproducible control primitive and evaluation harness that can be tested on proteins, constraint satisfaction, and learning systems.

Contents

1 Reader Contract (Engineering Framing)

This paper stands or falls on measurable improvements under controlled conditions:

- **No mysticism**: audio is treated as an engineered observation channel for a compressed global error signal.
- **No cherry-picking**: all claims of "speedup" require preregistered metrics, seeds, and compute budgets.
- **Safety boundary**: no biological irradiation/"jamming" claims are made here; those belong to Paper 1's preregistered experimental registry.

2 Background

2.1 Optimization on rugged landscapes

Many scientific search problems exhibit high-dimensional rugged landscapes with abundant local minima (protein folding is a canonical example). Standard methods (simulated annealing, MCMC variants, heuristic local search) frequently struggle when the objective provides only weak global guidance.

2.2 Sonification: from visualization to control

Sonification has a long history as a *visualization* aid [2]. Resonant Control treats sonification as a *control interface*: the audio stream is not only human-interpretable but also provides a scalar/attribution signal that can bias an algorithmic optimizer.

2.3 Consonance, roughness, and critical bands

We adopt a psychoacoustic notion of consonance in which near-frequency components within critical bandwidths generate roughness/dissonance [1]. In practice, a computable proxy for roughness is used as an objective-shaped signal.

3 System Overview

3.1 Architecture (dataflow)

At each optimization step:

$$\text{state} \rightarrow \text{features} \rightarrow \text{audio parameters} \rightarrow \text{roughness metric} \rightarrow \text{bias/selection.}$$

The design goal is *replayability*: given a logged trajectory and mapping version, the audio and roughness metric are regenerated exactly.

3.2 Determinism and logging

All evaluations must log:

- RNG seeds and acceptance decisions,
- per-step objective terms (e.g., strain/contact components),

- the derived audio event stream (MIDI-like), and
- the derived roughness metric over time.

4 Sonification Protocol (Bio-Audio Mapping)

This section specifies a mapping that is *ablation-ready*: each component can be toggled independently for controlled comparisons.

4.1 Inputs

For a protein folding state S, define:

- backbone angles (ϕ_i, ψ_i) per residue i,
- a constraint/strain decomposition $\mathcal{J}(S) = \sum_k \mathcal{J}_k(S)$,
- optional secondary-structure labels (helix/sheet/coil).

4.2 Pitch mapping

We require a deterministic mapping from geometry to frequencies. Define a wrapped angle feature

$$\theta_i \;:=\; \mathrm{wrap}(\phi_i + \psi_i) \in [-\pi, \pi), \qquad u_i \;:=\; \frac{\theta_i + \pi}{2\pi} \in [0, 1).$$

Fix an integer rung range $[r_{\min}, r_{\max}] \subset \mathbb{Z}$ and define the pitch rung:

$$r_i \;:=\; \mathrm{round}\big(r_{\min} + u_i\,(r_{\max} - r_{\min})\big) \in \mathbb{Z}.$$

We support two *ablation-ready* pitch modes:

- **ET12 (control)**: $f_i = f_0 \cdot 2^{r_i/12}$ (equal temperament).
- **ϕ-rung (hypothesis)**: $f_i = f_0 \cdot \varphi^{r_i}$ (geometric ladder).

All parameters (including $f_0, r_{\min}, r_{\max}$ and mode) must be frozen in a machine-readable mapping artifact before reporting results; we use `docs/paper3_sonification_mapping_v0.json` as the v0 spec.

4.3 Detuning mapping

Map constraint violation to detuning:

$$\Delta f_i \;=\; g\big(\text{local violation at } i\big),$$

where g is monotone and capped to prevent pathological audio.

Concrete v0 choice (cents, bounded). Let $s_i \geq 0$ be a *local strain proxy* (e.g., a per-residue attribution of $\mathcal{J}$). Define a detune value in cents:

$$\Delta c_i \;:=\; c_{\max}\,\tanh\!\Big(\frac{s_i}{s_0}\Big),$$

and apply it multiplicatively:

$$f_i' \;=\; f_i \cdot 2^{\Delta c_i/1200}.$$

The purpose of detuning is *not* to be musically perfect; it is to create a smoothly varying dissonance signal proportional to constraint violation while remaining bounded.

4.4 Timbre and spatialization

Use timbre to encode coarse structure class and stereo position to encode residue index (left-to-right).

Polyphony cap (required). To avoid $\mathcal{O}(N^2)$ auditory clutter for long sequences, we cap polyphony at K notes by selecting the top-K residues under a declared selection rule (e.g., top-K by s_i). The cap K and selection rule are part of the frozen mapping artifact.

5 Consonance as Objective

5.1 Roughness metric

Define a computable roughness proxy $R(\text{audio}(S))$ inspired by critical-band interference [1] (and common pairwise roughness approximations [?]). The core hypothesis is engineering-only:

> If the audio mapping preserves enough structure, then R can serve as a *global* error proxy correlated with folding quality (e.g., RMSD/contact satisfaction).

Pairwise roughness proxy (v0). For a set of active notes $\{(f'_i, a_i)\}_{i=1}^{K}$ (frequency and amplitude), define

$$R := \sum_{1\le i<j\le K} a_i a_j \left(e^{-\alpha x_{ij}} - e^{-\beta x_{ij}}\right), \qquad x_{ij} := \frac{|f'_i - f'_j|}{B(\frac{f'_i+f'_j}{2})},$$

where $B(\cdot)$ is a critical-bandwidth proxy and $\alpha, \beta > 0$ are fixed constants. This yields a bounded, differentiable "roughness" score that increases when frequency components crowd within critical bands.

5.2 Empirical validation task

Given logged trajectories, test correlation between R and conventional folding metrics (RMSD/contact satisfaction) under preregistered evaluation.

6 The Marco Polo Algorithm

6.1 Marco: dissonance attribution

Compute a per-residue contribution r_i to overall roughness R. Under a pairwise roughness proxy, a natural attribution is:

$$r_i := \sum_{j\ne i} a_i a_j \left(e^{-\alpha x_{ij}} - e^{-\beta x_{ij}}\right),$$

so that $R = \frac{1}{2}\sum_i r_i$. Any alternative attribution (e.g., via ablations of individual notes or gradient-free sensitivity) must be declared and fixed for the benchmark suite.

6.2 Polo: targeted perturbation

Select $i^\star = \arg\max_i r_i$ and apply a targeted perturbation (e.g., proposal distribution biased toward residue $i^\star$), subject to the same acceptance mechanism and compute budget as baseline.

6.3 Baselines and ablations (required)

- baseline optimizer (no audio),
- audio mapping only (no attribution),
- attribution only (no audio shaping),
- audio + Marco Polo,
- anti-Marco control: random residue targeting with matched compute.

7 Experimental Design (Benchmarks and Fairness)

7.1 Benchmarks

The v2 plan targets a small benchmark suite (e.g., Trp-cage, Villin HP35, BBA5) with sufficient seeds (e.g., 20 per condition) and a fixed compute budget.

7.2 Primary endpoint

Primary endpoint (preregistered): median time-to-native at a declared RMSD threshold under fixed budget; report effect sizes and confidence intervals.

7.3 Failure conditions

Resonant Control is falsified (as an improvement) if it fails to outperform baselines under preregistered budgets and ablations, or if any apparent gain disappears under anti-Marco controls.

8 Reproducibility Package

This draft requires a reproducibility bundle before any performance claim:

- code version + mapping version (hash),
- benchmark manifest and seeds,
- logs sufficient to regenerate audio and plots,
- one-command reproduction instructions.

A Supplement: Mapping Specification Checklist

To make the mapping independently reproducible, freeze:

- angle-to-pitch quantization rule,
- violation-to-detuning function g and caps,
- roughness metric definition,
- MIDI schema + synthesizer/rendering parameters (sample rate, normalization).

References

[1] Reinier Plomp and Willem J. M. Levelt. Tonal consonance and critical bandwidth. *The Journal of the Acoustical Society of America*, 38(4):548–560, 1965.

[2] Thomas Hermann, Andy Hunt, and John G. Neuhoff, editors. *The Sonification Handbook*. Logos Verlag, 2011.