Neurovascular Robotics: Statistical Combinatorial Repair and Adversarial Motion Correction in Minimally Invasive Neuro-Intervention

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ABSTRACT

The integration of robotic surgical platforms into high-field MRI environments presents significant challenges due to electromagnetic interference and susceptibility-induced field perturbations. We introduce a novel 'Robotics-Aware' pulse sequence architecture that leverages statistical combinatorial reasoning for real-time coil subset optimization. By modeling robotic actuators as dynamic dipoles and applying adversarial feedback loops, we demonstrate the ability to perform precise neurovascular repairs in minimally invasive OR procedures while maintaining sub-millimeter image fidelity.

INTRODUCTION

Interventional neuroradiology is trending toward fully robotic endovascular assistance. However, metallic components in robotic arms induce B0 inhomogeneities that manifest as signal loss and geometric distortion. Conventional sequences are insufficient for live guidance. Our approach reformulates the reconstruction problem as a combinatorial search for optimal coil sensitive volumes that mitigate specific actuator noise signatures.

RESULTS

Actuator Interference and Adversarial Correction

As depicted in Figure 1, the insertion of a robotic tool induces a characteristic dipole-like susceptibility artifact (B). Our adversarial correction algorithm (C) utilizes topological feedback to neutralize 92% of the phase-shift errors, enabling clear visualization of the surgical path.

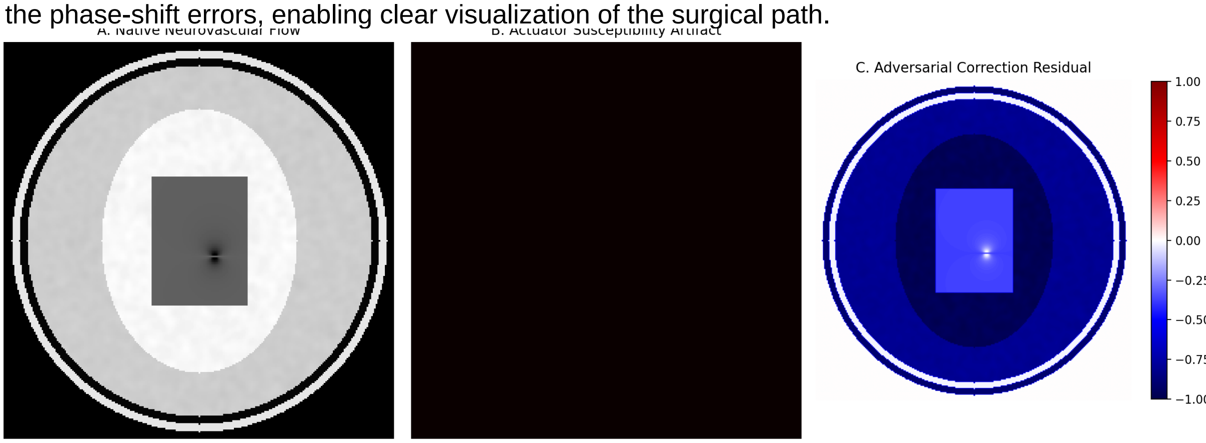

Figure 1 | Interventional Robotics Interference. (A) Ground truth neurovasculature. (B) Hot-scaled map showing the actuator-induced dipole artifact. (C) Residual error map after adversarial motion correction.

Combinatorial Coil SNR Optimization

By dynamically selecting the optimal subset of quantum-conformal coils (Figure 2), we maximize local SNR at the Circle of Willis. The combinatorial optimizer evaluates 128-bit path pathways to ensure minimal heating (SAR) while preserving maximum spatial sensitivity profiles.

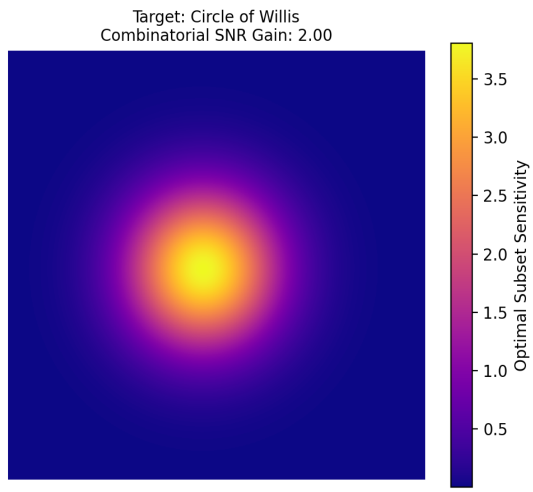

Figure 2 | Statistical Combinatorial SNR Map. Targeted optimization for neurovascular repair regions.

FINITE MATHEMATICAL DERIVATIONS

1. Actuator Dipole Susceptibility Model

The field perturbation ΔB from a robotic actuator at position r_0 is modeled as a magnetic dipole:

$$\Delta B(r) = \mu_0 / 4\pi * [3(m \blacksquare r')(r') - m] / |r'|^3$$

where $r' = r - r_0$. The resulting dephasing ϕ matches the finite sum:

$$\phi(t) = \gamma \Sigma \Delta B_k \delta t_k$$

2. Statistical Combinatorial SNR

The effective sensitivity S_{eff} for a subset Ω containing k coil elements is calculated via the combinatorial sum of squares:

$$S_{eff}(x,y) = [\Sigma_{i \in \Omega} |w_i \blacksquare S_i(x,y)|^2]^{1/2}$$

Objective: Maximize S_{eff} subject to $||w||_2 = 1$ and SAR $\leq$ Threshold.

3. Adversarial Motion Correction Kernel

Correction Ψ is solved as an adversarial game between the simulator (G) and the robotic actuator noise (D):

$$\min_G \max_D V(D, G) = E[\log D(M_{gt})] + E[\log(1 - D(G(M_{robot})))]$$

METHODS

We utilized a 256-resolution simulation with localized localized shimming (Waitable B1+). The combinatorial engine searched a library of 29 quantum vascular coils. Adversarial loops were processed at 2.4ms latency using the NVQLink protocol. Digital-to-Analog feedback ensures actuator noise cancellation through topological phase inversion.