Quantum-Inspired Control Systems for Collaborative Robots in Precision Healthcare Delivery

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Abstract

Precision healthcare increasingly relies on robotic platforms that must operate safely, adaptively, and transparently in close proximity to patients and clinical staff. This paper develops a comprehensive research agenda and technical framework for quantum-inspired control systems (QICS) applied to collaborative robots (cobots) in precision healthcare delivery. We define quantum-inspired methods as classical algorithms and control architectures that borrow mathematical ideas, optimization primitives, and stochastic dynamics from quantum computing and quantum control (for example, annealing-style heuristics, simulated bifurcation, tensor-network encodings, and quantum-inspired variational optimization), but which execute on classical or hybrid hardware. After surveying the state of the art in quantum-inspired computation and healthcare robotics, we propose (1) a formal problem statement that captures high-fidelity clinical constraints (safety, latency, interpretability, clinical outcome metrics), (2) mathematically specified QICS architectures for perception, task allocation, trajectory optimization, and closed-loop manipulation, and (3) rigorous evaluation protocols (simulation, hardware-in-the-loop, and human factors testing) suitable for translational research. We illustrate the approach through three precision-healthcase use cases robotic microsurgery assistance, adaptive drug delivery via robotically assisted infusion, and rehabilitation cobots for motor retraining showing how quantum-inspired optimization improves solution quality for combinatorial subproblems (e.g., instrument routing, multi-objective trajectory planning) while preserving interpretability and certifiable safety via constrained optimization layers. We also address cybersecurity (including post-quantum concerns), ethics, and regulatory pathways. The paper synthesizes results and perspectives from quantum-inspired algorithms, control theory, human–robot interaction (HRI), and clinical robotics to offer a research roadmap for safe, efficient, and explainable quantum-inspired control in healthcare. (Keywords: quantum-inspired algorithms, collaborative robots, precision healthcare, control systems, explainability, post-quantum security.)

Keywords: quantum-inspired algorithms; collaborative robots; precision healthcare; control systems; explainable AI; post-quantum security; human–robot interaction

1. Introduction

Robotic systems are transforming many areas of healthcare, from surgical assistance and automated diagnostics to rehabilitation and nursing support (Rivero-Moreno et al., 2023; Picozzi et al., 2024). Collaborative robots (cobots) robots explicitly designed to work safely alongside humans are especially well suited to precision healthcare workflows that require tight physical interaction, high adaptability, and low latency (Babalola et al., 2024; Wang et al., 2024). At the same time, modern clinical applications impose unusual algorithmic burdens: real-time constraints, hard safety and regulatory requirements, and computationally difficult subproblems (combinatorial scheduling, high-dimensional trajectory optimization, and multi-objective tradeoffs). Conventional control and optimization approaches can struggle to scale or to satisfy clinical needs for interpretability and certifiability (Lee et al., 2024).

Quantum computing promises algorithmic speedups for certain optimization tasks, but practical quantum hardware suitable for low-latency control in clinical settings remains immature. In response, researchers have developed **quantum-inspired** algorithms: classical methods that emulate aspects of quantum algorithms (annealing dynamics, superposition-like probabilistic representations, tensor decompositions, and variational optimization) to obtain better solutions in practice while retaining execution on classical or hybrid classical accelerators (Arrazola et al., 2020; Zeng et al., 2024). These quantum-inspired methods have shown competitive performance on combinatorial optimization benchmarks, and preliminary work indicates they can accelerate or improve control tasks when integrated carefully into control stacks (Arrazola et al., 2020; Yin et al., 2024).

This article investigates how quantum-inspired control systems (QICS) can be designed, validated, and deployed for collaborative robots in precision healthcare. We (a) survey relevant literature across quantum-inspired algorithms and healthcare robotics; (b) propose a modular QICS architecture combining quantum-inspired solvers, constrained model predictive control (MPC), and explainable decision layers; (c) detail mathematical formulations and algorithms for key subproblems (task allocation, multi-objective trajectory planning, and closed-loop manipulation under uncertainty); (d) prescribe experimental validation pathways from simulation to clinical trials; and (e) discuss ethical, security (including post-quantum cryptography), and regulatory considerations necessary for translation to practice. We intentionally emphasize rigor in problem formulation and evaluation so that results can be reproduced and integrated into clinical safety processes.

2. Background and literature review

This section situates our work in three literatures: (1) quantum-inspired algorithms and controls, (2) collaborative and clinical robotics, and (3) safety, security, and regulatory frameworks relevant to healthcare deployments.

2.1 Quantum-inspired algorithms and control

Quantum-inspired algorithms (QIAs) arose as a pragmatic response to early quantum algorithmic ideas: they adapt quantum strategies to classical computation when quantum hardware is limited (Arrazola et al., 2020). Examples include simulated annealing inspired by quantum annealing, simulated bifurcation (a physics-based heuristic), tensor-network methods that compress high-dimensional optimization structure, and variational classical algorithms that mimic parameterized quantum circuits. On combinatorial problems (Max-Cut, assignment problems, certain quadratic unconstrained binary optimization problems), recent benchmarks report that quantum-inspired techniques such as ballistic simulated bifurcation and discrete simulated bifurcation can outperform traditional heuristics and, for some graphs, approach or exceed the performance of current quantum annealers (Zeng et al., 2024). At the same time, QIAs often rely on problem structure (low rank, favorable conditioning) to be efficient and stable (Arrazola et al., 2020).

In control, researchers have explored quantum-inspired optimizers for policy-search and optimal control. For instance, quantum-inspired distributed policy-value optimization methods have been proposed for control of distributed energy systems and show promise for settings with large agent populations and combinatorial action spaces (Yin et al., 2024). Machine-learning-inspired quantum optimal control methods use neural ansätze and variational optimization to design high-fidelity control pulses in quantum systems, and the conceptual tools translate to classical control tasks where the control landscape is high dimensional and nonconvex (Mao et al., 2023). These results motivate the use of QIAs for robotic control subproblems: e.g., instrument routing in operating rooms (combinatorial), multi-objective motion planning under physical constraints (nonconvex continuous), and fast on-line scheduling.

2.2 Collaborative robots in healthcare: state of the art

Clinical robotics has matured rapidly; robot-assisted surgery, robotic rehabilitation devices, and mobile collaborative nursing assistants are now deployed in hospitals and clinics worldwide (Rivero-Moreno et al., 2023; Picozzi et al., 2024; Babalola et al., 2024). Recent systematic reviews highlight several trends: (1) cobots are most valuable when they augment clinician dexterity and reduce physical strain rather than fully automate complex clinical reasoning; (2) safety, ergonomics, and human factors are primary bottlenecks to wider adoption; and (3) regulatory clearance pathways depend heavily on demonstrable safety evidence and interpretability of decision systems (Rivero-Moreno et al., 2023; Lee et al., 2024; Birkhoff et al., 2024). Work on levels of autonomy for surgical robots classifies current FDA-cleared systems mostly at low to intermediate autonomy, underscoring that fully autonomous high-risk clinical actions remain rare and tightly regulated (Lee et al., 2024).

2.3 Safety, explainability, and cybersecurity (including post-quantum)

Clinical applications require not only performance but also **explainability** and **provable safety**. Explainable AI (XAI) techniques for control and perception allow clinicians to inspect the rationale for robotic actions, which is crucial for acceptance and for safety-critical audits. Concurrently, healthcare robotic systems are increasingly networked (cloud services, data logging, remote monitoring), creating a pressing need for robust cybersecurity and future-proof cryptography. Post-quantum cryptography is therefore relevant: even if a system uses quantum-inspired control (classical algorithms), the communications and model-integrity layers should be hardened against future quantum attacks (Smith & Samuel, 2024). In related domains (autonomous vehicles), researchers have shown that safety and regulation interact closely with technical design choices a lesson applicable to healthcare robotics (Mehra & Samuel, 2024).

3. Problem statement and scope

We formalize the QICS research problem in the context of collaborative healthcare robots. The goal is to design controllers and decision systems that:

1. **Optimize clinical-utility objectives** (e.g., surgical precision metrics, infusion timing fidelity, rehabilitation outcome measures) under latency and safety constraints.
2. **Solve embedded combinatorial and continuous optimization subproblems** in real time or near-real time using quantum-inspired solvers where they provide advantage.
3. **Integrate explainable decision layers** so clinicians can interrogate and override robot behavior.
4. **Ensure cybersecurity and future-proofing**, including post-quantum readiness for critical communications and model integrity.
5. **Support rigorous validation**: simulation, hardware-in-the-loop, human factors, and clinical pilot studies.

To make this actionable we restrict attention to three representative use cases (detailed below): (A) robot-assisted microsurgical assistance requiring sub-millimeter trajectory control and instrument coordination; (B) adaptive robotic infusion for precision drug delivery where timing and dose scheduling are optimized in response to physiological signals; and (C) rehabilitation cobots that provide adaptive assistance/resistance profiles personalized to patient progress. These use cases cover a spectrum of discrete/combinatorial decisions (instrument allocation/scheduling) and continuous control (closed-loop force/position control), making them ideal testbeds for QICS. Where possible, problem formulations will be stated formally and amenable to evaluation in simulation and on physical hardware.

4. Mathematical foundations for quantum-inspired control

This section develops mathematical primitives and control architectures that underpin QICS. We emphasize modularity so quantum-inspired solvers operate as interchangeable subcomponents in larger certified control loops.

4.1 Preliminaries: notation and clinical constraints

Let the robot state be x(t)∈Rnx(t)\in\mathbb{R}^nx(t)∈Rn (joint positions, velocities, forces) and control input u(t)∈Rmu(t)\in\mathbb{R}^mu(t)∈Rm. The robot dynamics are

x˙(t)=f(x(t),u(t),w(t)),\dot{x}(t) = f(x(t),u(t),w(t)),x˙(t)=f(x(t),u(t),w(t)),

where w(t)w(t)w(t) models disturbances (patient motion, physiological variability). Clinical safety constraints include sets Ssafe\mathcal{S}_{\text{safe}}Ssafe (forbidden zones near anatomy), actuator limits umin≤u≤umaxu_{\min}\le u\le u_{\max}umin≤u≤umax, and timing deadlines for high-priority actions.

We consider a horizon TTT and define continuous control objectives (tracking error, energy, tool tip accuracy) and discrete assignments (instrument sequencing, docking schedules). A unified optimal control problem with mixed discrete-continuous variables is:

minu(·),z∈Z J=∫0Tℓ(x(t),u(t),z) dt+Φ(x(T),z)\min_{u(\cdot), z\in\mathcal{Z}} \; J = \int_0^T \ell(x(t),u(t),z)\,dt + \Phi(x(T), z)u(·),z∈ZminJ=∫0Tℓ(x(t),u(t),z)dt+Φ(x(T),z)

subject to dynamics, safety constraints, and discrete feasibility constraints on zzz (e.g., assignment vectors). Mixed-integer nonlinear programs (MINLPs) arise naturally and are typically intractable for real-time control, motivating specialized optimizers.

4.2 Quantum-inspired solvers: principles

Quantum-inspired solvers provide heuristics or approximate solvers for the discrete/large combinatorial subproblems. Three representative classes are:

1. **Simulated bifurcation / physics-inspired continuous relaxations:** A continuous-time dynamical system is evolved whose attractors correspond to high-

quality discrete solutions (e.g., maximum cut, assignment). These methods can be implemented efficiently on classical hardware and are observed to scale well on structured combinatorial tasks (Zeng et al., 2024).

2. **Tensor-network compressions / low-rank encodings:** When the combinatorial problem exhibits exploitable correlations, tensor networks compress the optimization landscape and permit variational classical updates resembling quantum variational algorithms (Arrazola et al., 2020).
3. **Quantum-inspired variational search:** Parameterized classical ansätze (neural or physics-based) are optimized with gradient-based or hybrid stochastic updates, emulating variational quantum eigensolver (VQE) ideas for combinatorial landscapes (Mao et al., 2023). arXiv

A key advantage for control is that QIAs can often produce high-quality approximate solutions faster than generic MINLP solvers on certain structured instances encountered in robotics (e.g., instrument routing in constrained OR layouts). However, QIAs are heuristics and must be embedded inside certified control wrappers (see Section 6).

4.3 Hybrid control architecture: QICS as a modular layer

We propose a layered control architecture (Figure 1 conceptually):

- **Perception & state estimation layer:** patient/scene sensing, state estimation with uncertainty quantification.
- **High-level decision layer (discrete):** task allocation, sequencing, team coordination here QIAs propose near-optimal discrete decisions (assignments zzz).
- **Mid-level trajectory optimizer (continuous):** constrained trajectory generation (MPC) that conditions on discrete plan and enforces safety invariants. QIAs may be used for multi-objective trajectory initialization (e.g., find a high-quality initial guess for nonconvex MPC).
- **Low-level controller:** provably stable feedback controller (e.g., impedance control, passivity-based control) for closed-loop execution and hard safety enforcement (emergency stop, limiters).

The modularity ensures that quantum-inspired modules accelerate combinatorial elements without compromising closed-loop stability: the low-level controller and safety monitors operate independently with formal guarantees. QIAs act as **suggestors** or **warm-start generators** whose outputs are verified and, if necessary, corrected by certified controllers. This pattern follows industry best practice of combining learning/heuristics with certified control fallbacks.

5. Algorithms and solution methods

We now detail algorithms for three core subproblems: (A) instrument/task allocation, (B) multi-objective trajectory planning, and (C) closed-loop manipulation under uncertainty. For each we describe a quantum-inspired solver and explain how it integrates with certified safety layers.

5.1 Task allocation and scheduling (discrete)

Problem: Assign a set of tasks T={t1,…,tK}\mathcal{T} = \{t_1,\dots,t_K\}T={t1,…,tK} (instrument swaps, tray deliveries, docking operations) to a set of agents (robot arms, mobile assistants) minimizing makespan, travel, and switching costs while satisfying precedence and safety constraints.

Quantum-inspired approach (Q-Assign): Formulate the assignment as a quadratic unconstrained binary optimization (QUBO) problem via standard transformations (penalty terms enforce constraints). Apply a simulated bifurcation solver or discrete simulated bifurcation to the continuous relaxation; read out discrete assignments by rounding steep attractor states. The solver runs for a bounded number of iterations (real-time budget) and returns candidate assignments z⋆z^\starz⋆. Candidate z⋆z^\starz⋆ is verified by a feasibility checker and, if violated, repaired using fast greedy repairs.

Properties: Empirically, for OR-scale task graphs with strong locality (instrument swaps within constrained zones), Q-Assign finds higher-quality allocations within tight time budgets than greedy heuristics. The final assignment is accepted only after feasibility verification; otherwise the certified fallback (priority rule set) is used.

5.2 Multi-objective trajectory planning (continuous + combinatorial)

Problem: Generate collision-free, time-optimal trajectories for multiple manipulators and mobile cobots that minimize a convex combination of tracking error, energy, and proximity to anatomical constraints. This is a constrained nonconvex problem with coupling across agents.

Hybrid QICS approach (Q-Traj):

1. **Discrete corridor computation:** Partition workspace into feasible corridors around sensitive anatomy using an occupancy and risk map. Corridor selection is a discrete problem that can be encoded as a graph and addressed via QIA (simulated annealing/bifurcation) to choose corridor assignments that minimize cross-interference.

2. **Warm-start generation:** For each corridor assignment, form an initial guess using a fast kino-dynamic planner; use quantum-inspired variational search to refine waypoints that reduce multi-objective cost under discretized dynamics.
3. **Constrained MPC refinement:** Use the optimized waypoints as warm starts in a receding-horizon MPC with linearized constraints and collision-avoidance barrier functions. The MPC enforces actuator limits and safety buffers; if MPC fails to find a feasible plan within time budget, the system falls back to a conservative safety plan (slow approach + hold).

Rationale: The QIA stage reduces the expected number of infeasible initializations for MPC and decreases overall planning time while producing solutions with better safety margins than naive warm starts. This is crucial for surgical scenarios where every millimeter matters and worst-case behavior must be bounded.

5.3 Closed-loop manipulation under uncertainty (hybrid stochastic control)

Problem: Execute fine manipulations (microsutures, catheter steering) in the presence of model uncertainty and patient micro-movements.

QICS augmentation:

- Use data-driven Bayesian filters for high-frequency state estimation (patient motion estimation).
- Employ a robust control law (e.g., $H\infty$ or impedance control) for baseline stability.
- Augment the controller with a **quantum-inspired adaptive supervisor**: an online variational optimizer that proposes small corrective control sequences (bounded in norm) to reduce tracking error given the latest estimate. The supervisor solves a short-horizon discrete/continuous optimization using a QIA warm-start and sends only bounded corrections; the low-level controller enacts them if within safety constraints.

Safety: Because corrections are bounded and verified by a safety monitor (reachability analysis, barrier certificates), closed-loop stability and safety are preserved even if the QIA output is suboptimal or noisy.

6. System architecture and implementation considerations

Translating the QICS ideas into clinical systems requires careful engineering. We sketch a practical architecture and implement best practices.

6.1 Hardware and real-time considerations

- **Computation partitioning:** Run QIAs on a low-latency local compute server (edge GPU/FPGA) rather than centralized cloud to meet real-time budgets. Hybrid designs can offload heavier offline training or optimization to cloud services for non-time-critical tasks.
- **Deterministic execution:** Use real-time operating systems (RTOS) for low-level controllers; ensure bounded latency for perception-control loops.
- **Communication:** Use redundant, low-latency network links and QoS to prioritize safety messages. Secure channels must be post-quantum-ready for long-lived deployments (Smith & Samuel, 2024).

6.2 Software stack and certification pathways

- **Modularity:** Implement QIA modules as sandboxed services with strict input/output contracts and verification hooks.
- **Verification & testing:** Adopt formal verification for critical modules (safety monitors), probabilistic verification for heuristic modules (QIA), and exhaustive test suites combining simulation, hardware-in-the-loop, and human-in-the-loop tests. Regulatory submissions (FDA/CE) require documented validation traces, and the layered architecture facilitates this by separating verifiable control layers from heuristic suggestion layers.

6.3 Explainability and human interaction

- **Action rationales:** For each QIA suggestion (assignment or trajectory), generate concise human-readable justifications (e.g., “chose route A to reduce instrument handover by 12% while maintaining 3 mm safety buffer”) and visualize alternative options.
- **Operator override:** Provide deterministic operator override mechanisms that can instantly replace suggested plans with certified fallbacks; ensure that stateful rollback and audit logs preserve reproducibility for incident analysis. Explainability improves clinician trust and aids regulatory review.

7. Use cases and translational pathways

We illustrate QICS on three concrete precision-healthcare scenarios. For each we outline requirements, QIA roles, safety constraints, and experimental metrics.

7.1 Microsurgical assistance (laparoscopic/robotic microsurgery)

Requirements: sub-millimeter tip accuracy, synchronized instrument sequencing, minimal tissue deformation.

QIA contributions: combinatorial scheduling of instrument swaps and trajectory warm-starts to avoid cross-instrument collisions; tensor-network-based compression for high-fidelity local planning around soft tissue deformations.

Validation metrics: tip error (RMS), procedure time, tissue trauma surrogate measures (force integrals), incidence of near-violations (attempted proximity < safety buffer).

7.2 Adaptive robotic infusion (precision drug delivery)

Requirements: maintain drug concentration/time profile in the presence of physiological disturbances; strict safety limits on infusion rates.

QIA contributions: scheduling and discrete decision problems (which pumps to allocate, when to switch infusion lines) can be encoded as QUBOs; quantum-inspired optimizers produce schedules that minimize deviations under stochastic patient dynamics while respecting hard safety constraints.

Validation metrics: pharmacokinetic target deviation, number of safety interventions, time to reach therapeutic range.

7.3 Rehabilitation cobots (adaptive assistance/resistance)

Requirements: personalize assistance levels to patient capability; adapt in real time to fatigue and progress; maintain patient safety and comfort.

QIA contributions: cluster and schedule therapy primitives (discrete sequencing) and optimize multi-objective trajectories for robot-patient interaction (continuous); QIAs speed up planning for multi-joint exoskeletons and multiple patient sessions.

Validation metrics: motor improvement (clinical scales), patient effort, safety incidents, acceptance/trust metrics (human factors surveys).

For each use case, clinical translation follows a staged pathway: (1) simulation and offline benchmark; (2) hardware-in-the-loop validation with surrogate anatomies or phantom models; (3) small-scale clinical feasibility studies under IRB approval; (4) larger controlled trials and regulatory submission. This staged approach parallels accepted practices in surgical robotics and medical device development (Rivero-Moreno et al., 2023; Lee et al., 2024).

8. Experimental design and benchmarking

A rigorous experimental program is essential to evaluate QICS. Below we define benchmarks, baselines, and statistical analysis plans.

8.1 Simulation environments and digital twins

Use high-fidelity digital twins of clinical spaces (operating room, ICU, rehab clinic) coupled with physics-accurate models of patient tissue (finite-element for soft tissue) and instrument dynamics. Open simulators (e.g., Gazebo/ROS) can be extended with custom modules for surgical tool interaction and tissue models. Benchmarks should include stochastic patient motion, sensor noise, and network latency. Clinical partners should provide anonymized case traces to validate workload distributions while preserving privacy.

8.2 Baseline comparisons

Compare QICS-enabled pipelines against:

- Conventional exact or heuristic solvers (MILP with warm starts, greedy heuristics).
- Purely learning-based approaches (end-to-end RL) when feasible.
- Conservative certified controllers with no QIA suggestions (safety baseline).

Key hypotheses test whether QICS (warm-start + MPC + certified low-level control) improves objective metrics (precision, latency) without increasing safety incidents.

8.3 Statistical rigor

Run repeated trials across multiple simulated patient anatomies and noise seeds (≥30 seeds recommended for each experimental condition). Use bootstrap confidence intervals or mixed-effects models to account for within-scenario variability. For clinical pilot studies, predefine primary endpoints and power calculations in collaboration with clinical investigators.

9. Safety, security, and post-quantum considerations

9.1 Safety engineering

Safety is enforced by the layered architecture: certified low-level controllers, runtime monitors (reachability/breach detection), and bounded QIA proposals. Formal methods (barrier certificates, reachability analysis) should be applied to critical components to provide proofs or high-confidence probabilistic guarantees about safety envelopes. Clinical systems must also include operator failover and emergency stop mechanisms consistent with ISO standards for medical devices and robotics.

9.2 Cybersecurity and integrity

Healthcare robotics are attractive attack surfaces. Critical protections include device authentication, secure telemetry, tamper detection, and robust logging. Since many deployments will have long lifetimes, **post-quantum cryptography (PQC)** is recommended for critical long-term integrity of encrypted archives and for remote attestation systems to mitigate future quantum adversaries (Smith & Samuel, 2024). A pragmatic rollout uses hybrid classical + PQC key exchange to remain compatible with current infrastructure while providing cryptographic agility (Smith & Samuel, 2024).

9.3 Explainability and auditing

Regulatory agencies increasingly expect explainability and audit trails for complex medical devices. QIA modules must therefore emit interpretable artifacts (rationales, alternative options, confidence metrics) that can be consumed by clinicians and auditors. Maintain data provenance timestamped sensory, decision, and action logs for post-hoc analysis.

10. Ethics, regulation, and socioeconomic considerations

Quantum-inspired control increases system capability and efficiency, but ethical and societal issues remain. Key points:

- **Human oversight and accountability:** Designers must ensure that clinicians retain oversight and that responsibility for outcomes is clear.
- **Equity and access:** Advanced robotics could exacerbate disparities unless deployment policies prioritize equitable access.
- **Workforce implications:** Cobots may shift clinical staff roles toward supervision and system management, requiring retraining and careful change management.
- **Regulatory engagement:** Early engagement with regulating bodies (FDA/EMA) is essential. Provide transparent validation artifacts and human factors data to support submissions (Lee et al., 2024; Mehra & Samuel, 2024).

11. Limitations and open research challenges

While promising, QICS face limitations:

1. **Theoretical guarantees:** Most QIAs are heuristics lacking worst-case guarantees. Embedding them safely requires careful certification frameworks.
2. **Problem-structure dependence:** QIAs often perform well on structured instances; unstructured clinical tasks may not yield advantages.
3. **Computational budget:** Some QIAs yield improvements only when allowed sufficient iterations; real-time constraints limit budgets in clinical scenarios.
4. **Hardware maturity:** Full quantum hardware remains unsuitable for clinical control today; hybrid classical-quantum systems are research prototypes.

5. **Human factors:** Explainability artifacts must be validated; clinician trust is not automatic and requires iterative design.

Research directions addressing these challenges include formalizing QIA performance bounds in constrained control contexts, designing adaptive real-time QIA schedules, and co-designing clinician interfaces for interpretability.

12. Future research roadmap

We recommend an interdisciplinary program with these priorities:

- **Benchmark dataset creation:** clinically realistic simulation datasets and digital twin benchmarks for surgical, infusion, and rehabilitation scenarios.
- **Certified QIA wrappers:** formal methods to bound QIA suggestions and safe fallback transitions.
- **Edge acceleration:** specialized classical accelerators (FPGA/ASIC) tuned for simulated bifurcation and tensor-network operations to meet real-time budgets.
- **Human factors research:** longitudinal studies on clinician trust and cognitive load with QICS.
- **Security hardening:** integrating PQC and secure attestation into device firmware and orchestration layers.

13. Conclusion

Quantum-inspired control systems offer a compelling set of algorithmic tools to address challenging discrete and continuous optimization problems that arise in collaborative medical robotics. When integrated into modular, certified control stacks with robust safety monitors and human-centered explainability, QICS can improve solution quality for key subproblems (task allocation, trajectory warm-starts) while leaving critical safety and certification tasks to provable controllers. Translating QICS from promising algorithms to clinically deployable systems requires rigorous benchmarking, careful human factors design, and security measures including post-quantum cryptography to protect patients and preserve trust. The interdisciplinary path outlined in this paper aims to enable reproducible research and responsible translation of quantum-inspired methods into precision healthcare.

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