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A Multi-Domain Human-Centered Framework for Human-Robot Collaboration: Advancing Decision-Making, Situational Awareness, and Operational Efficiency

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Abstract

As the adoption of robotics becomes widespread and vital across diverse sectors and populations, such as industrial, military, medical, and emergency response domains, there is an even more pressing need to facilitate better and safer decisions and heighten operational oversight to ensure operational efficiency. This paper proposes a Human-Centered Framework for Human Robot Collaboration that considers collaboration on four distinct levels, namely operational, tactical, strategic, and institutional. From the bottom, we believe the operational level caters to real-time teamwork between people and robotic agents for a myriad of scenes across both indoor and outdoor scenarios. It also considers the various dynamics in terms of human-to-robot ratio on a collaborative level across these fields, such as factory assembly lines, military, and medical emergency units. The tactical level uses predictive and prescriptive algorithmic solutions that serve to adapt and adjust the levels of collaboration operationally from data insight, but also to provide tactical unit strategies that improve oversight capabilities on ongoing operations. The Strategic level takes the required data flows from these scenarios to provide direction to the various operations that occur at the operational. The strategic level also leverages real-time support from the tactical level for long-term planning. This also caters to system-wide adaptability and research and development to implement the policies from the institutional layer and enhance levels below it. Finally, the proposed apex of the hierarchy, the institutional layer, incorporates ethical and fairness guidelines, safety standards, and other forms of regulations to drive policy direction that trickles down and translates all lower layers to ensure sustainable and responsible HRC integration. By incorporating human-centered principles at all levels. This framework seeks to organize research and developmental efforts to improve operational efficiency holistically and enhance safety and adaptability across complex, evolving systems. Initial research ideas for future work are proposed based on this framework to validate and extend in the areas of Human-robot decision-making and critical cognitive conditions using cognitive and physical interface technologies.

Keywords
Human-Robot Collaboration (HRC), Human-Centered Framework, Situational Awareness, Decision-Making, and Collaborative Systems)

1. Introduction
Human-Robot Collaboration (HRC) has rapidly evolved from industrial automation toward complex, dynamic environments where flexibility, trust, and shared understanding are critical (Rodriguez-Guerra et al. 2021). Traditionally, HRC research focused heavily on optimizing robot autonomy. However, more recent trends emphasize human-centered HRC — positioning the human as an integral decision-maker rather than a passive supervisor (Heydaryan, 2018). Decision-making and situational awareness are foundational for effective teaming in uncertain environments. Endsley (1995) conceptualized situational awareness as "the perception of elements, comprehension of their meaning, and projection of their status in the near future," which has been widely applied to human-robot systems (Ajoudani, A et al., 2018). Recent HRC studies highlight how maintaining shared situational awareness improves mission success, decreases cognitive load, and supports adaptive decision-making (Hopko et al. 2022). Frameworks that neglect human decision support risk breakdowns in communication, increased errors, and reduced trust in robotic agents (Honig & Oron-Gilad 2018). Human-centered system design advocates embedding human cognitive capabilities, limitations, and preferences into the design process (Gasson, 2003). In HRC, this means creating interfaces, control systems, and robot behaviors that are intuitive, transparent, and adaptable to different skill levels (Eswaran et al. 2024). Key principles include: transparency in robot intentions and states (Hayes & Shah 2017); adaptive autonomy to match human needs dynamically (Dorais et al. 1999); and Real-time feedback mechanisms to preserve user engagement and control (Gupta, 2024). This paper presents a conceptual and architectural framework intended to guide future empirical validation and deployment studies in human-centered HRC systems.

Objectives for a New Framework
Given the increasing complexity and societal importance of HRC systems, a new HRC framework (Gervasi et al. 2020) is needed that prioritizes human cognitive needs at every interaction level, supports shared decision-making and real-time adaptability, and ensures ethical and regulatory considerations are built into system design from the outset. This paper addresses these needs by proposing a human-centered, multi-level HRC framework designed to enhance operational efficiency, safety, and human-robot teaming performance in dynamic, critical environments.

Novel Contributions
Unlike traditional HRC architectures that primarily focus on either operational execution or strategic autonomy, the proposed framework contributes a multi-domain human-centered structure that explicitly integrates situational awareness, adaptive decision-making, and institutional governance across four interconnected layers: operational, tactical, strategic, and institutional. The framework uniquely emphasizes continuous human cognitive involvement across all layers rather than limiting human participation to supervisory roles. Additionally, the framework extends prior layered HRC models by integrating adaptive autonomy, ethical governance, and cross-domain applicability within a unified architecture intended for dynamic and high-risk environments such as healthcare, defense, autonomous transportation, and emergency response.

2. Literature Review
Human-Robot Collaboration (HRC) has evolved beyond traditional industrial automation toward dynamic environments requiring flexibility, adaptability, and shared cognition (Mukherjee et al. 2022). Early HRC efforts

prioritized robot autonomy; recent trends emphasize human-centered collaboration, where humans actively engage in decision-making and dynamic teaming (Osa Arzuaga et al. 2024). Decision-making and situational awareness are critical in complex HRC systems. Endsley's (1995) model frames situational awareness (SA) as a three-stage process—perception, comprehension, and projection—which informs effective human-robot interactions. Maintaining shared situational awareness improves cognitive alignment between human and robot teammates, supporting faster, more accurate decisions, especially under stress (Gombolay et al. 2017). In HRC, poor situational awareness correlates strongly with higher error rates, trust breakdowns, and operational inefficiency (Hancock et al., 2011). Human-centered design integrates human abilities, limitations, and goals directly into system architectures (Gasson. 2003). Key features of successful human-centered HRC include transparency - robots explicitly communicate goals, actions, and constraints (Sado et al. 2023), adaptive Autonomy - robots dynamically adjust levels of control and assistance based on human needs (Khoramshahi & Billard 2019), and interactive feedback - continuous information exchange maintains engagement and optimizes performance (Żywiołek et al. 2025).

Layered Frameworks for Complex Systems

Layered control models are essential in robotics and human-machine systems to manage complexity (Faroni et al. 2020). Similarly, Cognitive Systems Engineering emphasizes layered human-system interaction, supporting better system adaptation to user behavior and cognitive states (Schuetz and Venkatesh 2020). The proposed multi-level framework naturally fits within these traditions while uniquely emphasizing decision-making and situational awareness across operational, tactical, strategic, and institutional levels. Layer control and interaction models are common in complex human-machine systems. For example, hierarchical control architectures in robotics separate low-level execution from high-level planning (Benito & Barrientos 2024). Similarly, Cognitive Systems Engineering (Woods & Roth 1988) introduced layered approaches to address human-machine interaction at different abstraction levels. The proposed framework aligns with and extends these traditions by explicitly integrating decision-making and situational awareness across operational, tactical, strategic, and institutional layers.

Gaps in Current Literature

Despite these advances, several gaps persist. Many HRC frameworks focus on either operational tasks or strategic planning but rarely integrate supervisory and policy levels. Few models explicitly embed dynamic decision-making and situational awareness across all system layers. Given that most real-world deployments still struggle with transferring laboratory insights into high-risk, critical applications (e.g., search and rescue (Delmerico et al, 2019), surgical robotics). The gaps can be summarized below as follows:

- Limited integration across operational, tactical, and strategic decision-making layers (Harrington & Ottenbacher, 2009).
- Insufficient emphasis on dynamic decision support and real-time situational awareness (Harper et al. 2023).
- Challenges translating laboratory HRC systems into unpredictable, real-world critical environments (e.g., search-and-rescue, combat zones, surgical suites) (Weber, 2023).

Comparison Table

Table 1. Comparisons of the proposed framework to previous frameworks

Framework	Human-Centered	Tactical Layer	Strategic Layer	Institutional Governance	Adaptive Autonomy	Situational Awareness
Traditional Layered Robotics	Partial	No	Yes	No	Limited	Limited
Cognitive Systems Engineering	Yes	Partial	Partial	No	No	Yes
Gervasi et al. (2020)	Yes	No	Partial	No	Partial	Partial
Proposed Framework	**Yes**	**Yes**	**Yes**	**Yes**	**Yes**	**Yes**

Comparative Analysis of Existing HRC Frameworks

Existing HRC frameworks largely focus on isolated dimensions of collaboration. For example, layered robotic architectures typically separate low-level execution from high-level planning but often lack explicit mechanisms for integrating human cognitive states into operational adaptation (Faroni et al. 2020). Human-centered frameworks such as Gervasi et al. (2020) evaluate collaboration effectiveness but provide limited guidance on institutional governance or long-term strategic adaptation. Similarly, cognitive systems engineering approaches emphasize human-system interaction but do not fully integrate real-time adaptive autonomy or cross-domain operational scalability.
In contrast, the proposed framework contributes:

- Explicit integration of situational awareness and decision-making across all collaboration layers.
- Inclusion of institutional and ethical governance as a functional system layer rather than an external constraint.
- Dynamic adaptability between humans and robotic agents based on operational conditions and cognitive requirements.
- Cross-domain scalability spanning manufacturing, healthcare, defense, autonomous vehicles, and emergency response systems.
- Integration of tactical supervisory intelligence between operational execution and strategic planning layers.

These distinctions position the framework as a more holistic human-centered architecture for complex HRC ecosystems operating in uncertain and dynamic environments.

Motivation for a New Framework

Addressing these gaps demands a human-centered, layered HRC framework (Gervasi et al. 2020) that: prioritizes human cognitive support and adaptability at every level, facilitates shared decision-making under time-critical and uncertain conditions, and embeds ethical, regulatory, and policy considerations into design and deployment.

3. Proposed Human Robot Collaboration Framework

The proposed human-centered framework for Human-Robot Collaboration (HRC) structures collaboration across four interconnected layers: operational, tactical, strategic, and institutional. These layers allow for the incorporation of human decision-making, situational awareness, and operational efficiency at each stage, ensuring that the human operator remains an integral part of the decision-making process, regardless of the complexity of the task (Table 1).

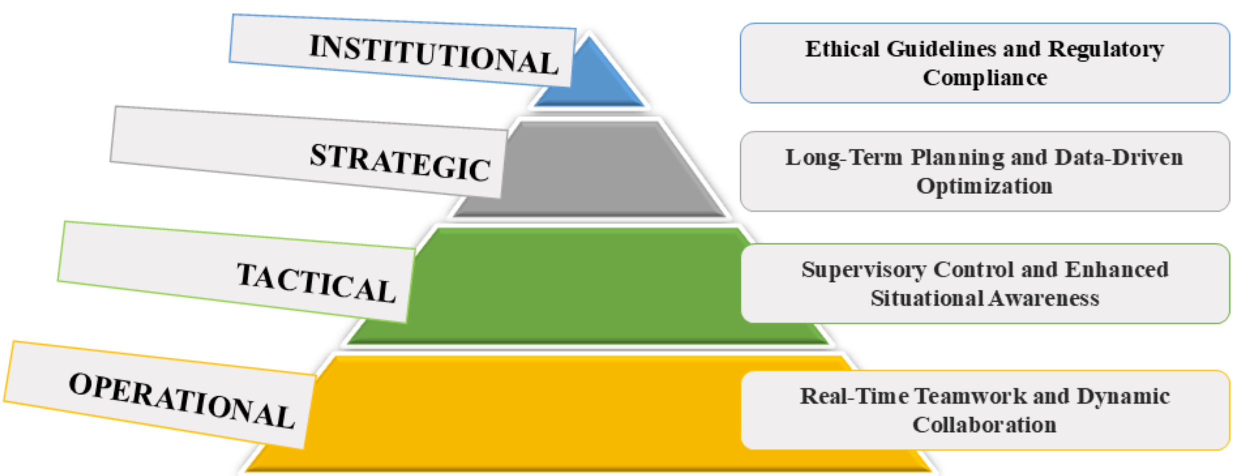

Figure 1. A Human-centered framework for Human-Robot collaboration: Advancing Decision-Making, Situational Awareness and Operational Efficiency

3.1. Operational Layer: Real-Time Teamwork and Dynamic Collaboration

At the operational level, the framework focuses on the immediate, real-time interactions between humans and robotic systems. This layer addresses situations where robots and humans work side by side, often in high-stakes environments such as assembly lines, surgical operations, or military operations. The key components at this layer include:

- **Human-Robot Interface (HRI):** The interface must be intuitive, supporting dynamic adjustments based on user expertise and the task at hand.
- **Real-Time Feedback:** Continuous updates on robot actions, state, and environment are provided to the human operator to ensure quick reaction times and task synchronization.
- **Adaptive Autonomy**: Robots must adjust their level of autonomy dynamically, depending on the cognitive load and performance of the human operator.

Key research areas at this level will involve tasks requiring high precision under stress, such as joint assembly in manufacturing or real-time patient monitoring during surgeries. Also, further studies for the incorporation of human-focused intelligence into robotic agents to allow for real-time adaptation to human gaps(Adamolekun et al, 2025).

3.2. Tactical Layer: Supervisory Control and Enhanced Situational Awareness

The tactical layer focuses on supervisory control and the enhancement of situational awareness through integrated sensor data, dashboards, and decision-support tools. This layer involves higher-level decision-making, where the human operator oversees multiple robots or robotic teams.

- **Interactive Dashboards**: Dashboards will aggregate data from sensors, cameras, and robotic systems, offering real-time status updates, alerts, and projections to improve the operator's awareness of the situation.
- **Sensor Integration**: Advanced sensors (e.g., cameras, LIDAR, force sensors) provide continuous feedback on both the robot's actions and its environment, enhancing situational awareness.
- **Collaborative Decision-Making**: The human operator oversees system-wide decision-making, focusing on adapting strategies as conditions change. Machine learning models may provide suggestions or predict optimal strategies.

This layer will be experimentally tested using collaborative tasks that require dynamic coordination between humans and robots, such as drone swarm control or coordinating multiple units in a robot search-and-rescue mission.

3.3. Strategic Layer: Long-Term Planning and Data-Driven Optimization

The strategic layer focuses on long-term planning, system-wide optimization, and research and development for continuous improvement. This layer involves decisions that shape the trajectory of the HRC system, including resource allocation, task prioritization, and performance evaluations.

- **Data Analytics:** Historical data, system logs, and performance metrics from the operational and tactical levels are analyzed to inform decision-making. Machine learning algorithms can detect patterns and provide predictive insights to optimize system performance.
- **System-Wide Optimization:** Decision-making involves strategic planning for system improvements, such as enhancing robot autonomy or optimizing human-robot task allocation.

Experiments at this level will focus on planning for high-complexity tasks that require long-term coordination and resource allocation, such as disaster response operations or large-scale manufacturing systems.

3.4. Institutional Layer: Ethical Guidelines and Regulatory Compliance

At the institutional level, the focus is on embedding ethical guidelines, safety standards, and regulatory compliance into the HRC system design and deployment.

- **Ethical Frameworks**: The system is designed to respect ethical principles such as fairness, transparency, and accountability, ensuring that decisions made by both humans and robots align with these values.
- **Safety and Compliance**: Standards for safety, data protection, and regulatory compliance are integrated into the system at every level to ensure that the deployment of robotic systems is safe and lawful.

- **Human-Centered Policies**: Policies governing the interaction between humans and robots must be developed to ensure that the deployment of robotic systems does not exploit or harm human workers.

This layer will be experimentally tested through compliance audits, ethical assessments, and the implementation of safety protocols in various real-world applications.

4. Applicability of Proposed Framework.

The proposed human-centered framework for Human-Robot Collaboration (HRC) has broad applicability across various domains and offers several potential pathways for further research and implementation. As industries and environments continue to evolve, the framework's adaptability and focus on decision-making, situational awareness, and human cognitive needs can significantly enhance operational efficiency, safety, and collaboration. Below, we explore the framework's potential applications and future directions for its implementation (Table 2).

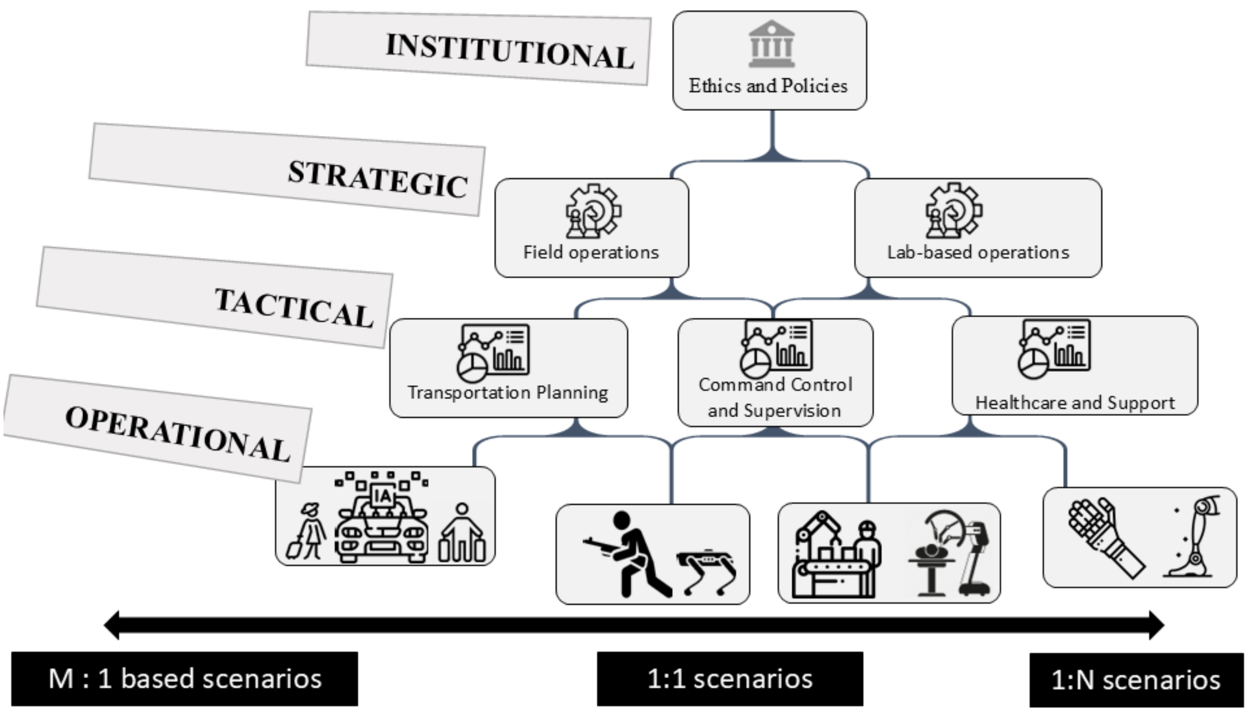

Figure 2. A Human-centered framework for Human-Robot collaboration: Advancing Decision-Making, Situational Awareness and Operational Efficiency Scenario-based separation

4.1.1. Industrial Automation and Manufacturing

In industrial settings, robots are already performing tasks such as assembly, material handling, and quality control (Rodriguez-Guerra et al. 2021). However, challenges remain in achieving seamless collaboration between human operators and robots, particularly in high-stress or dynamic situations. The proposed framework can optimize human-robot teamwork on the factory floor by enhancing decision-making through real-time data integration (e.g., sensor feedback on robot states and environments); improving situational awareness through interactive dashboards and augmented reality interfaces; and providing adaptive autonomy that adjusts robot behaviors based on the human operator's cognitive load and skill level(Alabi et al. 2025). Research could focus on team-based tasks where robots and humans work together on complex projects (e.g., automotive manufacturing) to study the dynamics of collaboration, error recovery, and adaptability. The development of more intuitive interfaces, including virtual or augmented reality, to enhance human understanding of robot behaviors, operational states, and predictive tasks (Al Boustani et al, 2021; Boud et al., 1999).

4.1.2. Healthcare and Medical Robotics
In medical settings, robotic systems are increasingly assisting surgeons, providing support in tasks such as surgery, diagnostics, and patient care. The human-centered framework is instrumental in improving medical robot deployment by enhancing surgeon decision-making through real-time feedback on patient conditions and robot performance, integrating situational awareness tools (e.g., real-time health metrics and robotic-assisted navigation systems) to support surgical teams in high-risk procedures. Trust and mental workload reduction can be improved by allowing surgeons to dynamically adjust robot autonomy according to task complexity (Harper et al.2023). Implementing the framework in surgical robotics, particularly for tasks requiring precision (e.g., minimally invasive surgery), to examine how situational awareness tools and adaptive autonomy affect outcomes and user satisfaction is important. Also exploring the role of robots in elderly care or rehabilitation, focusing on the development of non-intrusive, adaptive robots that support patients with varying levels of physical and cognitive abilities, is an area of potential research interest.

4.1.3 Military and Defense Applications
In defense, robots are used in scenarios such as bomb disposal, reconnaissance, and autonomous unmanned vehicles. The proposed framework addresses the complexities of decision-making and operational efficiency in high-pressure, high-risk environments by: enhancing mission planning and real-time coordination between human operators and robotic teams in battlefield environments; supporting situational awareness through data integration from multiple sources, including satellite imagery, ground sensors, and autonomous robots; and enabling adaptive autonomy where robots adjust their actions in response to shifting conditions on the ground(Barnes et al. 2013). Research focused on how human-robot teams can collaborate effectively in environments where mission parameters frequently change, emphasizing shared decision-making and role adaptation. Expanding the framework to include autonomous weapon systems, ensuring human oversight and decision support for ethical and legal considerations, is key.

4.1.4. Search and Rescue Operations
The proposed framework has significant potential in search and rescue (SAR) operations, where robots are deployed to locate victims, assess hazardous environments, and deliver aid. In such environments, human-robot collaboration is critical for efficient and safe operation. The framework enhances situational awareness by integrating real-time data from drones, robots, and environmental sensors. It also improves decision-making under stress by providing human operators with predictive models of victim locations or hazard zones and allows human operators to dynamically adjust robot behaviors based on real-time feedback from the environment (Gombolay et al.2023). Future research will focus on how robots and humans can adapt to rapidly changing environments, such as unstable building structures or dangerous weather conditions, while ensuring safety and mission success. Exploring multi-robot collaboration and coordination, where multiple robots work autonomously or in concert with human operators to cover larger areas in less time.

4.1.5. Autonomous Vehicles
In the context of autonomous vehicles (AVs), the human-centered framework can improve collaboration between drivers, operators, and self-driving systems. The framework can support human decision-making in critical moments when the vehicle is transitioning between autonomous and manual control (Alabi and Hayfron-Acquah, 2021). Enhance situational awareness by integrating sensor data and predictive models of road conditions, traffic, and obstacles. Ensure that the vehicle's autonomy level is adaptive, based on the cognitive load and situation of the human operator (Bied et al.2024). Testing the framework in semi-autonomous vehicles to develop systems that provide real-time decision support, particularly in critical situations like emergency braking or evasive maneuvers. Research will explore how fleets of autonomous vehicles can work together, with humans overseeing or coordinating operations for optimized traffic flow and safety.

4.2 Tactical Layer
The tactical layer serves as the nexus for human supervisory control in human-robot collaboration (HRC), enabling dynamic decision-making through integrated sensor data, interactive dashboards, and adaptive interfaces. In industrial settings, this layer allows supervisors to monitor and adjust robotic workflows in real time, such as rerouting autonomous forklifts during supply chain disruptions or recalibrating assembly-line robots to address defects. In military operations, it supports commanders in synthesizing battlefield data from drones and ground units to allocate resources or respond to emergent threats. Emergency response teams leverage tactical systems to coordinate robots in disaster zones—for example, prioritizing search-and-rescue areas based on live sensor feeds or environmental hazards.

Medical applications include robotic surgery teams, where surgeons use dashboards to track robotic assistants' actions and adjust plans based on real-time patient vitals. By unifying human intuition with machine precision, the tactical layer enhances situational awareness, mitigates cognitive overload, and ensures rapid, context-sensitive responses across high-stakes, fluid environments.

To advance the tactical layer's efficacy, research should prioritize context-aware AI interfaces that predict operator intent, such as adaptive dashboards that highlight critical data during medical emergencies or military crises (Barnes et al. 2013).. Developing interoperability standards to bridge disparate robotic systems (e.g., drones, exoskeletons, and autonomous vehicles) would enable seamless coordination in multi-agent operations like disaster recovery. Enhanced explainable AI tools are needed to clarify robotic decision logic for supervisors, fostering trust during time-sensitive tasks. Integrating biometric feedback (e.g., eye-tracking, stress sensors) could refine human-robot interaction by adapting robotic behavior to operators' cognitive states. Institutionally, frameworks for ethical oversight must address dual-use risks, such as militarized medical robots, while mixed-reality simulations could test tactical systems under edge-case scenarios like cyberattacks or sensor failures (Alabi and Ugboya, 2024). Finally, edge computing architecture should be optimized to reduce latency in data processing, ensuring real-time responsiveness. Collaborative efforts with policymakers and industry stakeholders will be critical to align these innovations with safety regulations and human-centered values, ensuring the tactical layer evolves as a resilient, adaptive pillar of HRC systems.

4.3 Strategic Layer

The strategic layer governs long-term planning and system-wide optimization in human-robot collaboration (HRC), aligning technological capabilities with organizational goals. In manufacturing, this layer enables predictive maintenance strategies by analyzing historical robotic performance data to minimize downtime and optimize production schedules. Healthcare systems leverage strategic frameworks to allocate robotic resources across hospitals, balancing surgical robot deployment with rehabilitation or telemedicine needs (Harper et al.2023). Military applications include multi-year research and development(R&D) roadmaps for autonomous systems, integrating battlefield analytics to forecast equipment requirements or hybrid human-robot force structures (Barnes et al. 2013). Supply chain networks use strategic HRC to model disruptions, such as rerouting global logistics fleets in response to geopolitical shifts or climate events. The layer also supports sustainability initiatives, for example, optimizing energy consumption in smart factories or reducing waste in agricultural robotics. By synthesizing cross-domain data and forecasting trends, the strategic layer ensures scalability, resilience, and alignment with institutional priorities, enabling organizations to adapt to evolving technological, economic, and regulatory landscapes.

Future research should prioritize explainable AI-driven analytics to demystify strategic decision-making, such as transparent models for predicting robotic workforce impacts in labor markets or environmental outcomes. Integrating quantum computing could accelerate large-scale optimization tasks, like simulating global supply chain resilience or energy-efficient smart city designs. Developing ethical foresight frameworks would address long-term societal risks, such as AI-driven job displacement or militarized robotics, ensuring strategic plans incorporate equity and accountability. Cross-domain collaborative platforms could unite stakeholders (e.g., policymakers, engineers, ethicists) to co-design robotics roadmaps for sectors like aging population care or climate disaster response. Enhanced resilience testing via digital twins or adversarial simulations would help stress-test strategic models against black-swan events, such as pandemics or cyberwarfare (Kibira et al 2023). Embedding sustainability metrics into HRC planning tools—like carbon footprint tracking for robotic fleets—could align innovation with climate goals. Finally, fostering public-private partnerships and interdisciplinary consortia will be critical to harmonize strategic HRC development with global standards, ensuring scalability without compromising human-centric values.

4.4 Ethical, Regulatory, and Policy Considerations

The institutional layer of the framework emphasizes ethical considerations, regulatory compliance, and safety standards, which are essential for the responsible deployment of robotic systems. This is especially critical in areas where robots interact closely with humans (e.g., healthcare, defense, manufacturing, aerospace). The framework ensures that the implementation of robotic systems adheres to established safety protocols, legal standards, and ethical guidelines. Continued work will focus on developing and refining policies that govern the ethical use of robots, particularly in areas like healthcare and defense, where privacy, safety, and accountability are paramount. Collaborating with regulatory bodies to establish industry standards for robot safety, transparency, and autonomy, ensuring that robots work in a manner that aligns with both societal values and technological advancements.

5. Conclusion
This paper proposed a multi-domain human-centered framework for Human-Robot Collaboration (HRC) that integrates operational execution, tactical supervisory control, strategic optimization, and institutional governance into a unified layered architecture. The framework contributes a structured approach for embedding human decision-making, situational awareness, adaptive autonomy, and ethical oversight across complex HRC environments.
Unlike existing frameworks that primarily emphasize either operational robotics or high-level planning independently, the proposed approach explicitly connects cognitive support mechanisms and institutional governance across all collaboration layers. The framework is designed to support scalable deployment in manufacturing, healthcare, autonomous transportation, defense, and search-and-rescue environments.

The present work remains primarily conceptual and serves as a foundational architecture for future empirical research. Current limitations include the absence of large-scale experimental validation and quantitative performance benchmarking across real-world deployments. Future work will focus on simulation-based and real-world validation studies involving adaptive autonomy, multi-agent coordination, human cognitive workload assessment, and situational awareness evaluation using standardized human factors metrics such as NASA-TLX and SAGAT techniques. Additional work will also investigate technology governance and resilience, ethical compliance mechanisms, and explainable AI integration for trustworthy HRC deployment. To practically validate the proposed multi-domain human-centered framework, a case study will be conducted using an extended-reality-enabled robotic English wheeling system that integrates a collaborative robot, force and position sensing, depth-camera-based deformation monitoring, and an XR interface for real-time operator guidance and feedback. Participants will complete a standardized sheet-metal-forming task under different levels of assistance, such as minimal assistance, basic robot support, and framework-supported adaptive guidance, using a repeated-measures design for variance analysis and significance testing.

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