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Modern Control System Architectures and Methods for Collaborative Manipulators

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INTRODUCTION & AIM

Robotics has become an integral part of industry, medicine, logistics, and services. Collaborative robots (cobots) can safely interact with humans in shared workspaces, combining human cognitive abilities with machine precision. The Human-Robot Collaboration (HRC) paradigm is a key direction of Industry 4.0. The effectiveness and reliability of collaborative manipulators depends primarily on their control system architecture, which coordinates motion, force, trajectory, and human interaction. This study analyzes modern control methods for collaborative manipulators and identifies effective architectural solutions, including impedance/admittance, sensor-based, AI-based, and hybrid control strategies.

METHOD

A systematic literature review was conducted covering HRC standards (ISO 10218, ISO/TS 15066) and key control strategies. Five main control approaches were analyzed and compared: (1) Impedance/Admittance Control — models force-displacement dynamics, enables safe flexible response; (2) Hybrid Force/Position Control — high precision, controls force and position on different axes; (3) Sensor- and Vision-Based Control — real-time adaptation via cameras and IMU; (4) AI-Based Control — fuzzy logic, neural networks, reinforcement learning for adaptive behavior; (5) Distance/Speed Control — ISO-compliant safety monitoring. Control architectures are classified as open-loop, closed-loop, human-in-the-loop, centralized, and distributed. The system operates at three levels: high-level (trajectory planning), mid-level (sensor fusion, adaptation), and low-level (joint control using PID/MPC/impedance algorithms).

RESULTS & DISCUSSION

Analysis shows that modern control systems evolve from classical position-based toward intelligent sensor-adaptive architectures. Impedance control stabilizes the system by regulating force effects via stiffness (K), damping (D), and inertia (M) parameters. Admittance control converts applied human force into natural motion. A hybrid admittance/impedance architecture combines both advantages, enabling precise force regulation, flexible response, and safe collision reaction. The proposed multi-sensor architecture integrates F/T sensors, joint encoders, IMU, camera, and LiDAR to estimate operator intent in real time. A safety supervisor (ISO 10218/15066 compliant) and an adaptive trajectory planning module operate in a unified real-time control loop. Key performance requirements: accuracy 0.1-0.5 mm, response time 10-50 ms, collision force limit ≤150 N. Human-in-the-loop and Distributed control approaches are identified as the most effective for safe and flexible HRC.

Table 1. Comparative Analysis of Control Approaches for Collaborative Manipulators

#	Control Method	Principle	Advantages	Limitations
1	Impedance/ Admittance Control	Models force-displacement dynamics between robot and environment	Natural response to human motion; Flexible reaction on collision; Widely used in HRC	Stability params hard to tune; Sensitive to external disturbances
2	Hybrid Force/ Position Control	Controls position on some axes, force on others simultaneously	High precision; Effective force control	Complex parameterization; Requires accurate model
3	Sensor & Vision-Based Control	Tracks operator motion via cameras and IMU; real-time adaptation	Improved safety & accuracy; Real-time adaptation	Depends on visual quality; High processing time
4	AI-Based Control (fuzzy, NN, RL)	Data-driven learning & adaptation of robot behavior	Adaptive in complex environments; Self-learning capability	Requires large datasets; Low interpretability
5	Distance/Speed Control	Monitors distance & speed per ISO standards	Simple and safe; Effective in industrial settings	Limited application scope; Does not interpret human intent

Table 2. Control Architecture Types for Collaborative Manipulators

Architecture Type	Description	Application
Open-Loop Control	Executes pre-set commands without sensor feedback	Simple motions, isolated environments
Closed-Loop Control	Control params updated in real-time based on sensor data	Core HRC approach □ safety & precision
Human-in-the-Loop	Integrates real-time human force, motion & proximity signals	Key principle in human-robot interaction
Centralized Control	All data processed in single central controller	Synchronous systems; higher latency risk
Distributed Control	Each module/sensor runs its own algorithm; data merged centrally	High reliability; low latency; ideal for multi-sensor HRC

CONCLUSIONS

The study analyzed modern control architectures for collaborative manipulators. A multi-level hybrid admittance/impedance control architecture with a safety supervisor and adaptive parameter module was proposed. This architecture ensures real-time adaptation to operator motion, precise force control, and safe HRC. The proposed system provides the scientific basis for next-generation cobot control in industrial, medical, and rehabilitation robotics. Future work will include MATLAB/Simulink modeling, followed by experimental validation on a physical prototype.

FUTURE WORK/ REFERENCES/ACKNOWLEDGMENT

Future Work: MATLAB/Simulink simulation of the proposed architecture; experimental validation on a physical manipulator platform; multi-sensor integration and safety module refinement.

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