From PID to Intelligent Control: Learning-Based Controller Design for Industrial Manipulators with Sensor Fusion

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Abstract. Modern production lines expect industrial manipulators to keep sub-millimetre accuracy and short cycle time while loads, friction, and ambient conditions change. This review examines practical control choices and how they interact with mechanical limits and perception. The survey covers peer-reviewed studies from 2021–2025 and two Chinese reviews with industrial relevance. The methods include structured screening of the controller series, proportional-integral-derivative baselines, adaptive and sliding mode designs, as well as reinforcement learning superposition, and evidence regarding structure-related bandwidth, stiffness, and clearance. There is also multi-sensor fusion for state and contact estimation. The analysis shows that most plants retain a stable inner loop, add feed-forward and simple observers, introduce adaptive or robust layers when uncertainty grows, and place learning above the stabilising loop where parts and scenes vary. Perception improves global alignment and contact safety but requires clear latency budgeting. The review provides scenario-level recommendations that balance accuracy, cycle time, and availability.

Keywords: Industrial manipulators; control algorithms; multi-sensor fusion; latency budgeting; fault diagnosis.

1. Introduction

Industrial manipulators now work in cells where tools, loads, and parts change during a shift. Plants still expect short cycle time and sub-millimetre accuracy. That mix creates a practical problem: a controller must stabilise coupled, nonlinear joints and also tolerate friction drift, payload variation, backlash, and temperature effects. Recent surveys describe how factories handle this pressure with a layered approach that connects control design, the arm's structure, and the perception stack.

At the controller level, the baseline in many lines remains proportional–integral–derivative (PID) control because it is transparent and easy to tune in industrial toolchains. Reviews report that much of the practical accuracy gain comes from engineering around this inner loop, for example gravity and friction feed-forward or observer-based estimation. When uncertainty grows, plants adopt model-reference adaptive control (MRAC) or sliding-mode control (SMC) variants to keep errors small under payload and friction changes. Learning methods enter where variability is high: reinforcement learning (RL) policies trained in simulation are combined with a stabilising classical loop, rather than replacing it outright. This pattern shows up across recent comparative articles and case studies.

The arm's mechanical limits set the bandwidth ceiling that any controller can reach. Degrees of freedom (DOF) bring dexterity but also singularities, inertia coupling, and numerical burdens in redundancy resolution; stiffness loss and transmission backlash reduce the usable closed-loop bandwidth and inflate tip error. Trend papers highlight these structural constraints and their impact on real-time budgets in higher-DOF cells, especially on legacy programmable logic controller (PLC) platforms.

Perception closes the loop at the cell level. Vision provides global pose; encoders and an inertial measurement unit (IMU) supply high-rate local state; force/torque signals enable safe contact behaviour. Multi-sensor fusion with the extended Kalman filter (EKF) or unscented Kalman filter (UKF) improves state or joint-torque estimates without adding sensors to every joint. A recent implementation shows UKF-based, sensorless joint-torque estimation that supports contact control on articulated arms. Survey articles also group "sensor integration and real-time perception" as a distinct theme and point out gaps in scalability and standardisation, which motivates explicit latency budgeting in software architectures.

Faults and wear change the plant over time. Reviews on fault diagnosis and fault-tolerant control describe pipelines that monitor motor current, vibration, and temperature, and they discuss digital-twin or machine-learning diagnostics for predictive maintenance. Taxonomies of manipulator faults underline common failure modes and the value of graceful degradation, such as safe gain updates or reduced-speed modes, to preserve availability.

This article synthesises peer-reviewed work published from 2021 to 2025 that reports controllers or fusion methods deployable on real hardware and those states constraints relevant to the shop floor. The coverage includes PID baselines and their engineering add-ons; MRAC and SMC families; RL layered above a stabilising inner loop, occasionally with a linear–quadratic regulator (LQR) at low level; structure–bandwidth links involving DOF, stiffness, and backlash; and fusion pipelines for vision, IMU, and force/torque sensing.

This article organizes its content around three core technical modules and scenario-driven recommendations. Section 2 reviews controller families and their deployment logic on the line. Section 3 summarises how structure limits and calibration shape achievable accuracy. Section 4 outlines perception–control integration and the need for a clear latency budget. Section 5 compiles scenario-level recommendations that balance accuracy, cycle time, and availability, based only on evidence in the cited literature.

2. Industrial Manipulator Control Algorithms: Evolution and State of the Art

2.1.Classical PID Control

PID stays the baseline because it is simple to tune and well supported in PLC toolchains. Plants pair an outer position loop with an inner velocity or torque loop. They add anti-windup and derivative filters. On rigid and calibrated arms, this meets many jobs. Problems show up with friction, payload swings, or flexible links, where overshoot rises and the loop settles slowly. Reviews explain that most real gains still come from engineering around PID: gravity and friction feed-forward, simple observers, and operating-point gain scheduling, while the inner PID remains [1, 2]. For cells that see faults, the PID + observer stack is also easier to diagnose and to recover than heavy model-based controllers [3].

2.2.Modern Adaptive and Fuzzy Logic Control

Adaptive control provides a suitable solution for robotic manipulators operating in environments where parameters are unknown or vary over time. One key advantage of this approach is its ability to automatically adjust control parameters in real-time, thus maintaining system performance even in the face of changes. Another related issue is that during highly dynamic tasks, the convergence time of the adaptive algorithm may limit its practicality in scenarios that require an immediate response. [1].

Adaptive/Neural Sliding-Mode Control (ASMC) starts from a robust SMC core and adds parameter adaptation or a neural approximator. This keeps robustness and reduces chattering. Results on cylindrical or serial arms show accurate tracking under disturbances, with care to avoid exciting flexible modes and to stay within compute budgets [1, 4].

Fuzzy-PID encodes operator rules. It helps when friction or backlash is hard to model. Plants accept the extra work of maintaining the rule base only when variants are many and models are weak [1].

2.3.Intelligent (Data-Driven) Control

Plants turn to data-driven control for warehouse pick-and-place. Policies are trained in simulation (MATLAB/RobotStudio) and evaluated on the task, often combined with a classical controller (e.g., LQR) to keep a stable low-level loop. In this setting, the hybrid RL + LQR scheme improves tracking accuracy and cycle measures compared with baseline geometric/DH approaches [5]. Model-based learning integrates learned system dynamics or active inference prediction tools into torque control. This lets the control loop flexibly handle unmodeled influences without disrupting its original stable structure [6]. Across reports, teams layer learning around classical loops, rather than replacing them [1].

3. Mechanical Structure and Control Implications

3.1.DOF Trade-offs and Bandwidth Needs

Degrees of freedom set dexterity and the burden on control. Two- to four-axis mechanisms suit planar dispensing or fast sorting and run with modest servo rates. Six-axis arms add redundancy for precise assembly, and they also bring singularities, inertia coupling, and null-space coordination. Reviews also note stiffness limits and accuracy loss near singular configurations, which make controller design and numerical handling more demanding on legacy PLCs [2].

3.2.Stiffness, Backlash and Error Propagation

Structural stiffness sets a ceiling for loop bandwidth. Small stiffness losses cause slower settling and greater tip error, and backlash boosts Cartesian variance if not compensated. Plants address these problems with offline calibration, such as laser trackers and DH identification, and online estimation during production [7]. UKF/observer-based joint-torque estimation can detect compliance and load effects without adding torque sensors to every joint [8]. Space-manipulator practice shows the same integration logic under higher safety demands, where sensing, planning, and control are designed together because the mission cannot tolerate failure [9]. For flexible cells that integrate a mobile base and a fixed arm, the proposed two-stage fusion method can sustain frame consistency during movement and minimize alignment errors, and this effect has been verified through experiments [10].

4. Perception–Control Integration

4.1.Multi-Sensor Fusion to Close the Loop

In the sensor fusion framework for joint-torque sensorless humanoid robots, multi-sensor fusion serves as the core to close the control loop. The system integrates signals from diverse sensors: joint encoders and IMUs provide high-rate joint state data (including position, velocity, and acceleration) to capture real-time dynamic changes of the robot; force/torque (FT) sensors monitor contact interactions with the environment to obtain contact force and torque information; motor current sensors offer data related to motor torque. These multi-source signals are fused through an UKF pipeline, which estimates key states such as external contact forces, friction torques, and motor torques, and further derives joint torques using the relationship between motor torque, friction torque, and gear ratio. This closed-loop process, driven by multi-sensor fusion, enables the robot to achieve precise torque tracking and stable manipulation without installing torque sensors on every joint [8]. In mixed mobile–fixed cells, multi-sensor fusion is the core to close the control loop, with a two-stage strategy. The first stage uses vision-based positioning (ArUco marker detection) to get high-accuracy object pose and frame alignment for stable initial positioning. The second stage fuses IMU and ultrasonic signals via EKF to compensate for ultrasonic limitations and suppress outliers. This two-stage fusion corrects positioning deviations during motion, maintains consistent coordinate frames between the mobile robot and the fixed manipulator, and closes the loop for real-time accurate positioning, ensuring the manipulator reliably tracks the mobile robot [10]. Surveys of industrial deployments report a better grasp of robustness when force/tactile is fused with vision [11]. Chinese manufacturing surveys describe the same trend and report factory cases where fused sensing reduced re-grasp and manual rework [7].

4.2.Real-Time Architecture and Latency Budgeting

Perception in the loop needs a clear latency budget. Reports converge on a layered design. Deterministic cores run the time-critical servo tasks. Best-effort cores run vision and planning. Recent reviews group “sensor integration and real-time perception” as a distinct research cluster and note scalability and standardization gaps, which motivate layered software designs and careful timing analysis [11]. The variable delays generated by drivers or networks in the factory can be controlled through adaptive estimation and compensation methods to maintain the tracking effect of the robotic arm, which is consistent with the view in the fault-tolerance review. The document also verifies the effectiveness of this technology through experiments. For example, when the driver delay increases, the adaptive method can still keep the root mean square error at a low level [12].

4.3.Error Modelling, Compensation and Fault Tolerance

To maintain the long-term accuracy of robotic manipulators, observers and diagnostic technologies are essential. Disturbance observers inject torque or current offsets to counteract errors caused by friction or gravity drift. Meanwhile, digital twin and machine learning diagnostics detect component wear and trigger safe gain updates or schedule adjustments before product quality is compromised [12]. Active inference torque control adds a prediction layer and reduces manual readjustment when the dynamics change [6]. Fault surveys list common failure modes and the signals used in practice, which supports the choice of observers and alarms in the cell [3].

5. Scenario-Driven Recommendations

A clean joint-level PID loop remains a practical baseline in assembly cells. Reviews note that much of the achievable gain in accuracy comes from engineering around the PID core, such as gravity and friction feed-forward and other simple enhancements, rather than replacing the inner loop. For arms without dedicated joint-torque sensors, UKF-based torque estimation demonstrates effective contact handling and compensation, which is useful for precise placement and compliant wrists. Periodic geometric or camera-based calibration helps keep frames consistent as fixtures and temperature change [1, 8].

When tools and loads change, fixed gains tend to drift away from the plant. Surveys describe MRAC as effective for reducing steady errors under payload variation, while also noting sensitivity to excitation and delay. Adaptive or neural sliding-mode designs offer robustness to disturbances, with attention to chattering and computational cost. In high-throughput, higher-DOF cells, trend papers emphasise budgeting compute for higher update rates and safe handling near singularities [1, 2, 4].

Stable hand-off depends on consistent frames and tolerant state estimation. A two-stage fusion pattern is reported: visual markers provide global pose when available; when vision is occluded, an EKF fuses IMU and range/odometry to maintain a high-rate local state. This switching design improves cooperation between a mobile base and a fixed manipulator without relying on heavy additional hardware [8, 10].

Approach and pose correction are handled by vision, while contact is controlled by force-limited behaviour in an impedance/admittance framework. Reviews of industrial deployments highlight that fusing vision with force/tactile sensing reduces re-grasp events and rework in less structured scenes. Joint-torque estimation with UKF provides an alternative to per-joint torque sensors and supports compliant motion under contact [8, 11].

Data-driven control becomes attractive when SKUs and scenes vary. A reported pattern is to train a reinforcement-learning policy in simulation and then pair it with a conventional stabilising controller, such as LQR or a PID-like low-level loop, during task execution. Experiments show improved tracking and pick performance compared with baseline geometric control, while the stabilising inner loop preserves safety and diagnosability [1, 5].

Long-run operation benefits from combining observer-based compensation for slow drifts with condition monitoring on the side. Fault reviews describe diagnostic frameworks that use current, vibration, temperature and other signals, and they discuss digital-twin or ML methods for predictive maintenance. When indicators degrade, systems can switch to safer gains or reduced-speed modes and retain a clear path back to a simple gain-scheduled PID for recovery [3, 12].

6. Conclusion

This review shows a stable pattern in modern cells. Teams begin with a clean PID inner loop, keep anti-windup and filtering, and add gravity and friction feed-forward. When payload, friction, or temperature vary more, they add model-reference or sliding-mode elements to keep errors small while protecting stability. When parts and scenes very quickly, they place learning above a stabilising low-level loop; they do not remove the inner loop. The reason is simple: maintenance, diagnosis, and safety work better when the core remains transparent.

The arm’s structure decides what control it can exert. Six-axis wrists bring dexterity but need higher loop rates and careful handling near singularities. Stiffness and backlash define the bandwidth ceiling. Plants hold accuracy with scheduled calibration and with online estimation that tracks slow drift. These mechanical facts make control choices realistic and prevent over-promising.

Perception belongs in the loop but must respect timing. Vision aligns global frames; encoders and IMUs provide high-rate state; force and tactile keep contact safe. Fusion pipelines such as EKF or UKF give the needed estimates without adding sensors to every joint. Software must separate deterministic servo tasks from best-effort perception and planning, with clear queues and clock sync. When networks or drives add delay, adaptive estimation and simple observers help keep tracking.

Across scenarios, the same logic applies. Precision assembly benefits from PID with feed-forward, calibration, and small amounts of vision feedback. High-speed sorting and variable loads push toward adaptive or sliding-mode designs. Mobile–fixed cooperation and contact-rich insertion need robust fusion and impedance behaviour. Warehouse picking uses learning at the supervisory level but relies on a stable inner loop. Fault-tolerant operation combines observers with diagnostics and a safe fall-back mode. These patterns give a practical map for upgrades without risky rewrites.

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