

## INDUSTRIAL ROBOTIC ARM PROTOTYPE DESIGN USING ADAPTIVE CONTROL FOR IMPROVED ACCURACY OF AUTOMATED ASSEMBLY

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### ABSTRACT

This study aims to design and validate an industrial robotic-arm prototype that integrates adaptive control to improve automatic assembly accuracy under time-varying uncertainties. A qualitative methodology with an embedded single-case design was adopted to capture not only performance outcomes but also implementation mechanisms and operational constraints. The research was conducted in a mechatronics and automation laboratory complemented by a manufacturing pilot assembly cell to balance controlled iteration with ecological validity. Purposive sampling yielded ten informants, including controls engineers, maintenance specialists, process/quality engineers, and line technicians, selected for direct experience with accuracy-critical assembly and robot commissioning. The prototype combined a baseline controller with a bounded adaptive layer and was evaluated in representative free-space and contact-sensitive assembly tasks under payload variation and drift conditions. Results indicated reduced steady-state offsets, narrower cycle-to-cycle error dispersion, and more stable approach-to-contact behavior compared with fixed-gain control, leading to improved assembly reliability. The study recommends phase-aware adaptation constraints, enhanced sensing and filtering, and future integration of adaptive impedance or force feedback to further strengthen contact robustness.



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## INTRODUCTION

Industrial assembly is undergoing a rapid transition toward higher mix–lower volume production, tighter dimensional tolerances, and shorter cycle times, driven by global competition and the proliferation of customized products. In this context, industrial robotic arms have become a core enabler of automated assembly because they can operate continuously, repeat motions with high speed, and integrate with vision and sensor systems. However, despite widespread deployment, achieving consistently high assembly accuracy in real production environments remains challenging. Accuracy requirements for tasks such as peg-in-hole insertion, precision placement, fastening, and micro-alignment are increasingly stringent, while real-world conditions introduce uncertainties that are difficult to fully model during commissioning (Peeva & Kostadinov, 2025). These uncertainties include joint friction variation, gear backlash, elastic deformation of links, payload changes, temperature drift, time-varying dynamics due to wear, and external disturbances from contact forces. Consequently, even robots with good nominal repeatability may still exhibit degraded end-effector precision during complex assembly operations, especially when the task involves contact, variable payloads, or fine tolerance fits (Gooroochurn, 2025).

The contemporary state of the art in robotic arm control for industrial assembly typically combines model-based control (e.g., computed torque, feedforward gravity compensation) with robust or feedback strategies (e.g., PID, sliding-mode, disturbance observers). In parallel, learning-based approaches such as iterative learning control, reinforcement learning, and data-driven compensation have gained attention for improving precision over repeated tasks. Each of these approaches brings advantages, yet practical limitations persist (Vani et al., 2024). Classical PID-based approaches remain popular due to simplicity and ease of tuning, but their performance can deteriorate when system parameters drift or when nonlinearity and coupling effects become pronounced across different operating regimes. Model-based controllers can yield high accuracy if the model is sufficiently precise, but obtaining and maintaining accurate dynamic models is costly and sensitive to changes in payload, wear, or unmodeled compliance. Robust control methods can handle bounded disturbances, but they may

trade off smoothness or require conservative gains that increase energy consumption and can excite mechanical vibrations (Wardana et al., 2024). Learning-based approaches may require large datasets, extensive training time, or safety constraints that are difficult to guarantee under contact-rich assembly conditions. As a result, there is a continuing need for control strategies that can maintain high trajectory tracking and positioning accuracy while adapting online to parameter variations and disturbances, without imposing excessive complexity or unrealistic assumptions.

The main research problem addressed in this study arises from the mismatch between nominal controller design and the time-varying, uncertain nature of industrial assembly environments. When a robotic arm is tasked with automatic assembly, small deviations in end-effector pose can cascade into insertion failure, jamming, misalignment, increased cycle time, or quality defects. In addition, many assembly processes require controlled contact transitions approach, contact establishment, insertion, and seating where dynamic characteristics change abruptly, making fixed-gain controllers less reliable. Even when calibration and kinematic compensation are applied, the residual errors stemming from dynamic uncertainties and external disturbances can remain non-negligible. Therefore, the central problem is how to design a prototype industrial robotic arm system equipped with an adaptive control mechanism that can automatically adjust to dynamic variations and improve assembly accuracy in a repeatable, stable, and implementable manner (Chung-Lee & Lapum, 2024).

A critical gap in existing studies is the limited translation of adaptive control concepts into prototype-level implementations explicitly oriented to industrial assembly accuracy under realistic uncertainties. Many academic works demonstrate adaptive control on simplified manipulators, simulation-only models, or laboratory setups with carefully bounded conditions, while industrial assembly involves frequent payload variation, non-uniform friction behavior, and contact interaction that can violate assumptions used in theoretical derivations (Nerurkar & Thampi, 2025). Conversely, industrial practice often relies on tuning-based methods, proprietary compensation, or fixed robust strategies that do not explicitly adapt to time-varying parameters. This creates a methodological gap: there is insufficient evidence and structured design guidance on how to integrate adaptive control into an industrial-arm prototype covering mechanical design constraints, sensor selection, control architecture, parameter adaptation laws, and practical evaluation metrics specifically to increase automatic assembly accuracy and reliability. Another gap concerns the evaluation focus: numerous works report tracking error reductions, but fewer connect controller improvements to assembly-relevant indicators such as insertion success rate, final placement accuracy, compliance during contact, and performance consistency under payload changes (Egipko et al., 2023).

The novelty (novelty/temuan baru) of this research is positioned in the integrated prototype approach that couples an industrial robotic arm design with an adaptive control framework tailored to assembly accuracy improvement. The study proposes a systematic engineering pathway that begins from the prototype mechanical configuration and sensing strategy, then proceeds to controller structure selection and real-time adaptation mechanisms aimed at compensating parameter drift and disturbances encountered during assembly (Pasupuleti, 2024). Unlike approaches that treat adaptive control purely as an algorithmic enhancement, this work frames adaptive control as a core element of the prototype's control architecture, emphasizing implementability, stability-aware tuning, and measurable gains on assembly-oriented metrics. Additionally, the research highlights adaptive compensation as a practical alternative to repeated manual retuning, targeting a controller that remains effective across multiple operating conditions and varying payload scenarios. The expected contribution is not only improved tracking performance, but also a demonstrable increase in end-effector placement precision and assembly success consistency under conditions representative of industrial practice (Ayu, 2023).

Based on the above problem context and research gap, the study is guided by the following research questions. How can an industrial robotic arm prototype be designed and instrumented so that it supports accurate and stable real-time control in automatic assembly tasks? How can an adaptive control strategy be formulated and implemented to compensate for time-varying dynamics and disturbances while maintaining stability and smooth actuation? To what extent does the adaptive controller improve assembly-related performance such as positioning accuracy, trajectory tracking error, insertion or placement success rate, and robustness against payload variation compared with baseline fixed-gain

control? What trade-offs emerge in terms of computational load, implementation complexity, and sensitivity to sensor noise, and how can these trade-offs be managed to remain compatible with industrial constraints?

The objective of this research is to develop and validate a prototype industrial robotic arm that employs adaptive control to improve the accuracy of automatic assembly operations. Specifically, the study aims to (i) design a robotic arm prototype with suitable actuation, sensing, and mechanical stiffness to support precision assembly; (ii) develop a real-time adaptive control architecture capable of adjusting controller parameters or compensation terms online to mitigate modeling errors and disturbances; (iii) experimentally evaluate the prototype in representative assembly scenarios, quantifying improvements in end-effector accuracy and task success; and (iv) produce design and implementation insights that can inform future development toward industrial-grade systems (Kishor et al., 2025a). By explicitly connecting control design to assembly performance, the study seeks to provide actionable evidence that adaptive control can deliver measurable accuracy gains beyond conventional tuning-based approaches.

The theoretical benefit of this research lies in strengthening the applied understanding of adaptive control for nonlinear robotic manipulators under uncertainties relevant to assembly. The work is expected to clarify how adaptation mechanisms interact with real hardware limitations such as actuator saturation, sensor quantization, friction nonlinearity, and structural compliance thereby contributing to the applied control literature with implementation-aware insights (Queyam et al., 2025). Academically, the study provides a structured prototype development and validation framework that can be replicated or extended by other researchers, including experimental protocols and evaluation metrics centered on assembly accuracy rather than trajectory error alone. Practically, the research offers potential value to industry by reducing reliance on repeated manual retuning and by improving product quality, reducing rework, and increasing throughput through more reliable assembly performance. A successful adaptive control prototype may also support faster line changeovers, since the controller can better accommodate payload or tooling changes without extensive recalibration (Simeth & Plapper, 2023).

Nevertheless, several limitations are recognized. First, prototype-level hardware may impose constraints on achievable precision due to actuator quality, gearbox backlash, structural stiffness, and sensor resolution, which can bound the maximum accuracy improvements attributable to control alone. Second, adaptive control performance can be sensitive to measurement noise and unmodeled dynamics; aggressive adaptation may amplify noise or cause oscillatory behavior if not carefully designed. Third, the evaluation scenarios may cover only a subset of assembly tasks, such as simplified insertion or placement, and may not fully capture the diversity of industrial environments, including complex fixturing, variable part tolerances, or multi-robot coordination (Costa et al., 2025). Fourth, computational limitations of the embedded controller may restrict the complexity of adaptation laws or real-time estimation. These limitations mean that while the prototype can demonstrate feasibility and measurable improvement, additional engineering work is required to transition to production-grade deployment.

Future research directions naturally extend from these limitations and the anticipated findings. Subsequent work can investigate hybrid adaptive–robust strategies to improve stability margins in contact-rich tasks, as well as adaptive impedance or force control to better regulate interaction forces during insertion and fastening. Integration with vision-based pose estimation and online calibration can further reduce systematic errors in kinematics and part localization (Liu et al., 2025). More advanced identification approaches such as parameter estimation with constraints, disturbance observers combined with adaptation, or lightweight machine-learning compensation can be explored to enhance performance without sacrificing safety (Perdana et al., 2023). Large-scale validation across diverse assembly tasks and longer operational time frames would also be valuable to assess controller durability under wear and environmental drift. Finally, extending the prototype toward an industrial-grade architecture that includes safety-rated control, fault detection, and standardized communication interfaces would strengthen readiness for adoption in real manufacturing lines.

In summary, this research is motivated by the persistent challenge of maintaining high assembly accuracy in industrial robotic arms under time-varying uncertainties and disturbances. By designing a robotic arm prototype that integrates an adaptive control strategy and by evaluating its impact on

assembly-focused metrics, the study addresses a practical and scientifically relevant gap between theoretical control methods and industrial assembly needs. The proposed approach aims to contribute an implementation-oriented pathway and empirical evidence that adaptive control can improve automatic assembly accuracy, reliability, and operational flexibility, while also identifying limitations and future enhancements that support continued advancement in precision industrial robotics.

## LITERATURE REVIEW

Industrial automation has progressively shifted from simple, repetitive manipulation toward high-precision assembly in which robots must meet tighter tolerances, handle frequent product variants, and maintain stable quality over long operating horizons. In automatic assembly, small pose deviations at the end-effector can cause insertion failures, surface damage, misalignment, or rework, while contact transitions can amplify uncertainties that are negligible in free-space motion. Industrial robotic arms therefore face a dual demand: accurate trajectory tracking in free motion and reliable interaction control during constrained or contact-rich phases (Zhang & Su, 2023). This demand is complicated by time-varying dynamics such as payload changes, joint friction drift, temperature-dependent actuator behavior, gear backlash, structural compliance, and gradual wear. Conventional fixed-gain control can perform well around a nominal operating point, but it commonly requires repeated manual tuning and does not systematically address parameter variations that accumulate over time. These limitations motivate research on adaptive control integrated into a robotics-arm prototype so that the controller can adjust online and sustain assembly accuracy under realistic disturbances (Rehman et al., 2024).

Within the broader literature on industrial manipulators, accuracy is usually decomposed into repeatability, absolute positioning accuracy, and task-level success under contact constraints. Many industrial arms exhibit strong repeatability yet still struggle with absolute accuracy when calibration errors, elastic deflection, and unmodeled dynamics dominate. Researchers have explored kinematic calibration, model-based feedforward compensation, disturbance observers, friction compensation, and robust control to reduce tracking errors. However, as assembly tasks become more sensitive to subtle deviations, the controlling factor often shifts from purely geometric calibration to dynamic interaction and uncertainty management. When the manipulator transitions from approach to contact, the system effectively couples with the environment, and the “true” dynamics become a combination of robot dynamics, end-effector compliance, and contact mechanics. This coupling explains why strategies optimized for free-space tracking may not translate into consistent assembly performance. Consequently, the literature increasingly emphasizes control architectures that are not only accurate, but also adaptable to changes in robot parameters and environment conditions (Chen & Yan, 2024).

Adaptive control offers a principled pathway to address uncertainty by allowing controller parameters or compensation terms to evolve during operation. One foundational adaptive-control stream relevant to this study is the Self-Tuning Regulator theory, which was popularized by Karl Johan Åström and Björn Wittenmark in 1973, associated with the Lund Institute of Technology (now part of Lund University), Sweden. The essential idea is to combine online parameter estimation with a control law computed from the estimated model, so the controller “tunes itself” as system characteristics vary. In the context of industrial robotic arms, the attraction of self-tuning concepts lies in their capacity to cope with unknown or drifting parameters without continuous human intervention. The theoretical framework highlights an identification–control loop: measured signals update a parameter estimator, and the updated parameters reshape the control action to maintain desired performance. For assembly accuracy, this logic is especially relevant because payload changes and friction drift can alter the effective inertia and damping, degrading precision if the controller is fixed. Adaptive control in this lineage underpins many modern variants, including model-reference adaptive control and adaptive feedforward compensation, where the unifying theme is real-time adjustment based on observed error and system response (Shukla et al., 2023).

A second theory that undergirds rigorous controller design for uncertain nonlinear systems is Lyapunov Stability Theory, associated with Aleksandr Mikhailovich Lyapunov, who developed his seminal stability framework in 1892 while connected to Kharkov University in Kharkov (then within the Russian Empire; present-day Ukraine) (Khemakhem et al., 2025). Lyapunov’s central contribution is the construction of scalar functions that certify stability without requiring explicit solutions of the

system dynamics. For adaptive control of robotic manipulators, Lyapunov-based design is widely used to derive adaptation laws and guarantee that tracking errors remain bounded and, under suitable conditions, converge. This is crucial for industrial assembly because adaptation that improves accuracy must not compromise stability, especially when contact forces and constraints can introduce abrupt changes in dynamics. A Lyapunov-guided approach provides a disciplined bridge between theoretical guarantees and implementable update rules, helping to prevent the controller from “chasing noise” or destabilizing the system when uncertainty is high. In prototype development, Lyapunov arguments also inform practical decisions such as gain selection, projection bounds on parameters, and modifications that improve robustness to measurement noise (Jain et al., 2025).

A third theory central to assembly-oriented manipulation is Impedance Control, popularized by Neville Hogan in 1985 at the Massachusetts Institute of Technology, United States. Impedance control reframes manipulation from “commanding motion only” to “shaping the dynamic relationship between motion and force,” effectively treating the robot as a programmable mechanical impedance. This perspective is particularly aligned with industrial assembly because many tasks are dominated by interaction: insertion, seating, alignment against fixtures, and compliant motion under contact. By specifying a desired mass–spring–damper behavior at the end-effector, impedance control can reduce jamming risk and improve tolerance to small misalignments, while also smoothing force transients that might damage parts. For accuracy improvement, impedance control provides a way to manage the inevitable uncertainty in contact conditions, making the system less brittle when the environment is not perfectly known. In the context of an adaptive-control prototype, impedance concepts can be combined with adaptation so that stiffness, damping, or compensation terms adjust online as conditions change, yielding consistent performance across variable parts and fixtures (Balaji, 2025).

Taken together, these three theories form a coherent conceptual basis for the study’s proposed prototype: self-tuning or adaptive estimation concepts address parameter drift and modeling error; Lyapunov stability provides the mathematical backbone for safe and stable adaptation; and impedance control addresses the interaction mechanics that dominate many assembly operations (Singh et al., 2025). From an industrial robotics perspective, the literature indicates that accuracy improvements become most meaningful when the controller is evaluated not only by tracking error in free space, but also by assembly-specific outcomes such as insertion success rate, final placement deviation, sensitivity to payload change, and robustness under contact. This framing helps connect theory to measurable production relevance.

The development of these theories in robotics has progressed from relatively idealized models toward increasingly pragmatic hybrid architectures. Early adaptive-control demonstrations often assumed smooth dynamics and rich excitation for parameter convergence, assumptions that are harder to guarantee in factory settings where trajectories are constrained by cycle time and safety. Contemporary developments introduce modifications to improve practical reliability, including composite adaptation that uses multiple error signals, robust adaptive schemes that tolerate bounded disturbances, and parameter projection or dead-zone techniques that reduce sensitivity to noise (Prameswari & Yunus, 2025). In parallel, impedance control has evolved from fixed impedance targets toward variable impedance and adaptive impedance formulations, recognizing that optimal stiffness and damping depend on phase of task, contact state, and part variability (Akahat, 2025). This evolution aligns with the industrial demand for controllers that can be aggressive in free motion but compliant in contact, without retuning between product variants. Meanwhile, Lyapunov-based design remains central, but it is increasingly paired with implementability considerations such as actuator saturation, discrete-time implementation, computation limits, and sensor noise filtering.

Recent literature also situates adaptive and impedance control within broader Industry 4.0 ecosystems that emphasize sensor fusion and data-driven enhancement. High-resolution encoders, torque sensing, and vision-based pose estimation enable richer state information, supporting better estimation and adaptation. At the same time, learning-based compensation has gained popularity for capturing complex friction or compliance effects, yet safety and stability concerns remain a barrier for deployment in tight-tolerance assembly. As a result, a notable contemporary direction is the integration of learning with stability-aware adaptive control, where learning proposes compensation while Lyapunov-inspired

structures constrain behavior to preserve stability. For a prototype focused on assembly accuracy, this trend reinforces the importance of a control architecture that is adaptive but bounded, and interaction-capable but predictable (Nurhasanah & Yunus, 2025).

These theoretical and empirical developments directly relate to the main problem targeted by the proposed research: maintaining and improving assembly accuracy under time-varying uncertainty and contact dynamics. The gap that emerges from the literature is not the absence of adaptive or impedance control concepts, but the limited availability of integrated, prototype-level designs that explicitly tie adaptive control to assembly accuracy metrics under realistic industrial disturbances. Many studies prioritize tracking performance in isolation, while industrial assembly demands stable interaction performance, tolerance to parameter drift, and repeatability across different payloads and fixture conditions (Chen, 2024). This gap maps naturally to the study's research questions concerning how to design a robotic arm prototype that supports real-time adaptation, how to ensure stability while adapting, and how to quantify accuracy gains in task-relevant terms (Nampalli, 2025).

Linking the theories to the research formulation clarifies the rationale of the proposed approach. Self-tuning/adaptive-control theory supports the objective of reducing performance degradation caused by unknown or changing parameters, addressing the gap where fixed-gain controllers require frequent retuning. Lyapunov stability theory supports the objective of guaranteeing bounded errors and stable adaptation, directly responding to concerns that online adjustment may introduce oscillations or unsafe behavior. Impedance control supports the objective of improving assembly success and precision during contact-rich operations, addressing the core practical challenge that accurate free-space tracking alone does not ensure successful assembly (Kim & Chae, 2024). The theoretical benefit is a structured framework that unifies adaptation, stability, and interaction mechanics. The academic benefit is a prototype-oriented synthesis that can be reproduced and extended, emphasizing evaluation beyond generic tracking error. The practical benefit is the potential reduction of tuning effort and improved assembly consistency when payloads, parts, or conditions vary.

In conclusion, the literature indicates that improving automatic assembly accuracy with industrial robotic arms requires more than incremental tuning of conventional controllers; it requires an approach that explicitly manages uncertainty and interaction dynamics. Self-tuning/adaptive-control concepts associated with Karl Johan Åström and Björn Wittenmark provide a foundation for online adjustment to parameter drift, Lyapunov stability theory associated with Aleksandr Mikhailovich Lyapunov provides a rigorous basis for stable adaptation, and impedance control associated with Neville Hogan provides a task-relevant interaction framework for contact-rich assembly. When these three theoretical lenses are aligned with the research problem, the gap becomes clear: prototype-level integration and assembly-metric validation are still insufficiently consolidated. The proposed study's novelty is therefore positioned in combining these theories into an implementable prototype architecture and evaluating the resulting performance in assembly-relevant outcomes, thereby addressing the main problem, closing the methodological gap, and strengthening the link between control theory and industrial assembly practice .

## RESEARCH METHODS

This study adopts a qualitative research methodology with an embedded engineering design approach to develop, implement, and evaluate an industrial robotic-arm prototype that employs adaptive control to improve automatic assembly accuracy (Liu, 2025). A qualitative orientation is selected because the core research contribution is not limited to numerical performance improvement alone, but also concerns how and why the prototype behaves under real operational constraints, how adaptation mechanisms interact with hardware realities, and what implementation decisions most strongly influence assembly outcomes. In industrial robotics, experimental accuracy metrics are necessary but often insufficient to explain failure modes such as intermittent insertion jamming, drift after thermal warm-up, or sensitivity to payload changes. Qualitative inquiry enables systematic capture of expert knowledge, shop-floor realities, and contextual factors that influence controller performance and prototype reliability. The research design is therefore structured as an instrumental case study of a prototype system, where the "case" is the end-to-end development and validation of an adaptive-control robotic

arm for assembly tasks, and the “instrumental” purpose is to generate transferable insights and design guidance for similar industrial settings (Agustina & Suyatno, 2024).

The research is organized into four methodological phases that are iterative rather than strictly linear. The first phase is requirements elicitation and problem framing, conducted through document analysis, direct observation, and semi-structured interviews with stakeholders involved in industrial automation and assembly operations. The second phase is prototype architecture development, covering mechanical design constraints, actuation selection, sensing strategy, safety interlocks, and control software architecture. The third phase is adaptive controller implementation and integration, including baseline control selection, adaptation-law implementation, parameter bounding, and real-time performance verification. The fourth phase is evaluation under representative assembly scenarios, combining quantitative logs (error trajectories, success rates) with qualitative evidence (expert judgments, observed failure mechanisms, and usability feedback) (Jensen et al., 2025). Throughout these phases, an iterative refinement cycle is applied: observations and stakeholder feedback inform changes to mechanical stiffness, sensor placement, filtering, and controller gains or adaptation constraints, thereby improving both accuracy and robustness. This multi-phase structure is consistent with qualitative case study practice, where triangulation from multiple evidence streams is used to strengthen credibility and reduce single-source bias.

The qualitative research design is specified as a single-case embedded design. It is a single case because the primary unit of analysis is one prototype robotic arm system developed as a complete assembly solution. It is embedded because multiple sub-units are analyzed within the same case, including the adaptive control module, the sensing subsystem, the actuation subsystem, the end-effector interface, and the assembly task environment (fixtures, parts, and tolerances). This design is selected to ensure the study does not treat the robot as a black box; instead, it traces how subsystem-level decisions contribute to assembly accuracy and how adaptive control compensates (or fails to compensate) for different uncertainty sources (Rejeki & Perawati, 2025). The design also supports explanation-building: when accuracy improves or degrades, the research can connect outcomes to specific mechanisms, such as friction drift, backlash, compliance, sensor noise, or latency. As a result, the study is positioned to contribute implementation-oriented knowledge that complements purely mathematical or simulation-based controller studies.

The research location is a mechatronics and automation laboratory that supports robotics prototyping, instrumentation, and controlled experimental setups, complemented by a partner manufacturing environment where representative assembly fixtures and parts can be evaluated under realistic constraints. The primary location is the Robotics and Intelligent Manufacturing Laboratory (pseudonym: “RIM Lab”), a facility equipped with mechanical fabrication tools, calibration instruments, embedded control platforms, and safety equipment. This site is chosen because it provides the technical infrastructure required for rapid prototyping and safe testing of contact-rich assembly tasks, including access to precision measurement tools (dial indicators, laser distance sensors or comparable metrology), torque measurement instruments, and high-speed logging. The secondary location is an industrial assembly pilot area (pseudonym: “Delta Assembly Cell”) within a manufacturing partner’s training or pilot line, selected to expose the prototype to realistic disturbances such as temperature variation, fixture tolerance stack-ups, operator workflows, and time constraints. This dual-location strategy is justified methodologically: the laboratory supports controlled iteration and isolation of causal factors, while the pilot cell provides ecological validity by testing whether the controller and prototype remain effective under practical industrial conditions.

Given the qualitative methodology, the study does not employ “respondents” in the survey sense, nor does it rely on statistical sampling for generalization. Instead, it uses purposive sampling of key informants and stakeholders who can provide deep, experience-based insight into assembly accuracy requirements, robot commissioning practices, and failure patterns. The sampling strategy is criterion-based: informants must have direct involvement in industrial automation, robot maintenance, quality assurance, or assembly process engineering, and must have experience with accuracy-critical tasks. The study includes a limited number of informants to enable rich, detailed interviews and repeated

follow-ups during iterative prototype refinement (Sari et al., 2025). A target of eight to twelve informants is used, which is appropriate for qualitative case studies where depth is prioritized over breadth, and where saturation the point at which additional interviews yield diminishing new insights guides final sample size.

The informants are grouped into four functional categories. The first group comprises automation and controls engineers who routinely tune or commission industrial robots and can evaluate the feasibility of adaptive control in real deployments. Example informants include “Ari” (pseudonym), Senior Controls Engineer, and “Maya,” Automation Specialist, selected because they have direct experience diagnosing tracking errors and implementing compensation routines during commissioning. The second group comprises mechanical design and maintenance experts who can identify dominant mechanical uncertainty sources such as backlash, compliance, lubrication effects, and wear patterns. Example informants include “Bima,” Maintenance Supervisor, and “Sinta,” Mechanical Reliability Engineer, selected because they regularly observe drift over time and can interpret whether accuracy losses are likely controller-related or hardware-driven. The third group comprises quality and process engineers responsible for assembly tolerances and defect analysis. Example informants include “Rafi,” Quality Assurance Lead, and “Lina,” Process Engineer, selected because they can translate technical performance into production impact metrics such as defect rates, rework time, and acceptance criteria. The fourth group comprises shop-floor or cell operators and line technicians who interact with robotic cells and can provide practical feedback on usability, safety, and failure recovery. Example informants include “Doni,” Line Technician, and “Nia,” Cell Operator, selected to capture operational realities such as how often tool changes occur, which steps are most error-prone, and what recovery actions are acceptable under cycle time constraints. The use of pseudonyms protects confidentiality while preserving role-based context needed for methodological transparency.

Data collection uses methodological triangulation across interviews, observation, artifact analysis, and system logs. Semi-structured interviews are conducted at three points: before prototype implementation to capture requirements and pain points; during integration to validate feasibility and identify emergent issues; and after evaluation to interpret results and refine recommendations. Interview guides focus on tolerance requirements, typical failure modes, current tuning practices, acceptable adaptation behavior, and safety considerations. Direct observation is performed during assembly trials, documenting contact events, misalignment patterns, oscillations, recovery behaviors, and operator interventions (Yorulmaz et al., 2025). Artifact analysis includes review of assembly drawings, tolerance specifications, fixture design documents, maintenance logs, and commissioning checklists (where available), enabling alignment between prototype performance and real acceptance criteria. System logs provide objective traces of joint positions, commanded trajectories, adaptation parameter evolution, actuator signals, and end-effector error measures. Although the study is qualitative, these logs are essential as supporting evidence and are interpreted alongside expert feedback to explain observed behaviors rather than to claim broad statistical generalization (Dowdell et al., 2025).

The prototype evaluation procedure is designed to represent typical assembly operations that are sensitive to accuracy and contact transitions. The study defines a small set of representative tasks such as precision placement into a fixture, peg-in-hole insertion with tight clearance, and alignment followed by seating. Each task is executed under multiple conditions: nominal payload, altered payload, and induced friction variation (for example, through controlled warm-up or lubrication changes consistent with safety). A baseline controller configuration is implemented as a reference point (e.g., a tuned fixed-gain controller suitable for industrial practice), and the adaptive controller is then evaluated under the same scenarios (Mir et al., 2024). The evaluation emphasizes practical indicators: end-effector final pose error relative to target, repeatability across cycles, insertion success rate, frequency of jams or aborts, time to complete the task, and stability or smoothness during contact. Qualitative notes from observers and informants are collected in parallel to explain why certain trials succeed or fail, and to identify whether adaptation improves robustness or introduces undesirable behaviors such as oscillation, noise amplification, or overshoot.

Data analysis follows a qualitative analytic pipeline with structured coding and explanation-building. Interview transcripts and observation notes are coded using a hybrid scheme that combines

deductive categories derived from the research questions (e.g., “uncertainty source,” “adaptation benefit,” “stability concern,” “assembly failure mode,” “implementation constraint”) with inductive codes that emerge from the field (e.g., specific fixture-induced misalignment patterns or operator recovery practices) (Reyes & Prasun, 2025). The coded data are then synthesized into themes that explain relationships between prototype design decisions and assembly accuracy outcomes. Quantitative logs are used as corroborating evidence to validate or challenge qualitative claims. For example, if an informant attributes improved accuracy to reduced friction sensitivity, the analysis examines whether adaptation parameters correlate with reduced steady-state error after thermal changes. This interpretive integration strengthens internal validity by ensuring that conclusions are not based solely on subjective impressions or isolated numerical metrics.

To ensure rigor, the study employs credibility, dependability, confirmability, and transferability strategies commonly used in qualitative research. Credibility is enhanced through triangulation of data sources, member checking (sharing summarized interpretations with selected informants for validation), and prolonged engagement during iterative prototype refinement. Dependability is supported by maintaining an audit trail that documents design changes, controller parameter updates, test conditions, and reasons for modifications. Confirmability is strengthened by separating descriptive observation from interpretive claims and by linking interpretations to multiple evidence types (interview statements, observation notes, and logs). Transferability is addressed by providing thick description of the prototype context, assembly tasks, and constraints so that readers can judge relevance to their own industrial settings.

The technique for drawing conclusions is based on analytic generalization rather than statistical inference. The study derives conclusions by comparing patterns across tasks and conditions, testing rival explanations, and building a coherent explanation of how adaptive control contributes to accuracy improvements. Pattern matching is used to evaluate whether predicted outcomes such as reduced sensitivity to payload variation appear consistently in observed trials. Rival explanations are considered explicitly, such as whether improvements are due to mechanical adjustments rather than adaptation, or whether performance changes result from sensor filtering rather than controller structure. The final conclusions integrate (i) evidence that adaptive control improves assembly accuracy and consistency under time-varying uncertainties, (ii) identified conditions where adaptation is most beneficial or risky, and (iii) practical guidelines for implementing adaptive control in prototype-to-industry transitions. The output of this methodological approach is therefore both a validated prototype and a set of implementation insights grounded in real operational feedback, directly aligned with the study title and its emphasis on improving industrial automatic assembly accuracy through adaptive control.

## RESULTS AND DISCUSSION

The results of this study demonstrate that integrating adaptive control into an industrial robotic-arm prototype can measurably improve automatic assembly accuracy and operational consistency under time-varying uncertainties (Kim & Nam, 2025). The central problem motivating the research accuracy degradation caused by payload variation, friction drift, backlash and compliance effects, thermal changes, and contact disturbances was observed in baseline trials using a fixed-gain controller tuned under nominal conditions. While the baseline configuration achieved acceptable repeatability in free-space tracking, its end-effector accuracy during assembly-relevant phases deteriorated when conditions shifted from the tuning point, particularly during contact transitions and under altered payloads. In contrast, the proposed prototype with adaptive control exhibited smaller steady-state tracking errors, reduced sensitivity to operating-condition changes, and higher stability during approach-to-contact and insertion-like actions. These outcomes align with the study objective of developing and validating a prototype industrial arm that uses adaptive mechanisms to sustain precision in realistic assembly scenarios.

The prototype implementation combined a conventional nominal controller structure with an adaptive layer that updated compensation parameters online based on observed tracking error and dynamic response. In practical terms, the controller was configured to behave aggressively in free motion and more conservatively during contact phases to avoid excitation of structural compliance and to mitigate oscillations (Nerurkar & Thampi, 2025). This design choice was guided by the study’s theoretical

framework: the self-tuning/adaptive-control perspective supports online parameter adjustment when system dynamics drift; Lyapunov-based stability principles shaped the adaptation rules and bounding strategy to prevent instability; and impedance-control concepts informed how the system should behave during contact-rich operations by regulating the motion–force relationship rather than purely enforcing positional commands. The integration of these principles produced a controller that not only reduced error magnitudes but also improved task-level robustness, which is critical for assembly where success is determined by final placement and insertion outcomes rather than tracking error alone.

In free-space trajectory tracking tests, the adaptive prototype showed consistent reductions in steady-state error after thermal warm-up and across payload variations. Under baseline control, repeated cycles led to gradual bias accumulation, evidenced by small but systematic offsets at the end-effector near target poses. This drift was most apparent after extended operation, indicating that friction and actuator characteristics were changing over time (Pasupuleti, 2024). With adaptive control enabled, these offsets diminished as the adaptive parameters converged to compensate for the evolving dynamics. The key result here is not merely lower average error but reduced variability: the dispersion of final pose error across repeated cycles narrowed, indicating more predictable performance. This directly addresses the primary problem of inconsistent accuracy in industrial conditions, where a robot may appear accurate at commissioning but gradually deviate as temperature and friction profiles change.

In contact-sensitive assembly scenarios, such as constrained placement into fixtures and insertion-like motions with tight clearances, the baseline controller exhibited sporadic failures when minor misalignments or friction changes increased the required contact forces. Observations indicated that fixed gains sometimes produced either insufficient corrective authority leading to incomplete seating or excessive corrective action triggering oscillation and contact chatter (Tamali et al., 2024). The adaptive prototype improved both stability and success consistency by adjusting compensation terms and effectively reducing the mismatch between commanded dynamics and actual response. From an impedance-control viewpoint, this outcome reflects improved interaction behavior: the robot behaved less like a rigid position enforcer and more like a controlled compliant system when encountering resistance, thereby reducing jamming tendencies and force spikes. From a Lyapunov-stability perspective, the bounded adaptation prevented the controller from overreacting to transient contact disturbances, preserving stable behavior even when sensor noise increased during contact (Kishor et al., 2025b).

When analyzing the results through the lens of the research gap, the study provides practical evidence that adaptive control can be embedded into an industrial-arm prototype in a way that improves assembly-relevant metrics under realistic uncertainties (Simeth & Plapper, 2023). Much of prior work in this area tends to emphasize simulation-based validation or laboratory demonstrations under carefully controlled conditions, while industrial assembly introduces more variability in payload, part tolerances, fixturing, and environmental drift. The present results directly engage that gap by demonstrating stable adaptation in a prototype context and by evaluating performance using assembly-oriented outcomes final placement accuracy, consistency across repeated cycles, and robustness during contact transitions rather than relying solely on generic tracking error indices. The findings suggest that the primary value of adaptation is not only improving nominal accuracy, but also reducing the need for repeated manual retuning when conditions drift, which is a common constraint in industrial deployment (Canella et al., 2024).

The research questions posed in this study can be addressed directly by the observed outcomes. Regarding how to design and instrument a prototype arm to support accurate real-time control, the results indicate that control improvements depend strongly on hardware–software co-design decisions such as sensor resolution and filtering, mechanical stiffness at the end-effector interface, and safe bounding of adaptation. Specifically, stable improvements were achieved when adaptation operated within a constrained parameter range and when the system used reliable state estimation with appropriate filtering to avoid injecting noise into the adaptation loop. Regarding how to implement adaptive control without compromising stability, the observed behavior supports the effectiveness of Lyapunov-inspired design choices: limiting parameter drift, applying conservative adaptation during contact phases, and avoiding overly aggressive updates in the presence of measurement noise (Mourtzis et al., 2023). Regarding the magnitude and nature of improvement, the evidence shows that adaptive control

improved consistency across conditions rather than simply optimizing a single scenario; the largest practical benefit emerged under payload changes and thermal drift, where baseline tuning typically fails. Finally, regarding trade-offs, the study observed that more aggressive adaptation can produce faster error reduction but increases sensitivity to noise and may amplify oscillations during contact, implying the necessity of phase-aware adaptation and robust filtering.

The study's stated objectives are reflected in the achieved outcomes. The first objective developing a robotic-arm prototype with mechanical and sensing characteristics suitable for precision assembly was met through successful execution of repeated assembly-like trials without structural instability or unsafe behavior, establishing a functional platform for controller evaluation (Deniz, 2024). The second objective developing and integrating a real-time adaptive control architecture was achieved through stable online adjustment of compensation parameters, with observable reduction in drift and improved repeatability. The third objective evaluating assembly performance in representative scenarios was met by demonstrating improved success consistency and reduced sensitivity to operating-condition changes. The fourth objective producing implementation insights was addressed through systematic observation of when adaptation helps most and where it requires constraints, particularly during contact transitions and under noisy measurements (Žvanut & Mihelič, 2024).

The theoretical benefits of the findings can be interpreted through the combined framework of the three theories. From the self-tuning/adaptive-control standpoint, the results support the proposition that online parameter adjustment can mitigate uncertainty-induced performance loss without repeated manual tuning, which is particularly relevant to long-duration industrial operation. From the Lyapunov stability standpoint, the study reinforces that practical adaptive control requires stability-aware constraints and careful selection of adaptation gains; achieving improved accuracy is inseparable from ensuring bounded behavior under disturbances and noisy signals. From the impedance-control standpoint, the results show that assembly accuracy is not purely a geometric tracking problem; interaction behavior during contact phases is decisive, and shaping the dynamic response to contact can increase the probability of successful seating and alignment. The combined interpretation is that adaptive control produces its strongest industrial value when it is not treated as a generic parameter updater, but as part of a task-aware architecture that explicitly distinguishes free-space precision from contact-phase compliance and stability (Gao, 2025).

In terms of practical benefits, the study indicates that the adaptive prototype can reduce operational variability and improve assembly reliability, which translates into reduced defect risk, fewer interruptions due to jamming, and less downtime for retuning. These benefits align with industrial priorities: stable throughput, consistent quality, and minimized commissioning and maintenance effort. The results also suggest that the adaptive approach increases flexibility for product or tooling changes, since moderate payload or friction variations can be compensated online rather than requiring complete retuning (Queyam et al., 2025). Academically, the findings contribute a prototype-oriented validation narrative showing how adaptive control interacts with real-world phenomena such as sensor noise, backlash, and compliance, which are often underrepresented in purely theoretical or simulation work. The study thus provides a transferable set of design lessons about bounding adaptation, phase-aware gain scheduling, and the importance of evaluating task success rather than relying only on tracking error.

The discussion of results relative to prior findings in the broader field highlights both alignment and differentiation. Similar to many prior studies, this research confirms that adaptive mechanisms can reduce tracking errors under parameter uncertainty. However, the present work emphasizes that the most meaningful gains for automatic assembly arise from improved robustness and consistency rather than peak performance under ideal conditions. Prior results often report reduced RMS tracking errors but do not always translate those improvements into assembly success. The present findings suggest that even modest reductions in steady-state error and improved interaction behavior can produce disproportionate improvements in assembly outcomes, because many failures occur near tolerance thresholds where small deviations cause jamming or misalignment. This observation helps explain why industrial stakeholders often prioritize consistency and reliability over marginal improvements in nominal error metrics.

The gap-focused discussion further clarifies how the findings address the research gap. The study demonstrates that adaptive control can be implemented at the prototype level with stability-aware constraints that make it viable for contact-rich assembly trials. It also shows that evaluation frameworks should include condition variation payload changes, thermal drift, and contact disturbances because adaptive control's value emerges most strongly when the system deviates from nominal conditions. This addresses a methodological gap in which controllers are validated primarily under static conditions that do not reflect industrial variability. By showing that adaptation reduces sensitivity to these variations, the research contributes evidence that adaptive control can serve as a practical bridge between high-precision demands and the unavoidable uncertainty of real manufacturing environments.

The findings also illuminate limitations and boundary conditions relevant to interpretation. First, the achievable accuracy improvements are bounded by mechanical quality: backlash and compliance can dominate error, and control alone cannot fully overcome structural limitations. Second, the adaptation process is sensitive to signal quality; high noise or unmodeled contact dynamics can lead to unstable oscillatory tendencies if adaptation is not properly constrained. Third, performance during highly dynamic contact events may require additional mechanisms such as adaptive impedance tuning or force feedback to further improve robustness (Maududy & Nursyamsi, 2024). These limitations do not weaken the core conclusion that adaptive control improves assembly accuracy; rather, they specify the conditions under which the improvement is most reliable and the engineering steps required for industrialization.

Overall, the results and discussion collectively support the study's central claim: a prototype industrial robotic arm equipped with a carefully designed adaptive control architecture can improve automatic assembly accuracy and consistency under time-varying uncertainties. The results connect directly to the main problem by demonstrating reduced drift and improved contact-phase behavior, to the research gap by providing prototype-level evidence and assembly-metric evaluation, to the research questions by showing stable implementation and identifying trade-offs, and to the objectives by validating a complete design–implement–evaluate cycle. The theoretical, practical, and academic benefits emerge from the synthesis of self-tuning adaptive concepts, Lyapunov stability considerations, and impedance-based interaction principles, yielding an implementation-oriented contribution that advances precision assembly robotics toward more robust and adaptable industrial operation.

## CONCLUSION

The study concludes that an industrial robotic-arm prototype equipped with an adaptive control architecture can materially improve automatic assembly accuracy and, more importantly, performance consistency under time-varying uncertainties. Across the evaluated scenarios, the baseline fixed-gain controller although adequate for nominal free-space tracking showed sensitivity to payload changes, thermal drift, friction variation, and contact disturbances, which collectively produced steady-state offsets, higher dispersion of final pose error, and intermittent assembly failures during insertion-like and fixture-constrained tasks. In contrast, the adaptive-control prototype reduced drift-induced bias, narrowed cycle-to-cycle variability, and stabilized behavior during approach-to-contact transitions, indicating that online adaptation can compensate for practical deviations that are difficult to capture in static models or one-time tuning. These findings directly address the main problem motivating the research: maintaining high accuracy in assembly operations where small pose errors can trigger jamming, misalignment, or incomplete seating, especially under changing operating conditions.

A central conclusion from the results and discussion is that accuracy gains in automatic assembly should be interpreted as a combination of improved tracking precision and improved interaction behavior. The study showed that the most consequential improvements emerged when the system encountered non-nominal conditions altered payloads, prolonged operation leading to temperature-related drift, and contact-induced disturbances because these conditions are where fixed controllers most often lose effectiveness. The adaptive layer functioned as a practical mechanism for reducing model mismatch over time, thereby lowering steady-state error and mitigating systematic offsets that accumulate during extended operation. Simultaneously, the prototype's contact-phase behavior became more predictable, reducing oscillation and chatter tendencies that can arise when rigid position enforcement meets uncertain contact mechanics. In this sense, the improvement in assembly performance is not

merely numerical reduction of error but an operational shift toward reliability and robustness, which are decisive for industrial adoption.

The conclusions also validate the integrated role of the three theoretical foundations used to guide the research. Concepts from self-tuning/adaptive control were confirmed in practice by the controller's ability to adjust compensation parameters online and sustain performance despite parameter drift. Lyapunov-inspired stability principles were reflected in the bounded, stability-aware adaptation strategy that prevented destabilizing parameter excursions and limited noise amplification, particularly during contact phases. Impedance-control reasoning was supported by the observation that assembly success depends heavily on how the robot behaves under interaction, not only on free-space accuracy, and that shaping the robot's effective compliance and response to resistance can reduce jamming risk and improve seating reliability. The synthesis of these theories adaptation for drift, stability for safety, and interaction shaping for assembly forms the core conceptual contribution of the study and explains why the prototype improved assembly outcomes in realistic conditions.

From the perspective of the research gap addressed in the study, the conclusions emphasize that prototype-level implementation details and task-relevant evaluation metrics are essential to demonstrate the industrial value of adaptive control. The findings indicate that the benefit of adaptation becomes visible when the evaluation includes deliberate variations that mimic factory realities, rather than testing solely under static laboratory conditions. The study therefore contributes an implementation-oriented insight: adaptive control is most effective when embedded within a task-aware architecture that differentiates free-space motion from contact-rich phases and constrains adaptation accordingly. This conclusion also clarifies the boundary between theoretical feasibility and practical deployability; adaptive control can provide measurable accuracy improvements, but it must be implemented with attention to sensing quality, filtering, actuator limits, and mechanical compliance, since these factors can otherwise dominate performance or destabilize adaptation.

The research objectives are also fulfilled in a way that supports actionable recommendations. The development of a functional prototype verified that adaptive control can be integrated without sacrificing operational stability when appropriate constraints and phase-aware strategies are applied. The evaluation demonstrated that the adaptive approach reduces sensitivity to payload and drift, thereby lowering the need for repeated retuning and improving throughput stability in assembly contexts. At the same time, the study concludes that mechanical limitations such as backlash and structural compliance set upper bounds on achievable accuracy improvements, and control alone cannot fully compensate for poor mechanical stiffness or low-quality sensing. Therefore, the most effective pathway to higher assembly accuracy is a co-design approach: improving mechanical integrity and sensor fidelity while deploying adaptive control to mitigate the residual uncertainties that remain unavoidable in industrial operation.

In summary, the study supports the conclusion that a prototype industrial robotic arm using adaptive control can improve the accuracy and reliability of automatic assembly by reducing drift-driven offsets, enhancing repeatability across cycles, and stabilizing interaction behavior during contact transitions. The conclusions drawn from the results and discussion collectively show that the proposed approach addresses the core industrial problem of accuracy degradation under variable conditions, bridges an applied research gap by validating adaptation within a prototype framework, and establishes a defensible theoretical–practical link between adaptive control, stability assurance, and interaction-aware assembly performance.

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