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Operator-in-the-Loop Digital Twin Enabled Augmented Reality for Assembly Quality Assurance

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Abstract

Ensuring dimensional and geometric quality during manual and semi-automated assembly remains challenging in low-volume, high-complexity manufacturing systems. Operator variability, incomplete process standardization, and part-level geometric deviations frequently lead to tolerance non-conformities, rework, and installation delays. While digital twins offer strong potential for process monitoring and optimization, their integration with human operators during assembly execution remains limited. This paper proposes an operator-in-the-loop digital twin (OIL-DT) framework for tolerance-driven assembly quality assurance, in which augmented reality (AR) serves as a real-time interaction layer between digital and physical domains. The framework integrates CAD-based geometric models, assembly process plans, and tolerancing intent within a cyber–physical architecture, enabling spatially registered guidance and real-time alignment verification during assembly execution. Unlike instruction-centric AR systems, the proposed framework embeds executable tolerance constraints directly into assembly execution. A Design for Six Sigma (DMADV) logic is adopted to ensure traceable links between quality requirements, tolerancing specifications, and AR-based enforcement mechanisms. The framework is experimentally validated on the assembly of a hybrid renewable energy generation unit. Compared with conventional procedures, the AR-enabled approach reduced installation time and eliminated recurring tolerance-related interruptions previously causing extended delays. The results demonstrate that embedding tolerance enforcement and execution traceability within an OIL-DT can significantly improve assembly robustness and consistency without reducing operator autonomy.

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Keywords: Augmented reality; Operator-in-the-loop; Digital twin; Assembly quality assurance; Tolerance design; Robust design

1. Introduction

Assembly quality assurance remains a persistent challenge in the production of low-volume, high-complexity engineered systems. Despite significant advances in automation, many industrial assemblies continue to rely on manual or semi-manual operations due to geometric complexity, frequent product variants, and limited economic justification for full automation. In such contexts, dimensional and geometric non-conformities are often introduced during assembly execution, driven by operator variability, incomplete process standardization, and deviations in manufactured parts. These non-conformities propagate into costly rework, installation delays, and reduced operational reliability, particularly when tolerances are not explicitly enforced during assembly execution [1]. In field-deployed assembly environments, where

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metrological infrastructure is limited and environmental variability is significant, tolerance-related deviations often arise not from micrometric manufacturing errors but from sequencing mistakes, directional misalignment, and incomplete constraint satisfaction during execution. In such contexts, tolerance control must operate at the execution level rather than relying solely on post-assembly inspection [2], [3].

Digital technologies have been increasingly adopted to mitigate assembly variability and improve process robustness. Model-based approaches, including digital twins (DTs), have demonstrated strong potential for simulation, process optimization, and system monitoring [4], [5]. DTs enable the synchronization of digital models with physical systems, offering valuable insight into system behavior and performance. However, most existing DT implementations focus primarily on automated systems or post-process monitoring. The integration of human operators as active elements within DT frameworks remains limited, particularly for manual or semi-automated assembly operations, where operator decisions and actions directly influence geometric quality [6]. Augmented reality (AR) has emerged as a promising technology to support human-centered assembly processes [7]. By overlaying digital information directly onto the physical environment, AR enables spatially registered, context-aware guidance that can reduce cognitive load and improve task execution [8]. In industrial assembly applications, AR has been shown to improve task comprehension, reduce assembly time, and enhance operator training [9]. Nevertheless, most AR-based systems remain instruction-centric, focusing on step-by-step guidance without explicitly embedding geometric constraints, tolerancing intent, or quality verification mechanisms [10]. As a result, while AR can improve efficiency, its potential role in enforcing assembly quality and tolerance compliance during execution has not been fully realized [11].

The convergence of DTs and AR offers an opportunity to address this gap. When coupled appropriately, AR can serve as a real-time interaction layer between the digital and physical domains of a DT, enabling continuous feedback between nominal geometric intent and the evolving physical assembly state. In this configuration, the human operator is no longer external to DT but becomes an integral component of the cyber-physical system. Such an operator-in-the-loop digital twin (OIL-DT) enables the capture, evaluation, and guidance of assembly actions, deviations, and corrective decisions in real time, thereby extending DT capabilities beyond monitoring toward active quality assurance. Despite its promise, the formalization of OIL-DT for tolerancing-driven assembly quality remains underexplored. The translation of design-stage tolerance allocation into execution-stage geometric admissibility rules has received limited attention. Existing AR-based approaches typically provide instruction-centric guidance without explicitly embedding functional tolerances, alignment constraints, or sequencing logic into real-time execution control. Without such traceability between tolerancing intent and operator actions, tolerance-related deviations are often detected only after fixation or inspection, increasing the risk of rework and deviation propagation. This limitation is especially critical in low-volume, high-complexity systems assembled in remote or infrastructure-limited environments, where preventive control during execution is essential.

This paper addresses these gaps by proposing a DT–enabled framework for operator-in-the-loop assembly guidance using AR, with a specific focus on geometric and tolerancing-driven quality assurance. The framework integrates CAD-based geometric models, assembly process plans, and AR-guided visualization within a cyber-physical architecture that enables real-time alignment verification and deviation prevention during assembly execution. A Design for Six Sigma (DFSS) Define-Measure-Analyze-Design-Verify (DMADV) methodology is adopted to structure the framework, ensuring traceable links between quality requirements, tolerancing specifications, and AR guidance logic [12], [13]. This paper contributes: I) proposes and formalizes an OIL-DT architecture in which functional tolerancing intent is translated into execution-stage geometric admissibility rules within an AR-mediated cyber–physical framework. This shifts tolerance control from post-assembly verification toward real-time enforcement during assembly execution. II) The feasibility of the proposed approach is assessed through an exploratory industrial pilot involving the assembly of a hybrid renewable energy generation unit in both controlled yard and remote field conditions, providing preliminary evidence of improved execution consistency and reduced installation delays in a low-volume, high-complexity assembly context.

The proposed framework is positioned as a methodological and architectural contribution aimed at operationalizing tolerancing intent during assembly execution. Rather than replacing high-precision metrology systems or formal conformity assessment, it complements traditional inspection by addressing tolerance control upstream at the execution stage. In this sense, the AR interface functions as a real-time geometric admissibility and decision-support layer within an operator-centered DT, supporting preventive deviation management under field deployment conditions. The remainder of this paper is organized as follows. Section 2 introduces the proposed OIL-DT framework and DMADV-based methodology underlying architecture to ensure traceability between tolerancing requirements and AR guidance. Section 3 details the AR-enabled mechanisms for assembly quality enforcement. Section 4 reports the case study and experimental results, and Section 5 concludes the paper with a discussion of key findings and future research directions.

2. Operator-in-the-Loop Digital Twin Framework and Tolerancing Formalization

DTs are commonly defined as dynamically synchronized digital representations of physical systems that maintain bidirectional data exchange between digital and physical domains [4]. In manufacturing, DTs are widely used for system monitoring, simulation, and process optimization. However, most implementations focus on automated production systems where machine states can be continuously measured and controlled. In manual and semi-automated assembly environments, system behavior is strongly influenced by human

actions, decisions, and experience, making the integration of the operator within the DT loop particularly important. The proposed framework adopts an OIL-DT architecture in which the human operator becomes an active component of the cyber–physical system governing assembly execution. In this configuration, the DT not only represents the system state but also provides real-time guidance and admissibility feedback during assembly operations. Assembly actions performed by the operator influence the physical system state, while the DT provides contextual information derived from nominal design intent, assembly planning, and tolerancing requirements. Fig. 1 illustrates the proposed OIL-DT architecture, in which AR serves as the coupling interface between the acceptable geometric relationships, alignment condition, digital, and physical domains.

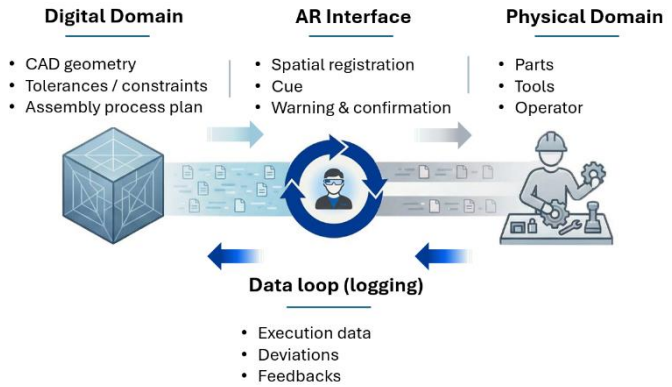


Fig. 1. Operator-in-the-loop digital twin architecture for assembly quality assurance.

The framework integrates two tightly coupled domains. The digital domain contains the nominal representation of the assembly system, including CAD geometry, assembly process plans, and tolerance-critical interface definitions. These elements encode functional design intent and define the admissible geometric relationships that must be respected during assembly execution. The physical domain corresponds to the real assembly environment, including components, fixtures, tools, and the operator responsible for performing the assembly tasks. AR provides the interaction layer between these domains. By spatially registering digital models with the physical environment, AR allows operators to visualize nominal geometry and alignment conditions directly within the workspace. This interaction enables operators to evaluate alignment conditions relative to design intent before irreversible operations occur. In this way, the DT extends beyond monitoring to become a decision-support and admissibility-control mechanism embedded within the execution stage of the assembly process.

2.1. DMADV Design Backbone for Operator-Centered Assembly Quality

To structure the development of OIL-DT, a Design for Six Sigma DMADV logic is adopted as a design backbone. Unlike DMAIC (Define, Measure, Analyze, Improve, Control), which is typically used to improve existing stabilized processes, DMADV is suitable for designing new systems or methodologies where the objective is to translate functional requirements into structured solutions. In the present context, DMADV provides a systematic approach for linking assembly quality requirements, tolerance-critical interfaces, and AR-based guidance logic within a unified framework. The methodology ensures traceability between functional design intent and the admissibility rules implemented during assembly execution. As illustrated in Fig. 2, DMADV provides traceability from assembly quality requirements to AR guidance logic and verification outcomes.

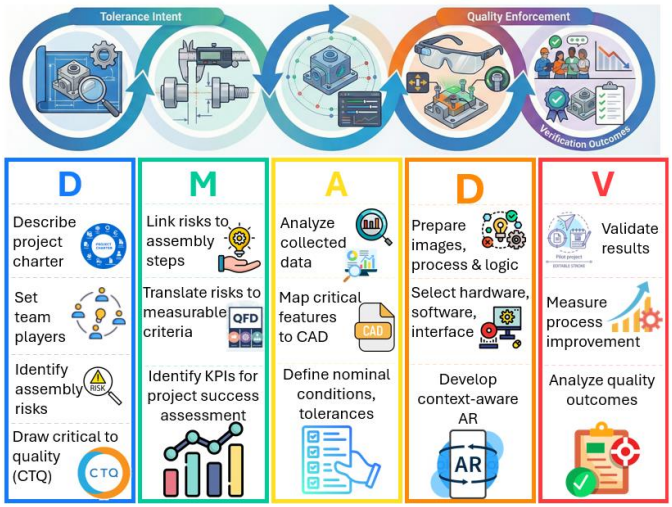


Fig. 2. DMADV-based traceability from assembly quality requirements and tolerancing intent to AR guidance logic and verification outcomes within the operator-in-the-loop digital twin framework.

In the Define–Measure phase, quality-critical assembly interfaces are identified by analyzing operations sensitive to geometric deviation, sequencing errors, or directional misalignment. These risks are translated into measurable characteristics such as alignment axes, constrained assembly directions, and mating surface conditions that must be respected during execution. During the Analyze phase, tolerance-critical features are mapped to geometric entities within the digital model. This step establishes explicit links between tolerancing intent and the digital representation of the assembly system. Interfaces with a high risk of deviation propagation are prioritized, and admissibility conditions are defined to ensure that assembly steps satisfy functional alignment requirements. In the Design phase, AR-based guidance is developed to expose these admissibility conditions directly to the operator. Assembly procedures are decomposed into discrete steps; each is associated with alignment cues and execution constraints that support correct positioning and sequencing before irreversible operations such as fastening or locking. The Verify phase evaluates the framework's effectiveness through pilot assembly operations. The objective is not statistical process optimization but rather verification that the proposed architecture can translate tolerancing intent into actionable guidance during assembly execution. Through this DMADV-driven design logic, tolerancing requirements defined during system design are operationalized within the execution stage of the assembly process.

2.2. Pose-Based Geometric Admissibility and Tolerance Formalization

A key element of the proposed framework is the formalization of tolerance enforcement through a pose-based acceptance rule that links nominal design intent to real-time assembly evaluation. For each tolerance-critical interface, a nominal component pose is defined in the digital domain based on CAD geometry and process planning. During assembly execution, the component pose estimated from AR registration is compared with this nominal pose to evaluate alignment conditions before irreversible operations such as fastening or locking. Let $T_n \in \mathrm{SE}(3)$ denote the nominal pose of a component defined in the DT (from CAD/process plan), and $\boldsymbol{T_e} \in \mathrm{SE}(3)$ the estimated pose obtained during AR-assisted assembly (from AR registration/tracking), where SE(3) represents the Special Euclidean group describing rigid body transformations in three-dimensional space. The relative pose error can then be presented as:

$$\Delta T = T_n^{-1} T_e = \begin{bmatrix} R_\Delta & t_\Delta \\ 0 & 1 \end{bmatrix} \quad (1)$$

Where R_Δ and t_Δ represent rotational and translational deviations between the two poses. To evaluate alignment during assembly execution, translational and rotational/angular misalignments (e_t and e_r) are quantified using the following metrics:

$$e_t = \|t_\Delta\|_2 \quad (2)$$

$$e_r = cos^{-1}\left(\frac{tr(R_\Delta)-1}{2}\right) \quad (3)$$

$tr(R_\Delta)$ denotes the matrix trace operator, and assembly progression to subsequent steps is allowed only when the admissibility conditions $e_t \le \tau_t \; and \; e_r \le \tau_r$ are satisfied, where τ_t and τ_r denote the admissible translational and rotational thresholds associated with a given interface. In this work, these thresholds are derived from the functional tolerance budget of the assembly interface. The tolerance budget represents the admissible range of geometric variation that does not compromise assembly feasibility, directional alignment, or sequencing integrity. Unlike dimensional inspection tolerances used in metrological verification, these admissibility thresholds are intended to prevent gross misalignment and constraint violations during execution. To generalize the formulation, the admissible threshold can be expressed as $\tau = \alpha\,(T - kU)$, where T denotes the functional tolerance associated with the interface, U represents the measurement uncertainty of the sensing modality, k corresponds to a confidence level (typically $k \approx 2$ @ 95% CL), and $\alpha \in [0.5,0.8]$ is a scaling coefficient reflecting the assembly stage and allowable alignment margin.

In the present exploratory implementation, thresholds were defined from functional assembly requirements rather than from experimentally characterized sensor uncertainty. The formulation, therefore, serves as a scalable framework illustrating how tolerance allocation and sensing uncertainty can be integrated into execution-stage admissibility control in future high-precision implementations. By embedding pose-based admissibility evaluation within OIL-DT, the framework translates design-stage tolerancing intent into real-time execution guidance, enabling deviations to be detected and corrected prior to fixation. This shifts tolerance control upstream in the assembly lifecycle, reducing the likelihood of deviation propagation and rework in manual and field-deployed assembly contexts.

3. AR-Enabled Assembly Quality Enforcement

The AR interface provides the operational layer through which the operator interacts with the DT during assembly execution. Rather than replacing operator expertise, the system acts as a contextual guidance tool that exposes alignment constraints, sequencing logic, and admissibility feedback directly within the operator's workspace. By spatially registering CAD models with physical components, the AR system allows operators to visualize nominal geometry and alignment conditions in situ. This enables evaluation of geometric admissibility relative to design intent before performing irreversible assembly actions. In this way, the system supports early detection and correction of misalignment conditions that could otherwise propagate into downstream deviations or rework.

Unlike instruction-centric AR systems that primarily provide step-by-step instructions, the proposed approach emphasizes geometric admissibility feedback. Visual cues highlight admissible alignment regions, orientation requirements, and assembly directions, helping the operator maintain compliance with tolerance-critical conditions throughout the execution process. Quality-critical steps are associated with explicit quality gates that prevent premature fixation or incorrect sequencing. For example, alignment conditions must be met before fasteners are tightened to ensure that the relative positioning of components is achieved before locking the assembly. This state-based guidance preserves execution flexibility while maintaining control over tolerance-critical conditions.

The prototype system was implemented on an industrial tablet equipped with an integrated RGB camera. Spatial registration between digital models and physical components is achieved through marker-based tracking using QR-coded fiducial markers attached to reference components within the assembly environment. Each assembly component is identified through its bill-of-material (BOM) number, which the operator selects manually within the AR interface before executing the corresponding assembly step. Automatic part recognition was not implemented in this exploratory deployment, as the primary objective was to evaluate the feasibility of AR-supported execution guidance under field deployment conditions.

To support operation in remote installation environments where network connectivity may be unavailable, all execution data are stored locally on the device. Logged information includes step confirmations, alignment checks, and operator feedback collected during assembly execution. This lightweight architecture allows the framework to operate in infrastructure-limited environments and provides a foundation

for future integration with more advanced sensing modalities or DT connectivity.

During assembly execution, the AR interface provides context-aware visual cues indicating admissible alignment relative to nominal geometry. Assembly steps are presented sequentially, and operators receive visual guidance indicating positioning constraints, orientation requirements, and component interaction conditions. When alignment conditions satisfy the admissibility thresholds defined in Section 2.2, the operator can confirm completion of the step and proceed to the next operation. If deviations exceed the admissible limits, the system highlights the misalignment and provides corrective guidance to assist the operator in restoring acceptable positioning (see Fig. 3). Rather than enforcing rigid automation, the system preserves operator autonomy by requiring explicit confirmation before progression. In safety-critical operations, supervisor validation can be required before the next assembly step is authorized. Through this interaction mechanism, the DT provides real-time awareness of deviations while allowing the operator to remain the primary decision-maker in the assembly process.

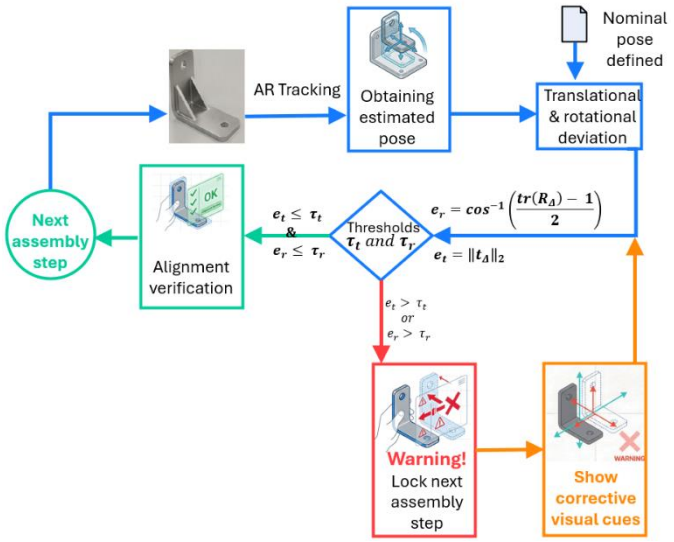


Fig. 3. Pose-based deviation evaluation and real-time feedback.

4. Case Study and Experimental Validation

The proposed OIL-DT framework was assessed through an industrial case study involving the assembly of a standalone hybrid renewable energy generation unit [7]. The system consists of multiple mechanical, electrical, and structural subsystems that must be assembled on-site under varying environmental conditions. Due to its geometric complexity, low production volume, and deployment in remote locations, the assembly process is largely manual and relies heavily on operator expertise. The system assembly has experienced installation delays and rework due to sequencing mistakes, misalignment of structural interfaces, or late detection of assembly inconsistencies. These issues often arise during field deployment, where corrective interventions are more difficult to perform. Given the low-volume and operational constraints, a fully controlled experimental comparison was not feasible. This context, therefore, provides a relevant environment for assessing the feasibility of AR-supported operator guidance and execution-stage admissibility control. During AR-supported execution, operators performed assembly tasks using spatially registered digital guidance displayed on the tablet interface. The system provided visual cues indicating nominal alignment conditions and required operator confirmation before progression to subsequent steps. Execution logs and operator feedback were collected to evaluate the approach's usability and practical impact (see Fig. 4).



Fig. 4. An example of operator assistance for wind turbine deployment.

Performance assessment focused on process-oriented indicators relevant to assembly robustness rather than on final dimensional inspection results. These indicators included: overall installation duration; occurrence of alignment or sequencing errors; rework or interruption events during assembly; perceived clarity and consistency of assembly instructions reported by operators. To characterize alignment robustness during execution, a First-Pass Alignment Rate (FPAR) indicator was introduced. Let N be the total number of tolerance-critical assembly steps and n_{pass} be the number of steps that satisfied admissibility conditions before fixation. The indicator is defined as:

$$\text{FPAR} = \frac{n_{\text{pass}}}{N} \tag{4}$$

Which reflects the proportion of assembly operations completed without requiring corrective repositioning. Observations from the pilot deployments suggest that the AR-assisted workflow improved execution clarity and reduced the likelihood of sequencing and alignment errors during assembly. In the controlled yard trials, the installation duration was observed to decrease by approximately 15% compared with conventional procedures, primarily due to improved sequencing clarity and earlier detection of alignment inconsistencies. Across the pilot deployments, an FPAR value of approximately 0.85 was observed for tolerance-critical steps, indicating that the majority of alignment conditions were satisfied on the first attempt before fixation. Operators also reported improved confidence in step sequencing and alignment verification when using the AR interface. While the limited number of deployments precludes statistical generalization, the observations demonstrate the practical feasibility of integrating tolerancing-driven admissibility guidance into operator-centered assembly processes,

particularly in field-deployment contexts where traditional inspection-based approaches are difficult to implement.

Operators also reported improved consistency and perceived safety during assembly. Visualization of nominal geometry and explicit execution checkpoints reduced reliance on tacit knowledge, particularly during alignment-sensitive steps. The digital twin additionally provided execution traceability, allowing post-assembly review of deviations and corrective actions and supporting continuous process improvement. Although the present validation does not constitute a controlled statistical comparison, the observed improvements (first-pass alignment and reduced installation duration) demonstrate the practical feasibility of integrating AR-enabled admissibility guidance within an OIL-DT for complex manual and semi-automated assembly contexts. These improvements were achieved without reducing operator autonomy, illustrating how digital guidance and human expertise can be effectively combined. The proposed approach does not aim to replace high-precision metrology systems; rather, it supports real-time alignment guidance and error prevention during assembly execution, while final conformity verification remains the responsibility of dedicated measurement systems.

5. Conclusions

This paper presented an operator-in-the-loop digital twin framework integrating augmented reality guidance with pose-based geometric admissibility evaluation for manual and semi-automated assembly processes. The proposed approach translates tolerancing intent defined during the design stage into execution-stage admissibility rules, enabling alignment conditions to be evaluated directly during assembly operations. Coupling the digital twin with AR-supported visualization enables operators to receive contextual guidance to prevent misalignment, sequencing errors, and deviation propagation before irreversible assembly actions occur. The framework extends tolerancing control upstream in the assembly lifecycle by enabling early detection and correction of deviations during execution rather than relying solely on downstream inspection. The framework was assessed through an exploratory industrial pilot that involved assembling a hybrid renewable energy generation unit for deployment in remote field environments. This context is characterized by low production volume, limited infrastructure, and strong reliance on operator expertise. Observations from pilot deployments indicated improved clarity of assembly instructions, high first-pass alignment rates, and reduced installation duration compared with conventional procedures. Although the limited number of deployments precludes generalization, these observations demonstrate the practical feasibility of integrating tolerancing-driven guidance within an operator-centered digital twin while preserving operator autonomy.

The proposed approach does not aim to replace high-precision metrology systems but to complement them by preventing deviations during assembly execution and supporting early detection of alignment inconsistencies. Future work will focus on integrating higher-precision sensing technologies, improving spatial registration methods, and experimentally characterizing uncertainty-aware tolerance thresholds. More detailed tolerancing rules tailored to specific assembly interfaces and operations will also be developed, together with larger-scale validation campaigns and controlled comparisons with conventional assembly procedures. These developments will allow the proposed approach to mature from an exploratory industrial pilot to a scalable digital twin architecture supporting tolerance-driven assembly guidance in complex manufacturing and field-deployment environments.

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