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A Novel 2D to AR Integration Framework for Quality Control of MEP Rough-ins in Concrete Slabs

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***Abstract*— Mechanical, electrical, and plumbing (MEP) rough-ins within concrete slabs are a critical construction phase where errors and omissions (E&O) often result in costly rework, schedule delays, and quality issues. Traditional reliance on 2D drawings limits spatial coordination, making it difficult for field personnel to identify potential conflicts before installation. Therefore, this paper aims to introduce a pilot-test-ready framework that integrates 2D construction drawings with augmented reality (AR) to enhance quality control during MEP rough-ins. The objective is to establish a framework for a mock-up pilot test. This paper focuses on the structure of the framework and the planned evaluation; data collection will occur in subsequent phases. This framework will outline a process for digitizing 2D drawings, aligning them with the real environment, and overlaying the information using an AR device (Trimble XR10 with Trimble Connect). Initially, the framework will be applied in a pilot test on a controlled mock-up environment. Then, it will be expanded into a controlled environment study and eventually tested in an uncontrolled field setting. While data collection is planned for future phases, this paper discusses the structure and methodology that will form the foundation for systematic testing and integration into construction quality management practices. The intellectual merit of this study lies in establishing a structured framework that enhances coordination and E&O detection during MEP rough-ins by integrating 2D construction drawings with augmented reality. The broader impact includes improving quality control practices, reducing rework and delays, and promoting technology adoption in the construction industry. Additionally, the framework acts as an educational tool that supports workforce development and prepares future engineers for emerging digital construction environments.**

***Index Terms*— Augmented Reality, MEP Rough-Ins, Concrete Slabs, Errors and Omissions, Quality Control, 2D Drawings, Human–technology interaction.**

I. Introduction

Mechanical, electrical, and plumbing (MEP) -related errors and omissions (E&O) during concrete slab preparation often need corrective actions that can compromise slab integrity and structural performance. Despite the critical nature of the construction phase, the existing literature lacks substantial coverage of issues related to errors in concrete slabs, such as the incorrect placement or complete omission of mechanical, electrical, and plumbing elements, and their impact on construction delays [1], [2]. Survey findings indicated that E&O in MEP rough-ins for concrete slabs were consistently reported as impactful, with no respondents indicating a zero impact on project outcomes [3].

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E&O are often identified at a later project stage, leading to costly revisions that can slow the project and result in additional costs [4].

To mitigate such issues, AR has been adopted in construction, primarily by overlaying 3D models, such as Building Information Modeling (BIM), onto the real-world to enhance visualization and error detection [5]. However, the use of 3D models is not universal, particularly in smaller or lower-budget projects, and the integration of augmented reality with 2D construction drawings has been largely overlooked [6]. In a survey investigating the advantages and disadvantages of paper-based information delivery methods, the findings revealed that challenges include cross-referencing, ambiguity in 2D formats, and insufficient information in 2D drawings, as acknowledged by approximately 70% of participants [7].

To address E&O issues in concrete slab rough-in for MEP systems on construction sites, a systematic categorization of these MEP rough-ins was conducted. The three most common MEP rough-in components are as follows: 1- Embedded items include anchors or inserts: An anchor is used in slabs-on-grade or walls to secure them to rock or nearby structures. This prevents any movement of the slab or wall relative to the foundation, adjacent structures, or rock [8]. While an insert refers to any material, other than reinforcing steel, that is rigidly placed within a concrete form for permanent embedding in the hardened concrete [8]. 2- Slab spaces created with forms, including block-outs or bulkheads: A bulkhead is a partition in formwork blocking fresh concrete from a section of the form, or a partition closing a section of the form, such as at a construction joint [8]. While a blockout: a space within a concrete structure under construction in which fresh concrete is not to be placed, called core in United Kingdom [8]. 3- Trade place tubes, also known as sleeves refers to pipe or tube passing through formwork for a wall or slab through which pipe, wires, or conduit can be passed after the forms have been stripped; and/or a device used around an anchor to accommodate adjustment and preloading of the anchor after the concrete has hardened [8].

The placement of these three components is prone to E&O. The four most common issues associated with these three components are as follows: i- Dimension, ii- Position, iii- Securing errors, and iv- Complete omissions. These E&O lead to problems such as delays, rework, and safety hazards.

Therefore, this paper aims to introduce a pilot-test-ready framework that integrates 2D construction drawings with augmented reality (AR) to enhance quality control during MEP rough-ins. The framework is designed to be tested initially in a controlled mock-up environment and then tested in a real-world construction setting.

The novelty of this study lies in the development of a structured and repeatable methodology for integrating traditional 2D construction drawings into an augmented reality (AR) workflow, thereby eliminating the need for building information modeling (BIM) or 3D modeling. Unlike most current AR applications that rely on fully developed BIM models, which are typically limited to high-budget or highly digitized projects, this framework offers a practical solution for 2D-only projects to implement AR for quality control.

The research focuses on MEP rough-ins within concrete slabs, a phase often overlooked in AR literature despite its susceptibility to irreversible errors. By formalizing a step-by-step process that aligns 2D drawings, intentionally introduces errors and omissions (E&O), and conducts controlled evaluations, this methodology offers a practical solution for real-world construction workflows.

II. Background

A. Errors and Omissions in MEP Rough-Ins

To demonstrate the existence of these E&O in MEP rough-ins, a survey was conducted targeting construction professionals involved in MEP installations. The objective was to assess the frequency, types, and causes of errors in concrete slab rough-ins and to explore their impact on project timelines and costs. The survey results indicate that E&O is widespread, leading to significant project delays, increased costs, and impacts on quality and safety. Specifically, 62.5% and 93.8% of participants reported that such errors result in delays and cost increases, respectively. Delays of 1-4 workdays were common, causing schedule disruptions [9]. In addition to time and cost implications, respondents identified E&O as a contributor to water infiltration, compromised structural integrity, and long-term performance issues [9]. Such design errors in MEP systems, often due to confined spatial allowances, are frequently undetected until construction, leading to substantial rework and increased Requests for Information that further exacerbate project delays and costs [10].

The findings highlight the importance of early intervention and comprehensive quality control processes to tackle the ongoing challenges in construction project management [3]. Unresolved E&O during slab rough-ins can propagate into later project stages, particularly during handover and occupancy, resulting in rework, safety hazards, reduced building performance, and increased maintenance demands. [11]

B. 2D Drawings in Field Execution

The traditional 2D drawing-based approach to concrete slab rough-in is prone to E&O. E&O of elements can necessitate costly rework, as the concrete has already been poured and cured. Traditionally, embedded locations are documented using "lift drawings" in an x-y plane [12]. These drawings are created by construction team members responsible for coordinating embed placement [12]. The process of producing and accurately positioning these drawings is time-consuming and labor-intensive. Such errors can lead to rework, delays, and safety risks during construction. Integrating 2D MEP drawings with emerging technologies can provide a more efficient and effective solution. E&O in MEP system placement and sizing diminishes operational efficiency, increases costs, and creates potential future problems. Relying on conventional construction practices, including onsite observations, manual data collection, and human-driven decision-making, can be time-consuming and costly. They may negatively impact project schedules, budgets, and the profitability of stakeholders due to the risk of errors and omissions [13]. Given these challenges, advancements in digital construction tools, such as Building Information Modeling and Mixed Reality technologies, offer promising avenues for mitigating these persistent issues [14], [15]

C. Augmented Reality in Construction

Building Information Modeling (BIM) and 3D modeling have been developed to reduce these E&O; they are typically confined to major, high-budget projects. The integration of AR with BIM offers several advantages, including improved visual representation of construction sites and enhanced management throughout the construction process, among other benefits[16]. Although BIM offers full-scale visualization and coordination across systems, it requires quite significant investment in training and investment in software and hardware [17] and a significant learning curve [18], which can impact the company's productivity during the transition period. AR presents a more accessible and agile solution for visualizing and coordinating critical construction elements, offering a flexible alternative to traditional 2D blueprints that often fall short in providing a comprehensive understanding of complex projects [19]. AR facilitates the visual comparison of digital models with the physical environment, enabling early detection of deviations and improving model reconciliation [20].

Despite growing interest in AR applications, several critical research gaps remain; most existing AR workflows assume the availability of detailed BIM models, leaving limited support for projects that rely primarily on traditional 2D drawings [19]. Moreover, studies highlight the high-risk nature of the construction phase, where rework is often necessary and can be irreversible [21], [22]. Furthermore, many AR studies emphasize technology demonstrations rather than providing a structured, scalable methodology suitable for pilot testing and phased deployment in real-world construction environments.

Therefore, this paper aims to bridge these gaps by proposing a novel framework for integrating AR with existing 2D MEP drawings to enhance the accuracy and efficiency of slab rough-ins, thereby minimizing E&O in projects that do not fully leverage BIM:

- Integrates traditional 2D drawings into AR visualization,
- Targets E&O detection during slab-embedded MEP rough-ins, and
- Establishes a structured pathway from pilot mock-up testing to real-world deployment.

III. Proposed Framework and Pilot Test Design

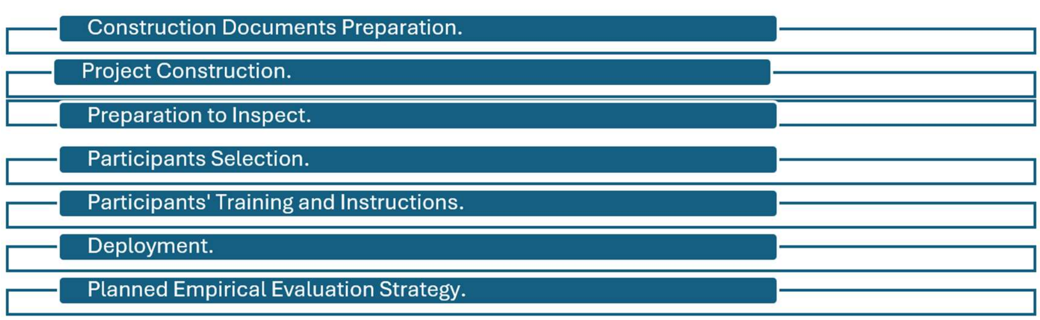

Figure 1. The processes of the Pilot Test and Controlled Environment Study

The selected framework method is appropriate for this study because it uses a controlled, step-by-step experimental design to ensure clarity and consistency in execution. The use of a full-scale physical mock-up with

intentionally embedded E&O provides a realistic yet controlled environment, enabling systematic comparison between traditional inspection methods and AR-assisted inspection. The framework consists of seven stages that are included in the pilot test, as shown in Figure 1: (1) Construction Documents Preparation; (2) Project Construction; (3) Preparation to Inspect; (4) Participants Selection; (5) Participants' Training and Instructions; (6) Deployment; and (7) Planned Empirical Evaluation Strategy. Each stage focuses on integrating the digital and physical components of the research environment to evaluate the impact of Augmented Reality (AR) technologies on mitigating MEP Rough-in error and omission (E&O) in concrete slabs.
The proposed structure will first undergo an initial pilot test using a controlled mock-up that simulates a concrete slab with embedded MEP components. The use of a full-scale mock-up aligns with prior research emphasizing the importance of controlled experimental environments in validating digital construction technologies [20], [23].

Stage 1: Construction Documents Preparation

This stage involves preparing and coordinating construction documents for the pilot test, specifically focused on a restroom mock-up with a complex MEP configuration prone to coordination issues. The drawings are refined to include layout adjustments, system separation, and detailed specifications for HVAC and piping, ensuring clarity and constructability.
Developed in Autodesk Revit and exported as PDFs, the coordinated drawings support both traditional inspection methods and AR-assisted workflows. All documents include a title block, complete dimensioning, and system legends for accurate interpretation, serving as the baseline reference throughout the pilot test. (see example Figures 2)

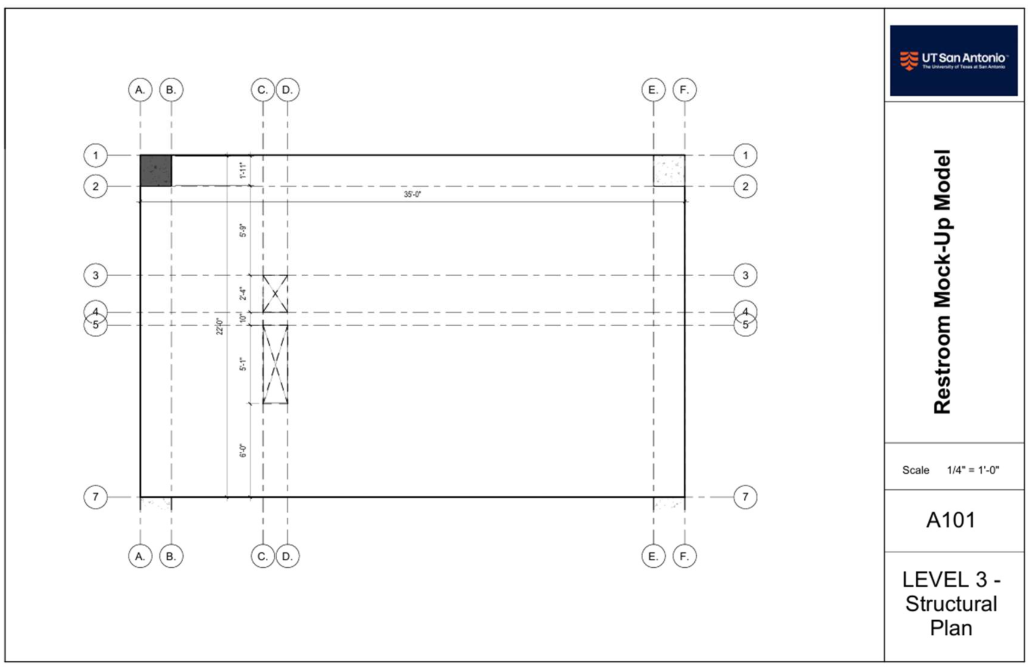

Figure 2. Floor Plan 3rd Level – Structural Drawings

Stage 2: Project Construction

The second stage involves constructing a full-scale restroom mock-up (22’ × 35’) that replicates a third-floor concrete slab and includes site preparation, slab formwork setup/materials, MEP rough-in installation, and intentional planned E&O (Figure 3). The elected components will intentionally have one of the following issues, as described in [24]: dimensional errors, where installed rough-in sizes do not match those specified in the construction drawings; positional errors, where components are incorrectly located or oriented relative to defined coordinates; securing errors, where components are improperly anchored or fastened; and complete omissions, where required MEP rough-ins are entirely absent from the installation. This structured classification ensures consistent introduction of controlled error scenarios, enabling effective assessment of detection performance across different inspection methods.

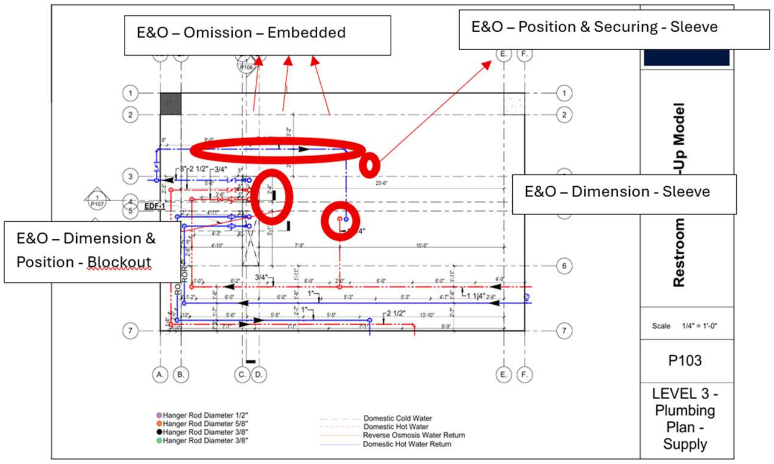

Figure 3. Floor Plan 3rd Level – Water Supply Plumbing drawings

These planned E&O (≈16% error rate) allow direct comparison of AR-assisted and traditional inspection methods in detecting MEP rough-in discrepancies.

Stage 3: Preparation to Inspect

In this stage, all inspection materials and digital workflows are prepared so that participants can conduct pilot inspections using either traditional 2D drawings on an iPad or AR via the Trimble XR10, while referencing the same design information. Finalized 2D drawings are uploaded and aligned on both platforms, and a QR code for a Qualtrics survey is established to document E&O (figure 4). By standardizing information access, visualization, and data capture, this stage isolates the effect of the inspection method itself for direct comparison between AR-assisted and traditional approaches.

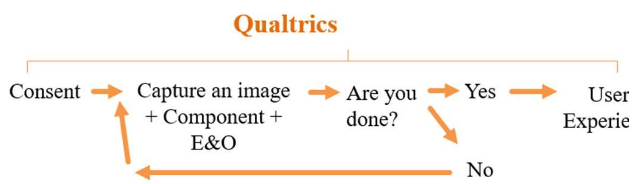

Figure 4. Report on the Qualtrics Survey

Stage 4: Participant Selection

In this stage, eight senior undergraduate students will be recruited. These participants will have a foundational understanding of construction processes, and will be randomly assigned to one of two groups using a random table. This method ensures unbiased group allocation and minimizes selection bias between the traditional and AR-assisted conditions [25]. The two groups are as follows:

- Group 1 (Traditional): The first group will perform inspection using standard methods (2D drawings on iPad/phone). Participants will rely on conventional ways, such as visual comparison and manual measurement, to identify any E&O.
- Group 2 (AR-Assisted): This group will perform inspection using AR through the Trimble XR10 device. Participants will view the digital overlay with the physical mock-up drawings and compare them to identify any E&O.

Both groups will engage with the same mock-up that replicates real-world construction scenarios, including the same pre-identified E&O of MEP rough-ins in concrete slabs. All participants will be engaged under the same conditions using the same mock-up, enabling a controlled comparison between traditional and AR-assisted methods.

Stage 5: Participants' Training and Instructions, and Pilot Test Preparation

This stage focuses on preparing participants for the inspection tasks. It aims to ensure that they possess the essential baseline knowledge and clearly understand the inspection process. This stage includes the following:

- Online Orientation / Fundamentals of MEP Systems and Readiness Test: All participants will complete an online orientation that includes a brief introduction to MEP systems, common installation errors, inspection procedures, and a readiness test to ensure baseline knowledge and preparedness. The readiness assessment, aligned with selected levels of Bloom's taxonomy (knowledge, application, and analysis), ensures participants understand and can apply fundamental concepts before site inspections.

- Device Training (Trimble XR10 with Trimble Connect): All participants assigned to the AR-assisted group will also complete focused device training on the Trimble XR10, consisting of a short, pre-recorded overview and a brief hands-on session to ensure operational familiarity without influencing inspection behavior. This training, including individual eye-tracking calibration, is intended to minimize technology-related learning effects and allow participants to focus on the inspection tasks.

Stage 6: Pilot Test Deployment (Inspection Workflow)

The sixth stage represents the core of the study, which is to evaluate the impact of using Augmented Reality (AR) technologies to mitigate MEP Rough-in E&O in concrete slabs, with pilot tests to be deployed. The purpose of this stage is to establish the procedures and measurement protocols that will enable a future comparison between AR-assisted and traditional inspection methods.

Stage 7: Planned Empirical Evaluation Strategy

Although this paper does not report outcome data, a structured two-phase evaluation plan has been developed to validate the proposed framework. The first phase will consist of a pilot implementation conducted using the constructed mock-up drawing. The purpose of this phase is to identify potential issues before full deployment. The second phase will involve a controlled environment/lab study in which the refined framework will be formally tested, and this is where the main hypothesis testing will occur.

IV. Conclusions

This paper introduces a framework structured for pilot testing that integrates 2D drawings with augmented reality to enhance quality control during MEP rough-ins in concrete slabs. By prioritizing methodology and phased implementation over immediate performance metrics, the study establishes a solid foundation for systematic testing and real-world application.

The next phase of this research involves full pilot deployment followed by a controlled empirical study to validate the framework and generate measurable evidence regarding its impact on error detection and construction quality. These subsequent stages will determine the framework's applicability to real-world conditions and its potential for broader integration into construction quality management practices.

Limitation

This research uses a physical mock-up that will be constructed without reinforcement steel to secure embedded items. In industry practice, anchors are typically tied to rebars to prevent displacement during vibration and concrete placement. To assess whether the absence of reinforcement significantly impacts participant performance, we will analyze survey findings. If more than 90% of participant responses are accurate, a revised physical mock-up that includes reinforcement will be developed to better reflect real-world conditions. The study is subject to several limitations across five key areas. Physical mock-up limitations arise from the slab's lack of reinforcement, which may affect anchor stability and reduce the applicability of results to real-world construction scenarios. Technology limitations reflect unforeseen challenges encountered with the hardware and software used during the pilot test. Similarly, data collection limitations involve unanticipated difficulties in capturing accurate and consistent measurements. Safety limitations highlight potential risks encountered during on-site activities, while training limitations pertain to unexpected challenges in preparing participants to use the inspection tools effectively. Together, these constraints should be considered when interpreting the study's findings.

Future Work

Following the pilot test, the framework will be extended through two additional phases. The controlled environment study will take place in a laboratory or training facility, where variables can be carefully managed to facilitate systematic data collection and enable performance comparisons. The uncontrolled field deployment will involve implementation on an active construction site, allowing assessment of the framework's real-world applicability, robustness, and integration into existing quality management practices. Together, these phases will generate quantitative and qualitative evidence to determine whether integrating 2D drawings with augmented reality measurably improves E&O detection and construction quality outcomes.

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