Human-Centered Design and Development of a UAV-UGV Hybrid Robotic System for Confined Space Inspection in Lean Construction 4.0

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Abstract

Inspection and maintenance of confined spaces in critical infrastructure pose major challenges for the Architecture, Engineering, Construction, and Operation (AECO) industry, including high safety risks, substantial inefficiencies, and heavy dependence on manual labor. Despite the promise of Industry 4.0 technologies, the adoption of autonomous systems remains limited due to insufficient user-centric design. This research presents the design, development, and real-world validation of a novel hybrid robotic system tailored for confined-space inspection. The system integrates a custom hexapod Unmanned Ground Vehicle (UGV) with a DJI Mini 4 Pro Unmanned Aerial Vehicle (UAV), developed through the combined principles of Lean Construction 4.0 and Human-Centered Design (HCD). A socio-technical approach grounded in the Unified Theory of Acceptance and Use of Technology (UTAUT) ensured alignment between advanced robotic capabilities and the practical needs of maintenance professionals. The platform employs an autonomous navigation stack based on Frontier Exploration and RTAB-MAP SLAM, enabling the UAV to generate and execute inspection flight paths independently. Captured imagery is processed via photogrammetry into high-fidelity 3D digital twins. Field trials conducted in an operational central infrastructure facility in Alberta, Canada, demonstrated a 62.5% reduction in inspection lead time, improved workflow efficiency from 40% to 76.2%, and a 59.16% decrease in human exposure to hazardous environments. By bridging technical performance with user acceptance and lean principles, this hybrid system establishes a replicable framework for autonomous inspection, significantly enhancing safety, efficiency, and sustainability in infrastructure asset management.

Keywords –

Lean Construction 4.0, Human-Centered Design, UAV-UGV Collaboration, Confined Space Inspection, Autonomous Robotic System

1 Introduction

The management of civil infrastructure is currently facing a precarious intersection of aging assets and a diminishing skilled workforce [1]. Facilities ranging from wastewater treatment plants to petrochemical refineries and subterranean utility tunnels rely on a labyrinth of confined spaces—areas defined by limited means of entry and exit, not designed for continuous human occupancy, yet housing vital operational components [2-4]. These environments are inherently hostile, frequently presenting atmospheric hazards such as oxygen deficiency, toxic gas accumulation (e.g., Hydrogen Sulfide), and the risk of engulfment or physical entrapment [5-7].

Despite the inherent dangers, the inspection of these spaces remains a fundamental requirement for regulatory compliance and structural health monitoring. The prevailing industry standard relies heavily on manual entry, a process that is arguably archaic in the face of modern technological capabilities [4, 7, 8]. Traditional inspection workflows are characterized by rigid, permit-heavy bureaucratic processes that prioritize safety through administrative controls rather than engineering elimination [5, 8]. A single inspection can require days of preparation, involving atmospheric testing, the erection of tripod rescue systems, the deployment of standby rescue teams, and the arduous process of "locking out" and "tagging out" energy sources [2]. This creates a scenario where the actual value-added activity—the visual assessment of a pipe or valve—constitutes a fraction of the total time and resource expenditure.

The construction and facility management sectors have long been criticized for lagging productivity growth compared to manufacturing [9]. Lean Construction emerged as a response, adapting the principles of the Toyota Production System (TPS) to the built environment. Its core tenet is the maximization of value through the systematic elimination of waste [10]. However, "traditional Lean" often hits a ceiling when constrained by human physical limitations [11, 12].

In that respect, Lean Construction 4.0 represents a theoretical evolution that synergizes Lean principles with the cyber-physical technologies of the Fourth Industrial Revolution (Industry 4.0) [13]. This paradigm posits that technology—specifically robotics, Internet-of-Things (IoT), and Artificial Intelligence—is not merely a tool for automation but a catalyst for Lean transformation [13]. By empowering the human inspector with a robotic agent, the constraints of the traditional workflow can be overcome. Robots do not require oxygen; they do not suffer from fatigue; and they can operate in environments that would be legally or ethically impermissible for humans [2, 14, 15]. This shift moves the safety hierarchy of controls from fallible approaches such as “Personal Protective Equipment (PPE)” and Administrative Controls” to "Elimination," substantially removing the human from the hazard entirely. Moreover, while single-robot solutions exist, they cannot simultaneously provide persistent ground mapping and rapid vertical aerial coverage without significant trade-offs in reach, stability, and energy efficiency.

While the theoretical benefits of robotic inspection are clear, the practical adoption of such systems in the construction industry has been sluggish. This resistance is rarely due to a lack of technical capability but rather a failure of design [2]. Robots developed in academic “greenhouses” often fail to address the nuance of the field: the dusty, wet, unstructured reality of a job site, and the cognitive load they place on operators who are typically tradespeople, not robotics engineers [2, 16].

This research addresses this gap by anchoring the technical development of the robotic system in Human-Centered Design (HCD). HCD is an iterative philosophy that places the end-user at the heart of the design process [17]. It argues that a robot is only as effective as the human-robot interaction (HRI) allows it to be [17, 18]. By employing focus groups, usability testing, and the Unified Theory of Acceptance and Use of Technology (UTAUT) [19], this study ensures that the resulting system is not just a technological advancement, but a practical tool that enhances the worker's capabilities.

This paper presents the end-to-end development of a hybrid UAV-UGV inspection system. The research is guided by three primary hypotheses:

H1: The application of an HCD framework will significantly improve the usability of robotic systems compared to current manual workflows.

H2: A robot-based system will facilitate more efficient information flow, reducing lead times and increasing value-added activity ratios.

H3: The deployment of autonomous robots will measurably reduce human involvement in hazardous inspection tasks.

The following sections will dissect the theoretical underpinnings of the approach, detail the intricate technical architecture of the hexapod and drone subsystems, analyze the algorithmic logic of the SLAM and exploration stacks, and present empirical data from a real-world case study. The overall system concept and collaborative workflow are illustrated in Figure 1, which depicts (a) the custom hexapod UGV called “Bubble” performing autonomous SLAM and frontier-based exploration using an NVIDIA Jetson Nano, YDLIDAR G4, and RealSense RGB-D camera; (b) the DJI Mini 4 Pro UAV executing a photogrammetry mission with pre-planned coverage paths derived from the UGV-generated map; and (c) the integrated workflow in which UGV map data are handed off to the UAV for mission planning and execution, ultimately producing layered digital outputs.

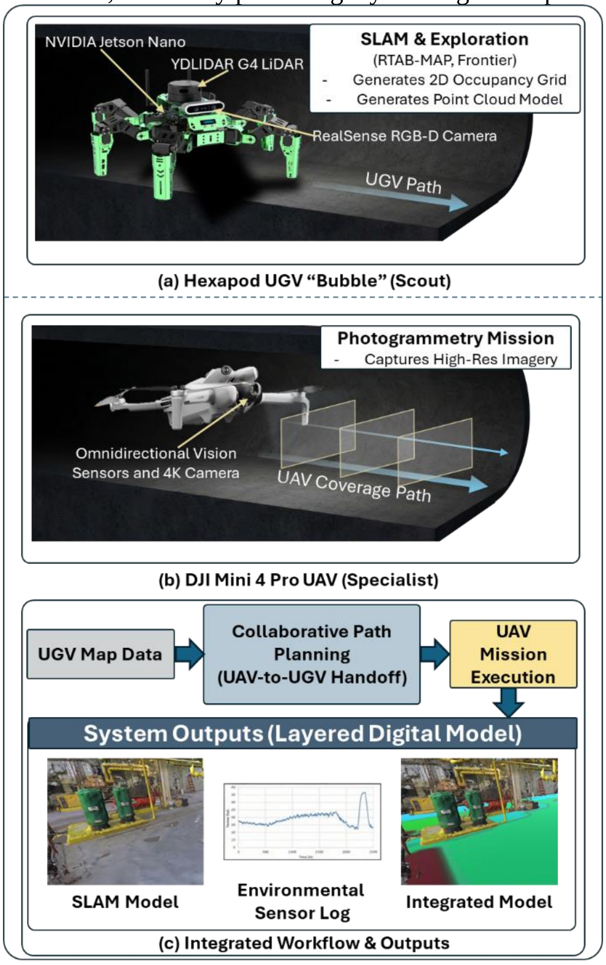

Figure 1 Overview of the hybrid UAV-UGV robotic

system for confined space inspection.

2 Theoretical Framework and Literature Review

2.1 The Convergence of Lean and Industry 4.0

The integration of production theory, people and culture, and Industry 4.0-inspired digital technologies, termed Lean Construction 4.0 (LC 4.0), represents a transformative opportunity for the AECO industry [13]. Traditional Lean focuses on process optimization through human-centric methods (e.g., Last Planner System), while Industry 4.0 introduces automation and data exchange [13]. The synergy lies in their shared goals: both aim to reduce waste and variability.

In the context of inspection, the 8 Wastes of Lean are omnipresent, including waiting for permits, unnecessary motion and transportation of safety gear, defects in subjective data, over-processing of manual reports, and non-utilized talent of skilled tradespeople.

The LC 4.0 framework presented in this section directly supports H2 by illustrating how cyber-physical systems eliminate the eight wastes, thereby facilitating more efficient information flow and increasing value-added activity ratios. A robot serves as a physical agent that digitizes the environment (Transformation) and automates the movement of data (Flow).

2.2 Human-Centered Design (HCD) in Construction Robotics

The construction industry is unique in its dynamic, unstructured nature. Unlike a factory line where a robot performs repetitive tasks in a controlled cage, construction robots must navigate changing terrains and interact with diverse human teams. This necessitates a design philosophy that goes beyond functional requirements.

Human-Centered Design involves four key phases [17]:

- Empathize: Deeply understanding the user's needs, often through ethnographic study.
- Define: Synthesizing these needs into actionable problem statements.
- Ideate: Generating a wide range of solutions.
- Prototype & Test: Iterative development with continuous user feedback.

This study integrates HCD with the UTAUT model, which iteratively develop the design the artifact of interest by continuously observing users' technology acceptance measured through the four constructs:

- Performance Expectancy: Does the robot help me do my job faster/better?
- Effort Expectancy: Is the robot easy to use?
- Social Influence: Do my peers and supervisors support its use?
- Facilitating Conditions: Does the organization provide the necessary infrastructure and support?

Addressing "Effort Expectancy" is particularly critical. System affordance is crucial in enabling and maintaining the consistent usage of robotic systems [20]. The interface and autonomy level must be tuned to the "Facilitating Conditions" of a typical maintenance department. By integrating Human-Centered Design with the UTAUT model, this section operationalizes H1, providing the methodological foundation for ensuring technology acceptance and improved usability among maintenance professionals.

2.3 The Hybrid UAV-UGV Paradigm

Confined spaces are heterogeneous environments. They may consist of long, flat tunnels (favorable to UGVs) intersected by vertical shafts or high ceilings (requiring UAVs) [4]. UGVs offer superior payload capacity, battery life, and stability. They can carry heavy LiDARs and computers but are limited by terrain obstacles and verticality [21]. On the other hand, UAVs offer unrestricted 3D mobility but are severely constrained by battery life (flight time) and payload [22]. In GPS-denied environments, they also struggle with drift and stability [23].

Table 1 Rationale for Platform Selection

Platform	Key Selection Criteria	Rationale
Hexapod UGV (Bubble)	Superior terrain adaptability, high payload for LiDAR + onboard computer, stability on wet/slippery surfaces	Outperforms wheeled/tracked UGVs in debris-filled tunnels; provides persistent mapping
DJI Mini 4 Pro UAV	Ultra-light (<249 g), omnidirectional sensing, VPS navigation, 48 MP camera	Fits through manholes and reaches vertical shafts/overhead piping inaccessible to UGVs

A hybrid UAV-UGV system was deliberately chosen over single-platform alternatives. Legged platforms with integrated high-resolution sensors lack vertical reach; adding arms increases complexity without solving aerial coverage needs. The UGV–UAV tandem delivers complementary strengths—persistent ground mapping plus rapid 3D aerial inspection—while minimizing communication overhead through a simple one-way map hand-off. This collaborative approach optimizes energy efficiency and data coverage [24, 25]. This hybrid UAV-UGV paradigm enables H3 by measurably reducing human exposure to hazards while leveraging the complementary strengths of both platforms.

3 Robotic System Design and Technical Architecture

The developed system is a custom-engineered solution designed to meet the specific constraints of confined space inspection: limited size, lack of GPS, low lighting, and the need for high-fidelity data.

3.1 The Ground Segment: Hexapod UGV Architecture

The ground platform is called 'Bubble', named by one of the co-authors' daughters. As shown in Figure 2, Bubble is customized based on the Hiwonder JetHexa, a six-legged robot chosen for its superior terrain adaptability compared to wheeled or tracked counterparts.

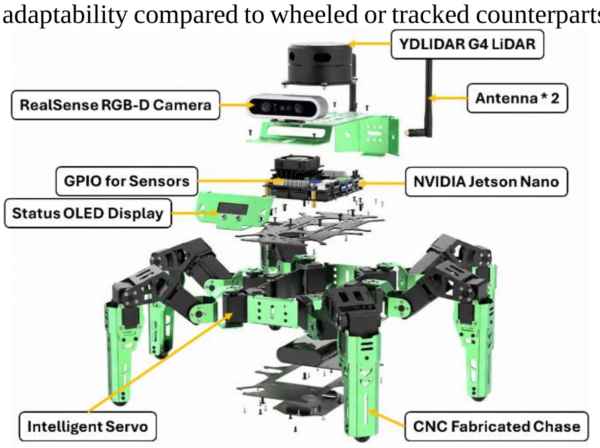

Figure 2 Bubble Components

3.1.1 Mechanical Design and Kinematics

The structure uses a full-metal aluminum alloy frame with 18 high-torque HTS-35H intelligent serial bus servos offering precise position feedback. The robot employs an inverse kinematics engine and supports two primary gaits: a fast tripod gait (statically stable with three legs in contact) for rapid mapping on flat terrain and a ripple gait ($\geqslant$5 legs in contact) for slippery or uneven surfaces typical of confined infrastructure.

3.1.2 Computational Core

Bubble's onboard computing is powered by an NVIDIA Jetson Nano (B01), featuring a 128-core Maxwell GPU and quad-core ARM Cortex-A57 CPU. This embedded platform enables real-time execution of computationally intensive tasks — including SLAM, point-cloud processing, and navigation — directly on the robot using CUDA acceleration, eliminating the need for cloud offloading.

3.1.3 Sensor Suite

Bubble is equipped with a multimodal sensor array designed for GPS-denied perception:

- LiDAR: EAI YDLIDAR G4 (360° FOV, 16 m range, 5–12 Hz) for precise occupancy grid mapping of walls and obstacles.
- RGB-D Camera: Intel RealSense Astra Pro on a 2-DOF pan-tilt mount for dense 3D point clouds and detection of negative obstacles.
- Environmental Monitoring: DHT22 sensor for temperature and humidity logging (non-toxic metrics only; sensor suite can be swapped as required).

3.2 The Aerial Segment: UAV Specifications

The aerial component is the DJI Mini 4 Pro. Its ultra-compact size (<249 g) and omnidirectional obstacle sensing system allow navigation through narrow conduits and manholes. The drone uses Visual Positioning System (VPS) technology for stable flight in GPS-denied environments and is equipped with a 1/1.3-inch CMOS sensor capable of 48 MP stills and 4K/60 fps HDR video, sufficient for high-resolution photogrammetry.

3.3 Software Architecture and Algorithmic Stack

The UGV operates on Ubuntu 18.04 LTS running ROS Melodic. The software stack integrates navigation, mapping, and decision-making nodes.

3.3.1 Simultaneous Localization and Mapping (SLAM): RTAB-MAP

The UGV employs Real-Time Appearance-Based Mapping (RTAB-MAP), a Graph-Based SLAM approach that is superior to filter-based methods (like GMapping) for this application due to its robust loop closure detection.

The system employs Real-Time Appearance-Based Mapping (RTAB-MAP), a graph-based SLAM approach chosen for its robust loop closure detection [26]. The map is maintained as a pose graph with nodes (robot poses + sensor data) and edges (geometric constraints) [26].

Memory management moves older nodes to long-term storage, ensuring efficient operation on the Jetson Nano [26].

3.3.2 Autonomous Exploration: Frontier-Based Navigation

Autonomous exploration is achieved through a Frontier Exploration algorithm [27]. LiDAR data is rasterized into a 2D occupancy grid, and the Wavefront Frontier Detector identifies boundaries between free and unknown space [27]. Frontiers are grouped and evaluated by a utility function considering information gain and travel cost [27]. The Timed Elastic Band (TEB) local planner generates kinematically feasible trajectories for the hexapod [27].

3.3.3 Collaborative Path Planning (UGV-to-UAV Handoff)

As shown in **Error! Reference source not found.**, the collaborative workflow consists of five stages. The UGV first generates a 2D occupancy grid map and SLAM model. Safe traversable areas are extracted, and the boustrophedon cellular decomposition algorithm computes coverage paths [28]. The resulting 2D coordinates are converted into 3D waypoints at a pre-defined altitude and exported as KML/KMZ files compatible with the DJI flight controller. The UAV then executes the pre-calculated mission using its onboard obstacle avoidance as a safety layer.

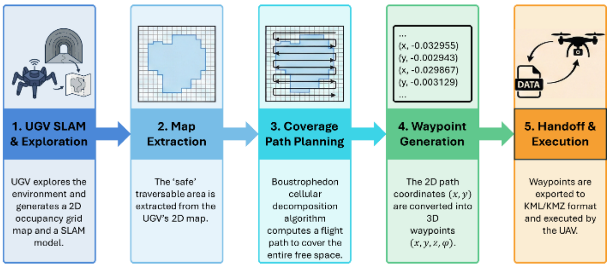

Figure 3 Collaborative Path Planning Workflow

3.4 Reality Capture: Photogrammetry Pipeline

High-resolution images from the UAV are processed in Bentley ContextCapture using a standard photogrammetry workflow: Structure-from-Motion (SfM) for camera pose estimation, dense reconstruction for 3D point clouds, and mesh & texture generation. The result is a high-fidelity 3D digital twin suitable for remote visual inspection and defect annotation.

4 Human-Centered Design Process

The system development followed an iterative HCD framework integrated with the UTAUT model, consisting of four phases.

4.1 Phase 1: Empathize and Define

The research began with a deep dive into the user experience. Focus groups were conducted with 28 industry practitioners from Alberta, Canada, including tradespersons (5), foremen (7), engineers (11), and project managers (5). Participants were required to have a minimum of five years experience working in building/facility management, construction inspection, and related fields. The focus group was approved by the University of Alberta Human Research Ethics Boards (Ethics ID Pro00147080).

Focus groups explored user needs through the UTAUT lens. Focus groups revealed two dominant user concerns: (i) fear of complex interfaces that would require extensive training and (ii) the need for rugged hardware capable of withstanding dust, moisture, and physical abuse. Value Stream Mapping (conducted via direct observation and timing of five complete traditional inspection cycles) quantified a 35-day lead time with only 40 % value-added activity and produced a baseline SUS score of 73.8 from the 28 participants.

4.2 Phase 2: Ideate and Prototype

Virtual prototyping in NVIDIA Isaac Sim tested robot morphologies, sensor layouts, and control interfaces. Low-fidelity virtual prototypes were tested with a subset of 12 participants using structured A/B usability sessions. The projected SUS score improved from 63.1 (initial engineering-heavy dashboards) to 75.2 (task-oriented designs) before physical fabrication.

4.3 Phase 3: Develop and Deploy

The physical system (Hexapod + Drone) was built and deployed in the target facility. The UGV successfully navigated the access tunnel and cell floor, generating the occupancy map. The UAV utilized this data to fly a coverage pattern, capturing the upper infrastructure. The mission resulted in a multi-layered dataset: a 3D photogrammetry model for visual inspection, a SLAM point cloud for geometric verification, and a sensor log (temperature/humidity) for environmental health monitoring.

4.4 Phase 4: Monitor and Improve

This ongoing phase focuses on longitudinal data collection. Future plans for the Hexapod + Drone design include analyzing system logs to optimize battery usage, refining the AI defect detection algorithms, and continuously gathering user feedback to update the interface.

5 Case Study Results and Evaluation

The field trials were conducted in an operational central infrastructure facility in Alberta, Canada, over three days (6–7 April 2025). Data collection included: (i) timed observation for Value Stream Mapping (pre- and post-deployment), (ii) SUS surveys administered immediately after each mission (n=8 participants), (iii) automated robot logs for navigation metrics, and (iv) photogrammetry model quality assessment using Bentley ContextCapture metrics. Three full-scale deployment trials were performed with 8 on-site participants (3 tradespersons, 3 engineers, 2 managers).

The deployment of the system in the Alberta facility provided empirical data to test the research hypotheses. A summary of the key performance indicators is shown in Table 2.

Table 2 Results of Key Performance Indicators of Case Study

Metric	Traditional Workflow	Robotic Hybrid System	Improvement
Inspection Lead Time	35 Days	13.1 Days	62.5% Reduction
Flow Efficiency	40%	76.2%	+90.5% Increase
Hazardous Exposure	94.67%	38.67%	59.16% Reduction
System Usability (SUS)	73.8	82.9	+12.3% Increase

5.1 Usability and Acceptance (H1)

Post-deployment surveys using the System Usability Scale (SUS) yielded a score of 82.9, as shown in Figure 4. This is a marked improvement over the baseline of 73.8. In usability terms, this shifts the system from "Good" to "Excellent", according to the scale developed by Bangor, et al. [29]. It indicates that the HCD process successfully mitigated the complexity of the technology, creating a tool that maintenance workers felt confident using. This validates H1.

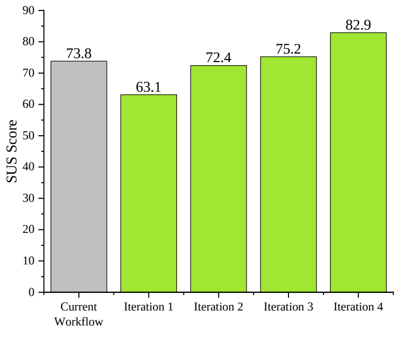

Figure 4 SUS - Current Workflow and Iterations

5.2 Efficiency and Flow (H2)

The Value Stream Map for the robotic workflow showed a dramatic transformation. The total time to complete an inspection cycle dropped from 35 days to 13.125 days—a 62.5% reduction. The ratio of value-added time to total lead time increased from 40% to 76.2%. The robot eliminated the 14-day "Pre-Inspection" delay entirely (no permits required) and compressed the "Data Translation" phase from 3 days to hours via automated photogrammetry. This validates H2.

5.3 Safety Impact (H3)

The percentage of time humans spent physically engaged in hazardous execution tasks dropped from 94.67% (manual entry and measurement) to 38.67% (remote supervision and robot deployment), as shown in Figure 5. This represents a 59.16% reduction in direct human exposure to confined space hazards. By moving the operator from the "hot zone" to a control station, the system fundamentally alters the risk profile of the job. This validates H3.

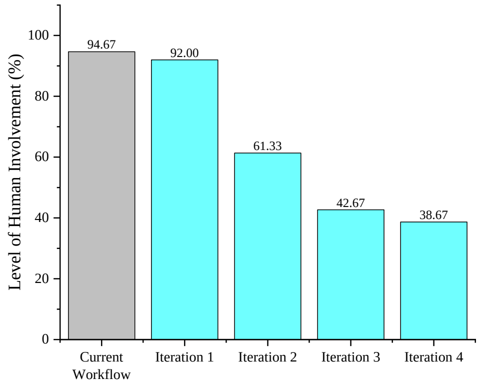

Figure 5 Level of Human Involvement in Hazardous Inspection Tasks of the Current Workflow and Iterations

5.4 Navigation and Exploration Performance

The UGV completed autonomous frontier-based exploration of an 85 m² confined cell in 52 minutes with 98 % map coverage and an average localization error of 4.2 cm. The UAV executed 100 % of its pre-planned photogrammetry missions without intervention, achieving 92 % image overlap and completing the flight in 11 minutes.

6 Discussion

The success of this project was not defined solely by the hardware but by the methodology. The application of Lean Construction 4.0 provided the "Why" (waste reduction), while Human-Centered Design provided the

"How" (user acceptance) for the whole system design. This dual approach prevented the common pitfall of "solutionism," where technology is applied to a problem without understanding the workflow it disrupts. The robotic system did not just automate the inspection; it re-engineered the process to remove administrative bottlenecks. The hybrid architecture proved valuable. The UGV provided the stability and persistence needed for mapping, while the UAV provided the agility for vertical inspection. The use of RTAB-MAP and Frontier Exploration enabled a level of autonomy that potentially reduced the cognitive load on the operator.

However, challenges remain. Visual SLAM and visual odometry on drones can suffer from "drift" in environments with repetitive textures (e.g., long, smooth concrete pipes) or poor lighting. While the LiDAR helped anchor the UGV, the UAV is more vulnerable to VPS failure in dust or darkness. Future iterations must explore sensor fusion techniques, potentially integrating Ultra-Wideband (UWB) beacons deployed by the UGV to create a local "GPS" network for the drone. Additionally, the current workflow requires a data handoff that could be further automated into a seamless, single-command mission. Moreover, the attitude of UAV path is now pre-defined by the inspector. Future works should aim to automate this process by integrating machine learning algorithms in the drone. It is worth noting that DJI offers limited API supports on the latest models. Thus, it is also recommended to apply customized UAV for the hybrid system.

This study demonstrates that the barrier to robotic adoption in construction is not cost or capability, but integration. By proving that a relatively low-cost system (Bubble + Mini 4 Pro) can deliver enterprise-grade results when wrapped in a proper workflow, this research offers a scalable model for Small and Medium Enterprises (SMEs) in the sector. It signals a shift in the workforce, where the value of a tradesperson evolves from their ability to physically access a space to their ability to interpret the data coming out of it.

7 Conclusion

This paper presents a compelling validation of a human-centered, lean-driven approach to robotic inspection in confined spaces. The developed hybrid UAV-UGV system successfully navigated the complex, hazardous environment of a live infrastructure facility, delivering high-fidelity digital twins while significantly reducing operational lead times and human risk.

The study confirms that the principles of Lean Construction 4.0—when operationalized through robust robotic autonomy and user-centric design—can fundamentally transform asset management. By eliminating the "waste" of hazardous entry and bureaucratic waiting, the system unlocks true value: safer workers, faster data, and more resilient infrastructure. As the AECO industry continues its digital transformation, frameworks like the one presented here will be essential in bridging the gap between the promise of automation and the reality of the job site.

8 Acknowledgements

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