A Survey-Controlled Photogrammetric Framework for Consistent Multi-Floor Geometry Estimation in Robotic Facade Installation

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Abstract -

Robotic facade installation across multiple floors necessitates millimeter-level geometric accuracy to ensure reliable anchor alignment and panel placement. The present paper proposes a survey-controlled sensing and modeling framework that integrates a construction tool with high-resolution close-range imaging to establish a consistent multi-floor reference frame. The utilization of facade anchors is facilitated through the employment of survey markers, which serve to localize these anchors. The registration of dense, image-based geometry to the survey frame enables the execution of precise height transfer and inter-floor alignment. The resulting survey-referenced geometry is aligned with an existing design Building Information Modeling (BIM)/Industry Foundation Classes (IFC) model and evaluated against survey ground truth to verify multi-floor consistency, error propagation, and anchor-level suitability for robotic facade installation. The proposed framework is predicted on the explicit addressing of multi-floor alignment and error propagation, thereby providing a reliable geometric foundation for robotic facade installation and reproducible accuracy evaluation across floors.

Keywords -

Construction, visual, localization, BIM, Measurement, installation, robotics.

1 Introduction

The installation of robotic facades across multiple floors necessitates geometric accuracy at the millimeter to centimeter level. Errors in inter-floor alignment, encompassing anchor positions, floor-to-floor height, and coordinate transfer, have the potential to accumulate and directly impact panel fit-up.

Recent advancements in fiducial-marker localization, high-precision surveying, and photogrammetric reconstruction have the potential to enhance on-site construction geometry. Specifically, markers facilitate reliable camera pose estimation, total stations facilitate the establishment of multi-floor control networks, and high-resolution imaging supports detailed facade and edge reconstruction. However, extant research has largely treated these components in isolation or focuses on documentation, with limited attention to survey-controlled multi-floor alignment and its direct integration into robotic facade installation.

The proposed framework integrates a construction tool with high-resolution imaging into a unified sensing and modeling pipeline with iterative robotic feedback. By anchoring measurements to a survey-defined reference frame, it ensures consistent multi-floor alignment and accurate execution-time synchronization between the physical construction and the design BIM.

2 Related Work

This part is devoted to a critical review of the extant literature concerning marker-based localization, high-precision surveying, photogrammetric building modeling, and BIM–robotics integration. It identifies the research gaps that this paper aims to address.

2.1 Marker-based localization

Visual fiducial markers are widely used for camera pose estimation and calibration in robotics and computer vision. AprilTag [1] provides reliable 6-DOF pose estimation from a single image and is robust to lighting changes and partial occlusion, with later versions improving detection accuracy and efficiency [2][3]. ArUco markers [4] offer a similar approach with built-in error correction.

Fiducial markers are also commonly used for sensor calibration, including camera–laser calibration and ChArUco boards that combine checkerboard features with marker IDs [5][6]. Prior studies have further evaluated detection robustness and pose ambiguity under challenging conditions [7]. Beyond pose estimation, recent work [8] shows that dense AprilTag grids can be used to reconstruct survey-grade facade geometry from calibrated images via triangulation and plane fitting, extending fiducial markers from local localization to large-scale geometric referencing in the built environment. In construction applications, markers are typically used for localization, while workflows that integrate surveyed fiducials across multiple floors with BIM and geospatial datasets remain largely unexplored.

2.2 High-precision surveying and Scan-to-BIM in construction

High-precision surveying is a cornerstone of construction quality control. Recent studies have evaluated scan-to-BIM workflows based on terrestrial laser scanning (TLS), with a focus on the impact of scanner accuracy, registration strategy, and modeling choices on the quality of the resulting BIM model. Skrzypczak et al. [9][10] assess the accuracy of scan-to-BIM for a multi-story office building, while others demonstrate the application of scan-to-BIM in the context of historic churches and complex interior spaces. The study [11][12][13] demonstrates that achieving centimeter- or millimeter-level agreement with control measurements is contingent upon the meticulous design of the survey network. Related work on online data acquisition and building modeling for building renovation highlights the role of timely and built-in data integration in renovation workflows [14], which will be further improved in future research.

The majority of Scan-to-BIM studies concentrate on documentation of entire spaces and neglect to address the anchor-level, cross-floor alignment necessary for the installation of facade panels. Furthermore, there is a paucity of integration between total-station control networks and high-resolution close-range imaging in the context of survey-grade ground truth generation and rigorous validation of multi-floor alignment accuracy. In contrast to Scan-to-BIM workflows, which prioritize post-construction documentation or renovation, the present study focuses on execution-time geometric control in new building construction, where a design BIM is already available.

2.3 Image-based photogrammetric reconstruction

Image-based photogrammetry has been the subject of extensive research as a method for extracting geometric information from perspective imagery. Classical methods rely on multi-view geometry, camera calibration, and feature correspondence to recover three-dimensional structure from overlapping images, typically via structure-from-motion and projective reconstruction pipelines. These techniques facilitate the recovery of facade planes, edges, and relative spatial relationships directly from images without direct contact measurements.

Recent advancements in this field have extended classical photogrammetry by incorporating learning-based components and architectural priors to enhance its resilience under conditions of limited viewpoints, occlusions, and complex urban scenes. The viability of such approaches has been demonstrated in the reconstruction of facade geometry and metric relationships from sparse or street-level imagery at large scale, primarily for applications in mapping, visualization, and urban analysis [15][16][17]. Other studies infer heights and facade geometry from single images or panoramas using deep learning and geometric reasoning [18][19][20], and extend these methods to 3D city modeling and Scan-to-BIM pipelines [21][22].

Nevertheless, image-only photogrammetric methods are susceptible to camera pose uncertainty, scale ambiguity, and environmental conditions, which restrict their applicability for precision-critical construction tasks. Consequently, the present paper adopts photogrammetry as a complementary measurement modality within a survey-controlled framework. In this framework, image-derived geometric features are anchored to a stable reference system to support the accurate installation of robotic facades.

2.4 BIM–robotics integration

The integration of BIM and robotics is a pivotal subject in the domain of construction automation. BIM functions as a centralized information repository for robotic assembly, additive manufacturing, inspection, and autonomous construction systems, as evidenced by [23]. Bibliometric studies [24] indicate that the field of construction robotics is undergoing rapid growth and diversification, particularly in the domains of automated fabrication and mobile on-site platforms.

Research on BIM–GIS integration shows that combining spatial and semantic models enables robot navigation and planning in complex construction environments [25]. Recent work further extends BIM by incorporating laser scanning and photogrammetry to support digital twins and automated quality verification [21], while also providing essential geometric and semantic constraints for safe robotic operation [26].

The majority of extant studies presuppose a precise design BIM and concentrate on the manner in which robots consume BIM information. In contrast, this project focuses on generating as-built BIM/IFC models from survey control and image-based measurements, and on using the resulting geometry to support robotic multi-floor facade installation.

3 Problem Definition

3.1 Multi-floor alignment challenges

The installation of robotic facades across multiple floors necessitates the maintenance of consistent geometric alignment between anchors, panels, and reference frames over vertical distances. In practice, minor inaccuracies in floor-to-floor height transfer, control point propagation, or coordinate transformations can accumulate across levels, resulting in misalignment between panels installed on different floors. These effects are of particular significance when facade elements span multiple storeys or must satisfy tight tolerance constraints at panel joints and anchors.

3.2 Challenges of maintaining consistent reference frames

In the context of multi-floor construction, geometric errors frequently emerge not from individual measurements but from inconsistencies in reference frames, transformation chains, and floor-to-floor transfer. Despite the fact that individual sensing modalities can offer reasonable local accuracy, minor inconsistencies in alignment, referencing, or propagation across floors can accumulate and result in misalignment at panel joints and anchors. The central challenge in robotic facade installation is therefore to maintain a consistent, traceable, and verifiable geometric reference across multiple floors throughout the planning and execution phases.

3.3 Requirements for precision in robotic installation

In new building construction, a detailed design BIM is typically available prior to facade installation. However, ensuring that robotic installation across multiple floors conforms to the design geometry remains challenging due to cumulative inter-floor alignment errors, reference frame inconsistencies, and execution-time uncertainties.

3.4 Need for BIM-constrained sensing and execution

Addressing these challenges necessitates a framework that integrates high-precision sensing with an existing design BIM to support execution-time alignment during robotic facade installation. In order to ensure consistent cross-floor alignment with verifiable precision, a unified pipeline combining survey control, image-based reconstruction, and BIM/IFC representation is necessary.

4 System Architecture

Fig.1 illustrates the execution-time workflow. The establishment of a global reference frame across multiple floors is the primary function of survey control. Based on this reference frame, images are acquired and utilized for photogrammetric localization, and the resulting measurements are registered to the survey frame to obtain survey-anchored geometry. This geometry is employed to generate robot commands for facade installation. Subsequent to the execution, re-localization and verification are carried out to effect an update to the geometric state. Subsequently, verified states and deviations are integrated with the existing design BIM/IFC model as as-built information. And Fig.2 offers a comprehensive overview of the proposed system architecture and data flow for robotic facade installation across multiple floors.

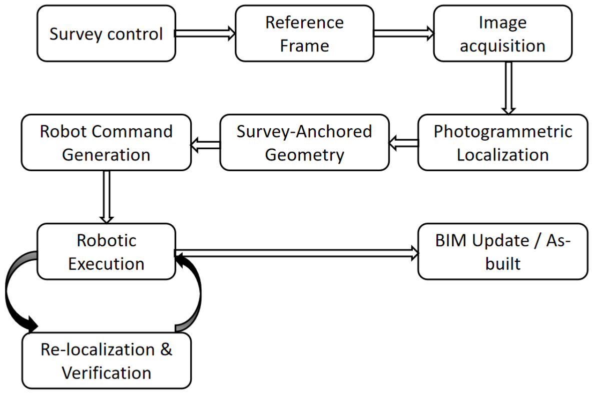

Figure 1. Survey-controlled workflow for multi-floor robotic facade installation

4.1 Survey-controlled reference framework

A Leica iCON iCS50 construction tool establishes a global reference frame that spans multiple floors and serves as the geometric backbone of the system. Each facade anchor is equipped with a Leica survey marker, enabling repeatable and survey-grade localization. By observing these markers across storeys, consistent floor-to-floor height transfer and inter-floor alignment are ensured. This survey-controlled reference frame provides stable geometric ground truth for subsequent sensing, fusion, and robotic operations.

4.2 High-resolution sensing and geometric reconstruction

High-resolution close-range images are captured using a Hasselblad camera to obtain dense geometric information of facade surfaces, anchors, and panel interfaces. Image observations are linked to the survey reference frame through fiducial markers, enabling reconstructed geometry to be expressed in global coordinates. This combination of sparse, high-accuracy survey measurements and dense image-based reconstruction supports both local installation verification and building-scale geometric analysis.

4.3 Robotic installation context

Robotic platforms operating on different floors are referenced to the same global coordinate system defined by the survey framework. This shared reference enables coherent spatial alignment during multi-floor facade installation

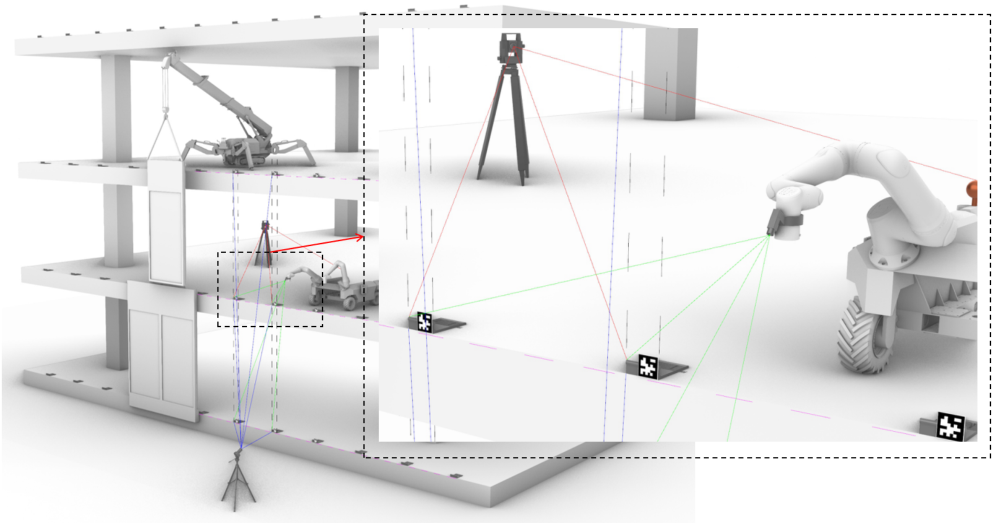

Figure 2. Conceptual illustration of a multi-floor robotic facade installation workflow

and reduces cumulative geometric errors. The architecture is designed to support installation planning, execution, and verification without assuming perfect design geometry, by grounding alignment and verification in survey control.

4.4 BIM / IFC integration

Survey- and image-derived measurements are integrated with an existing design BIM/IFC model to provide execution-time verification and structured documentation of as-built deviations during robotic facade installation. Anchor positions, facade geometry, and inter-floor relationships are stored within a unified BIM model, enabling comparison with design BIM and survey-observed as-built measurements. This integration supports automated quality documentation, traceability of geometric deviations, and downstream analysis throughout the building lifecycle.

5 Methodology

A methodology has been proposed for the systematic evaluation of millimeter-level accuracy in robotic facade installation across multiple floors. This methodology integrates controlled experiments, survey- and image-based sensing, data fusion, and evaluates the results against survey ground truth. Each methodological component addresses a specific aspect of the problem definition outlined in ***Problem Definition***, and collectively, they form a coherent evaluation pipeline.

5.1 Controlled and multi-floor experiments

Controlled experiments are conducted on buildings with multiple floors to evaluate whether robotic facade installation can satisfy millimetre-level geometric accuracy requirements. Anchors equipped with Leica survey markers are distributed across storeys and measured using a Leica iCON iCS50 construction tool, forming a vertically connected survey control network.

Survey-measured anchor coordinates are treated as ground truth. Image-based and fused measurements are evaluated relative to this reference in order to distinguish local single-floor errors from cumulative inter-floor alignment effects.

For the f-th floor, the mean vertical residual is defined as

$$r_f = \frac{1}{|\mathcal{A}_f|} \sum_{a \in \mathcal{A}_f} \left(z_a^M - z_a^S \right), \tag{1}$$

where $\mathcal{A}_f$ denotes the set of anchors on floor f, and z_a^S and z_a^M are the survey-measured and model-derived heights of anchor a, respectively.

The cumulative vertical drift up to floor F is expressed as

$$D(F) = \sum_{f=1}^{F} r_f. \tag{2}$$

The installation accuracy requirement is defined as

$$|D(F)| \leq \tau, \qquad \tau \in [2, 8] \text{ mm}, \tag{3}$$

reflecting typical tolerance limits for robotic facade installation.

Fig.3 illustrates how anchor-level vertical residuals are averaged at each floor and accumulate across multiple

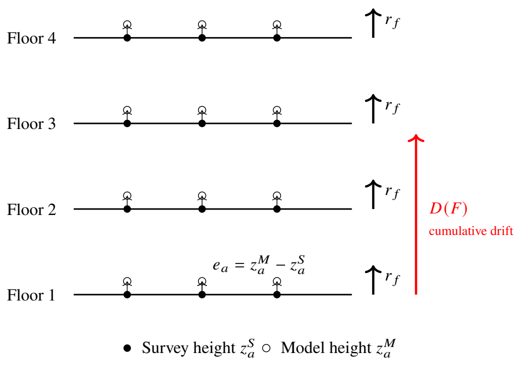

Figure 3. Illustration of equations(1)(2)(3)

floors into a cumulative vertical drift that affects multi-floor robotic facade installation accuracy.

5.2 Camera calibration and photogrammetry

The Hasselblad camera is calibrated using a standard photogrammetric procedure to estimate intrinsic parameters and lens distortion. Based on solid theory basic [27][28][29], Camera poses are initialized via fiducial marker detection and refined using bundle adjustment by minimizing reprojection error.

Given image observations $\mathbf{x}_{ij}$ of 3D points $\mathbf{X}_j$ in camera i, the optimization problem is formulated as

$$\min_{\{\mathbf{P}_i\},\{\mathbf{X}_j\}} \sum_{i,j} \left\|\mathbf{x}_{ij} - \pi(\mathbf{P}_i, \mathbf{X}_j)\right\|^2, \quad (4)$$

where $\pi(\cdot)$ denotes the camera projection model.

To enforce metric consistency with survey control, anchor points measured by the Leica iCS50 are incorporated as constraints:

$$\min \sum_{i,j} \left\|\mathbf{x}_{ij} - \pi(\mathbf{P}_i, \mathbf{X}_j)\right\|^2 + \lambda \sum_{k \in C} \left\|\mathbf{X}_k - \mathbf{X}_k^S\right\|^2, \quad (5)$$

where C denotes the set of survey-observed anchors and $\mathbf{X}_k^S$ their survey coordinates.

5.3 Leica and camera data fusion

Survey measurements and image-derived geometry are fused within the global coordinate system defined by the Leica iCON iCS50. Anchor-mounted survey markers serve as control points linking image space and survey space.

A rigid transformation $(\mathbf{R}, \mathbf{t})$ is estimated using weighted least squares:

$$\min_{\mathbf{R},\mathbf{t}} \sum_k w_k \left\|\mathbf{p}_k^S - (\mathbf{R}\mathbf{p}_k^I + \mathbf{t})\right\|^2, \quad (6)$$

where $\mathbf{p}_k^S$ and $\mathbf{p}_k^I$ denote survey and image-derived coordinates of anchor k, and w_k represents measurement confidence [30].

To improve robustness against occlusions and misdetections, a robust cost function $\rho(\cdot)$ is applied:

$$\min_{\mathbf{R},\mathbf{t}} \sum_k \rho\left(\left\|\mathbf{p}_k^S - (\mathbf{R}\mathbf{p}_k^I + \mathbf{t})\right\|\right). \quad (7)$$

The residual covariance after fusion is estimated as

$$\mathbf{\Sigma}_{\text{reg}} = \frac{1}{N-1} \sum_{k=1}^{N} \mathbf{e}_k \mathbf{e}_k^\top, \quad (8)$$

where $\mathbf{e}_k$ denotes the post-registration residual of anchor k.

5.4 Accuracy evaluation against survey ground truth

Geometric quantities derived from the fused survey–image model are evaluated against survey control measurements provided by the Leica iCON iCS50. Survey-measured anchor coordinates are treated as ground truth, enabling a direct assessment of anchor-level consistency and multi-floor error propagation.

For each anchor a, the vertical residual is defined as

$$\Delta z_a = z_a^M - z_a^S, \quad (9)$$

where z_a^S denotes the survey-measured vertical coordinate and z_a^M the corresponding model-derived value.

To assess suitability for robotic facade installation, a pass-rate metric is introduced:

$$\eta(\tau) = \frac{1}{M} \sum_{m=1}^{M} I\left(|\Delta z_m| \le \tau\right), \quad \tau \in [2, 8] \text{ mm}, \quad (10)$$

where M is the number of evaluated anchors and $I(\cdot)$ denotes the indicator function.

This evaluation focuses on anchor-level geometric consistency, inter-floor error propagation, and compliance with tolerance requirements relevant to precision-critical robotic installation.

To further characterize error distribution, standard statistics of the vertical residual Δz_a are evaluated:

$$\text{RMSE}_z = \sqrt{\frac{1}{M} \sum_{a=1}^{M} (\Delta z_a)^2}, \quad e_z^{\max} = \max_a |\Delta z_a| \quad (11)$$

In addition, full three-dimensional anchor deviation is defined as:

$$e_a^{3D} = \|\mathbf{p}_a^M - \mathbf{p}_a^S\|_2 \quad (12)$$

To assess cross-floor consistency, the inter-floor transfer error between adjacent floors is introduced:

$$E_{\text{transfer}}(f, f+1) = \left|(z_{f+1}^M - z_f^M) - (z_{f+1}^S - z_f^S)\right| \quad (13)$$

These metrics complement the pass-rate definition by capturing error magnitude and multi-floor consistency.

5.5 IFC data mapping

Survey- and image-derived as-built geometry [31][32] is mapped into IFC representations to enable structured storage, comparison, and documentation.

For each anchor a, the geometric deviation is expressed as

$$\Delta \mathbf{p}_a = \mathbf{p}^{\mathrm{IFC}}_{a,\text{as-built}} - \mathbf{p}^{\mathrm{IFC}}_{a,\text{design}}, \tag{14}$$

with the vertical component Δz_a explicitly recorded. These deviations are stored in IFC property sets and associated with anchors, panels, and floors.

6 Experimental Plan

The experimental plan represents the most critical component of the proposed future work, as it provides the quantitative evidence required to validate multi-floor alignment accuracy, error propagation behavior, and robustness under realistic construction conditions. Although experimental data will be acquired in later project phases, measurement layouts, marker placement rules, and observation strategies are defined in advance to ensure reproducibility and comparability.

6.1 Benchmark scenarios

Three benchmark scenarios are defined to progressively evaluate geometric accuracy from local to building-scale conditions:

- Single-floor scenario: This scenario evaluates local geometric accuracy within a single storey, isolating sensing, calibration, and fusion errors without inter-floor propagation. It establishes the baseline performance of the Leica-camera system.
- Cross-floor scenario: This scenario evaluates two adjacent floors jointly, focusing on floor-to-floor height transfer and coordinate consistency. It represents the minimum requirement for facade panels spanning multiple storeys.
- Full-height scenario: This scenario evaluates anchors distributed across the full building height. It exposes cumulative vertical drift and long-range error propagation, representing the most demanding case for robotic facade installation.

6.2 Marker placement strategy

Leica survey markers are placed on the facade following a regular grid layout to provide stable geometric control in both horizontal and vertical directions. The placement strategy defined to balance coverage, redundancy, and practical deployment constraints is as follows:

Table 1. Planned Leica marker layouts for benchmark scenarios.

Scenario	Floors	Spacing (m)	Grid (C×R)	Markers
Single-floor	1	2.0	3–4 × 2	6–8
Cross-floor	2	2.0	3–4 × 2	12–16
Full-height	3–5	2.0	3–4 × 2	18–40

- Horizontal and vertical spacing: 2.0 m.
- Markers are mounted at or near facade anchor locations where possible.
- At least one vertically aligned marker column is maintained across floors to support height transfer.
- All markers are observable from at least one construction tool setup.

6.3 Planned marker layout summary

The planned marker configurations for the three benchmark scenarios are summarised in Table 1.

6.4 Marker visibility and construction tool setup plan

To ensure reliable multi-floor alignment and redundancy in survey observations, a structured construction tool setup plan is defined for future experiments using the Leica iCON iCS50.

- Each marker is observed from at least two distinct station setups.
- Adjacent floors share common visible markers to form a continuous vertical control network.
- Station locations are selected to maximize facade coverage while avoiding shallow incidence angles.

6.5 Deviation measurement

Geometric deviations are quantified relative to survey-grade ground truth provided by the Leica iCON iCS50. Deviations are evaluated at anchor level, panel level, and across floors, with a focus on millimetre-level tolerances required for robotic installation.

Deviation metrics include local anchor residuals, inter-floor height differences, and cumulative vertical drift. All measurements are evaluated against predefined tolerance thresholds to assess installation feasibility.

6.6 Reproducibility and robustness testing

To assess reproducibility, experiments are repeated under varying acquisition conditions, including different camera viewpoints, lighting conditions, and station configurations. Robustness is evaluated by introducing controlled perturbations such as partial marker occlusions and reduced visibility.

Statistical consistency across repeated trials is analysed using variance, confidence intervals, and failure rates relative to millimetre-level thresholds.

7 Conclusions

This paper presented a survey-controlled sensing and execution framework for robotic facade installation in new building construction, where a design BIM is available. By integrating a Leica iCON iCS50 construction tool with high-resolution close-range imaging and BIM-based representation, the proposed pipeline establishes a consistent multi-floor reference frame for precision-critical installation.

The framework defines a unified process that links survey control, dense image-based geometry, and BIM/IFC mapping, enabling reliable robotic facade installation and quantitative validation of multi-floor accuracy, error propagation, and installation tolerances against survey ground truth. The proposed pipeline is designed to address inter-floor alignment and error propagation within a survey-controlled framework, thereby providing a coherent and reproducible solution for precision-critical robotic facade installation across multiple floors.

The proposed framework contributes to the **AMALTEA** project by providing a survey-controlled execution pipeline for robotic facade installation in new building construction.

Acknowledgement

The research presented in this paper was originally carried out in the context of the Horizon project **AMALTEA**. **AMALTEA** has received funding from the EU's Horizon Europe program under Grant Agreement No. **101189678**.

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