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Cognitive Robotics for Digital Twin–Enabled Automation in Structural Panel Fabrication and Installation

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Abstract— **This paper presents an integrated system that combines robotics, depth vision, and digital twin technologies to automate and enhance the fabrication of structural wooden panels and their installation on-site by human workers. The methodology for enabling better and faster panel production and on-site installation integrates AI and Robotics into BIM (Building-Informational-Model), allowing the entire build process to be simulated and optimized in a digital environment before deployment. The robotic system for panel assembly and the computer vision system work hand in hand with the robots, making real-time decisions, detecting issues, and ensuring consistent quality. The interface to a digital twin enables on-site crew guidance for seamless panel integration into new homes. The system is evaluated on more than 50 real-world panels and demonstrates improvements in installation efficiency by reducing the time needed to frame the house by 70%, decreasing the cost by approximately 30%, and improving quality traceability, compared to conventional building methods. This work exemplifies cognitive collaboration between robots and humans in modern manufacturing environments.**

I. INTRODUCTION

The global construction industry faces persistent challenges in labor shortages, rising material costs, and increasing demands for energy-efficient, disaster-resilient housing [1], [2]. Modern prefabricated construction offers a promising path forward, yet to fully realize its potential, it must leverage advanced automation technologies [3], [4]. In particular, the fabrication of structural wooden panels, a core building block for prefabricated housing, presents an opportunity for robotic solutions that ensure high precision, repeatability, and scalability, while reducing dependency on skilled manual labor [5]–[7].

Traditional onsite framing methods are labor-intensive, prone to variability in quality, and dependent on the availability of skilled workers. Panel fabrication in conventional setups often lacks integrated quality control and digital traceability, resulting in higher rework rates, inefficient sequencing, and material waste. While some off-site prefabrication facilities have improved efficiency, they are often constrained by standardized panel designs, limiting customization and adaptability to individual architectural plans.

Research in robotic construction has advanced in several directions, including automated timber assembly, CNC-based component fabrication, and BIM-driven (Building Information Modeling) workflows [7]–[10]. Commercial systems for panel prefabrication exist, offering speed advantages over traditional methods, but these typically rely on fixed design templates and manual coordination between design and manufacturing teams. They rarely achieve direct integration of architectural plans into robotic workflows, and fewer still implement real-time, vision-based quality assurance that compares fabricated panels to their digital design twin.

In this paper, we present a flexible, end-to-end framework that bridges the gap between architectural design and robotic fabrication. Our approach integrates a Home Configurator—capable of producing a 3D BIM model of the entire house—with a robotic panel assembly system. From the digital house model, the system automatically extracts all panel specifications (geometry, component list, drilling patterns) and sends them directly to the robotic assembly cell. This removes the constraint of predefined house templates, enabling customer-tailored designs to be manufactured without additional manual programming.

On top of the assembly automation, we introduce:

- Vision-Based Quality Assurance (QA): Using a Zivid depth camera, the system captures the assembled panel in 3D and compares it against the CAD model from the digital twin, detecting dimensional deviations in real time.
- Knot Detection System: Each stud is scanned before assembly to detect knot positions. A nailing mask is generated for each panel to avoid placing fasteners through knots, improving structural integrity. The system can reassign a stud to a different panel position if necessary.
- Digital Twin + QR Integration: Each finished panel is assigned a unique QR code linking to its location in the building, associated plumbing and electrical installation requirements, and handling instructions for on-site crews.

The proposed system has been deployed and evaluated on more than 50 real-world panels. The integration of automated QA and material grading with digital twin–based installation guidance resulted in:

- 70% reduction in house framing time,

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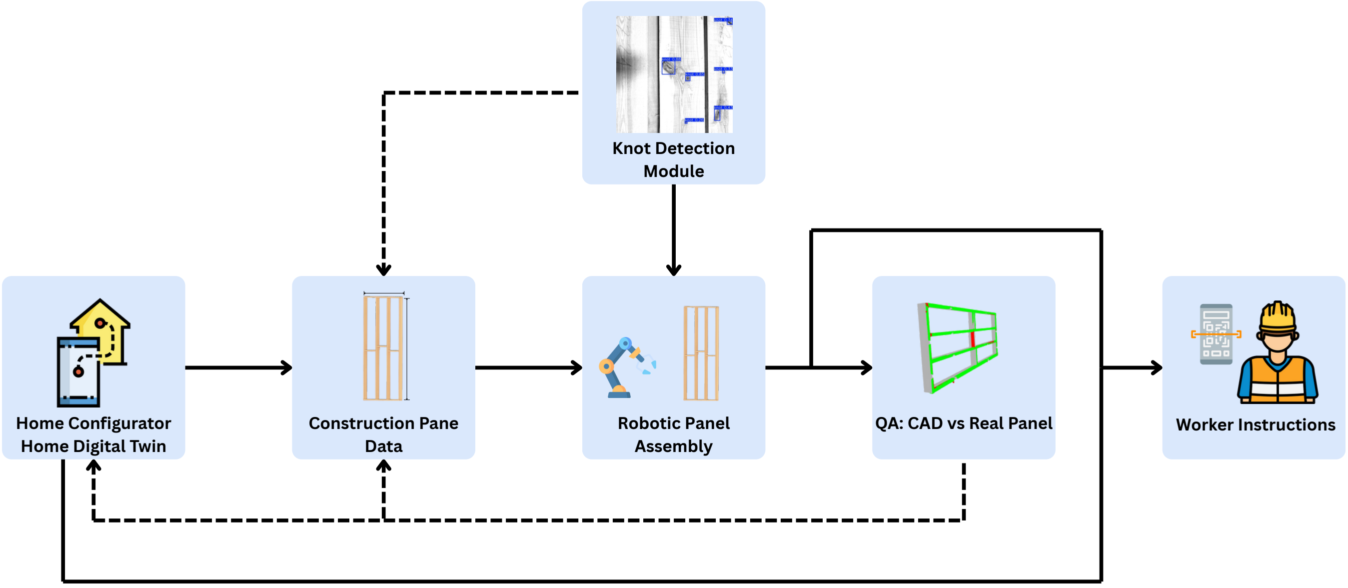

Fig. 1: Overview of the cognitive robotic panel fabrication system.

- 30% cost reduction compared to conventional building methods,
- Significant improvements in installation accuracy and traceability of components.

By enabling cognitive collaboration between robots and human installers, this framework contributes to the emerging field of construction robotics as an example of how digital planning, AI-driven inspection, and flexible robotic workflows can transform prefabrication and onsite assembly.

II. RELATED WORK

Robotic solutions for panel fabrication have emerged in both research and industry as a way to reduce labor demands and improve assembly precision. Early systems focused primarily on fixed-sequence robotic nailing and screwing in predefined jigs, offering speed gains but limited flexibility in accommodating design variations. More recent efforts integrate Computer Numerical Control (CNC) processing for cutting and milling timber components, and robotic placement of studs and sheathing panels. However, many of these implementations are optimized for mass production of standard panel types, limiting their applicability to custom architectural designs. [11]–[16]

Building Information Modeling (BIM) has enabled a greater degree of digital integration in construction, allowing design data to be shared across disciplines. Several academic works have explored BIM-to-robot pipelines for structural assembly and modular housing, but these often require manual interpretation or intermediate file conversions to adapt the BIM output for robotic use. Commercial BIM-driven fabrication systems do exist, yet they are typically hard-coded for specific product lines and do not dynamically adapt to non-standard panel geometries or installation patterns [9], [13], [14].

Automated quality assurance (QA) in prefabrication is still a developing field. Current industrial systems tend to rely on post-process inspection using laser scanners or manual gauges, rather than in-process, vision-based feedback. Research prototypes have explored 3D vision for dimensional verification, but few integrate QA data directly into the robotic control loop to enable real-time corrective actions [6], [15], [17], [18].

Material classification, particularly knot detection in lumber, is well studied in the context of sawmill automation, where 2D imaging and laser scanning have been used to detect defects for cutting optimization [19], [20]. However, the use of knot localization in relation to panel nailing maps remains largely unexplored in construction robotics. Integrating these data into the robotic assembly process provides an opportunity to improve structural performance and long-term durability.

Digital twin concepts are gaining traction in construction, offering the ability to track component status and link built-in data to the design model. Some prefabrication workflows have adopted QR or RFID tagging for logistics tracking, but integrating installation-specific guidance - such as precise plumbing and electrical routing - into a panel's digital identity is still rare in practice.

While existing solutions demonstrate progress in robotic assembly, BIM integration, and construction QA, they often remain siloed and lack the end-to-end connection between architectural design, robotic fabrication, material quality control, and on-site installation support. Our work addresses this gap by introducing a flexible, BIM-to-robot framework that integrates real-time QA, material grading, and digital twin–based guidance into a single cognitive manufacturing pipeline for custom prefabricated housing.

III. SYSTEM ARCHITECTURE

The proposed system architecture (Fig. 1) establishes a fully integrated workflow that connects digital design, robotic

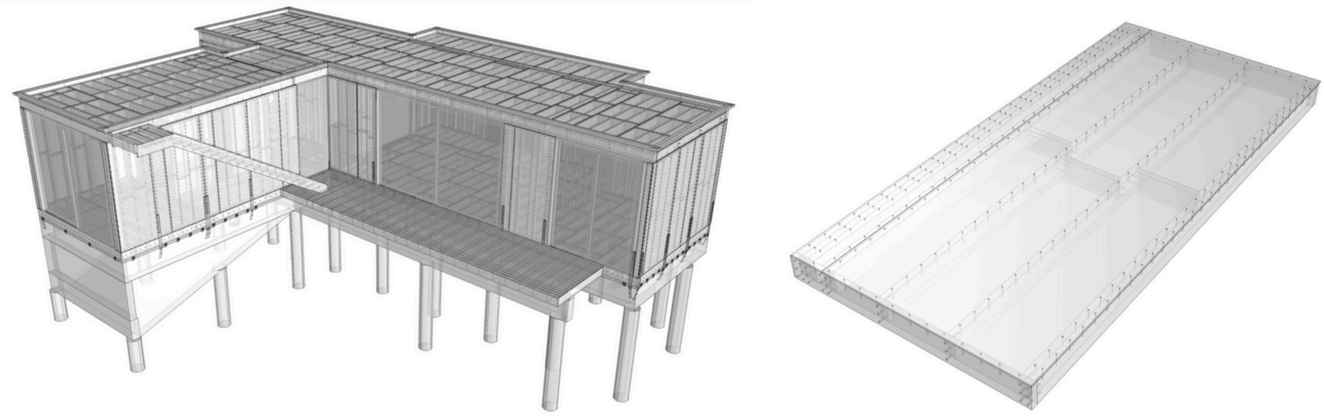

Fig. 2: Left: Designed home in Rhinoceros 3D, Right: One of panels extracted from Home Configurator.

fabrication, and on-site installation through a combination of advanced automation and digital twin technologies. The process begins in the Home Configurator, where a complete 3D digital twin of the house is created. This digital twin model captures all the architectural details (panel dimensions, component layouts, and location of the plumbing and electrical systems). Then, the system automatically extracts construction panel data, ensuring that design intent is translated directly into machine-readable fabrication instructions. These instructions drive the robotic panel assembly stage, in which industrial robots precisely position wooden studs, apply sheathing, and perform nailing operations with high repeatability. Before assembly, each stud is inspected by a vision-based knot detection module that localizes knots and cross-references their positions with the nailing plan, allowing the system to assign studs to panel positions where knots will not compromise structural fastening. Once assembled, each panel undergoes quality assurance through a depth vision inspection that compares the fabricated component with its corresponding CAD model from the digital twin, allowing dimensional deviations to be detected and corrected before deployment. The final step links each physical panel to its virtual counterpart via a unique QR code, which the on-site crew can scan to access installation guidance, exact placement within the building, and detailed instructions for integrating plumbing and electrical systems. In this way, the proposed framework supports a continuous data-driven construction process in which digital planning, automated fabrication, and human installation are seamlessly connected.

A. Home Configurator

The Home Configurator is implemented using the Rhinoceros 3D platform, which functions as the central environment for both architectural design and automated panelization. Within this software, the complete house is modeled in detail (Fig. 2 left), and the system automatically generates the panel layout, including the precise placement of all studs, nails, and sheathing panels (Fig. 2 right). This approach ensures that the structural design is accurately represented while producing a data-rich model that supports downstream automation. From the Rhinoceros environment, the exact coordinates and specifications for each panel element are extracted, providing the robotic system with all coordinates required for fabrication without manual intervention, throught JSON file (Listing 1.). This direct connection between design and manufacturing enables a seamless transition from digital planning to physical production.

Listing 1: Example JSON structure used for robotic panel fabrication.

```
{
  "metadata": {
    "panel_id": "wall_001",
    "coordinate_frame": "workbench_frame",
    "units": "mm"
  },
  "assembly_sequence": [
    {
      "step": 1,
      "operation_type": "place_stud",
      "tool": "stud_gripper",
      "target": {"x": 302.895, "y": 61.119, "z": 13
          .970, "rx": 180, "ry": 0, "rz": -90},
      "approach_offset": {"z": 100},
      "speed": "v500",
      "zone": "z10"
    },
    {
      "step": 2,
      "operation_type": "nail",
      "tool": "nail_gun",
      "target": {"x": 159.105, "y": 77.660, "z": 4.
          657, "rx": 90, "ry": 0, "rz": 180},
      "approach_offset": {"z": 50},
      "speed": "v100",
      "zone": "fine"
    },
    {
      "step": 3,
      "operation_type": "place_plywood",
      "tool": "plywood_gripper",
      "target": {"x": 153.829, "y": 61.119, "z": 15
          .081, "rx": 180, "ry": 0, "rz": 0},
      "approach_offset": {"z": 150},
      "speed": "v300",
      "zone": "fine"
  }]
}
```

B. Robotic Panel Production

The robotic panel fabrication system is designed to automate the assembly of wooden studs and plywood into fully structured building panels. By taking over repetitive and physically demanding tasks, as well as safety-critical operations such as nailing, the system significantly improves both production efficiency and workplace safety. Panel specifications, including the precise placement of each stud, plywood sheet, and nail, are defined in a structured JSON file generated during the design phase. This file is directly integrated into the robot program within ABB RobotStudio, enabling the robot to follow the exact build plan without manual reprogramming. This custom Python code reads a JSON file and establishes socket communication with an ABB robot. Data is extracted from the JSON sequentially and transmitted to the robot. On the robot side, the `operation_type` parameter triggers the corresponding procedure to execute the specific operation (place stud, nailing, or place plywood). This data-driven approach ensures a high degree of flexibility, allowing panels of varying dimensions and layouts to be produced with minimal setup changes. The hardware configuration consists of an ABB IRB 6700 industrial robot equipped with a set of custom-designed tools for picking and positioning studs, handling plywood sheets, and executing nailing operations (Fig. 3). The robot's basic programming, tool calibration, and workcell configuration are all performed within ABB RobotStudio, ensuring accurate spatial alignment between the digital model and the physical build environment. Workbench calibration for wall assembly is performed by establishing a workobject coordinate frame that is consistently defined in both the virtual environment (RobotStudio) and the physical workspace. All subsequent coordinates for assembly operations are then transformed relative to this workobject frame, ensuring precise correspondence between digital planning and physical execution. This integration of software, hardware, and structured design data creates a seamless workflow from digital panel specifications to precise, repeatable robotic assembly, making the system adaptable to a wide range of prefabricated construction scenarios. However, at this stage of development, human workers still need to cut and place studs in the stud rack for the robot to handle them properly.

Fig. 3: Robotic panel assembly system with an example of panel.

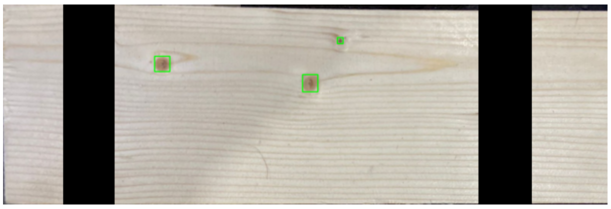

Fig. 4: Knot detection algorithm output. Black area indicates regions where nails cannot be placed for particular stud dimension.

C. Vision-based QA and Knot Detection

The system employs an automated knot detection algorithm to examine the surface of each stud, identifying both the position and size of knots. Once detected, these locations are cross-referenced with the panel's predefined nailing zones. If a knot falls within a critical fastening point, that stud is automatically reassigned to a less critical position in the assembly, preventing potential structural weaknesses. For the knot detection algorithm YOLO network is used. To retrain the newtwork A large-scale image dataset of wood surface defects for automated vision-based quality control processes [21]. This particular data set have 4000 images with different knot sizes and types. Figure 4 shows an example output of the knot detection algorithm, where the black area indicates regions where nails cannot be placed, allowing knot detection to be excluded in those areas.

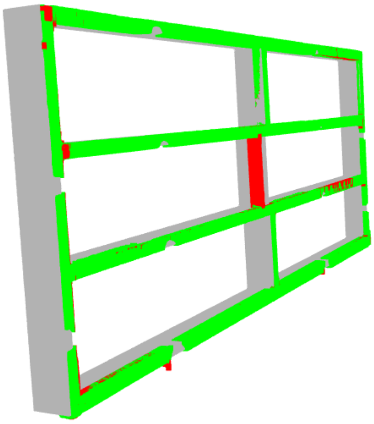

Fig. 5: Example of CAD model and point cloud comparison. Green points indicate areas where the point cloud aligns with the CAD model, while red points highlight deviations from the expected geometry.

Quality assurance is carried out using a Zivid 3D depth camera, which produces high-resolution point cloud data. The camera is mounted on the robot, which captures multiple scans of the panel from different viewpoints to achieve full coverage. The individual scans are then merged into a single, using the Iterative Closest Point (ICP) algorithm. After merging, basic noise reduction is performed through outlier removal and depth-based filtering. In the final step, the cleaned point cloud is directly compared against the CAD model generated in the Home Configurator, enabling accurate verification of assembly quality and dimensional compliance (Fig. 5).

D. QR and Digital Twin Integration

Each completed panel is labeled with a unique QR code that provides direct access to its installation metadata, including the layout position within the structure, the precise locations of holes for plumbing and electrical installations, and detailed handling instructions. By scanning the code with a handheld device, installation crews can quickly retrieve all relevant information on site, enabling them to work more efficiently, reduce errors, and ensure accurate placement and integration of the panel.

IV. EVALUATION AND RESULTS

The system is tested on tree types of panels (floor, ciling and wall panels) with more than 50 different panel sizes. The panels are made of 2”x4” and 2”x6” studs.

The precision and recall of the knot detection and localization algorithm is more than 90% (Fig. 6). The algorithm is train and tested on data collected on-site during the panel production but also with the data publicly available online.

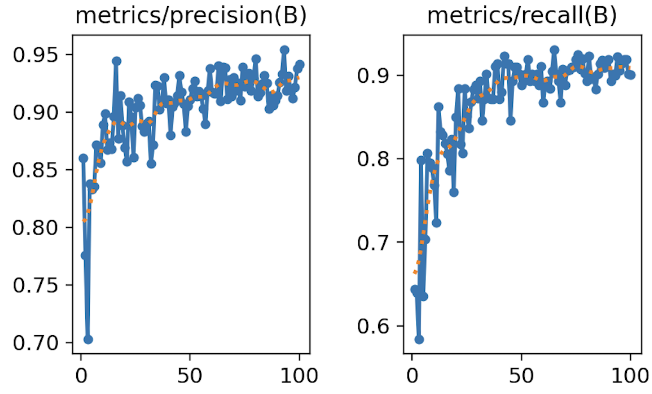

Fig. 6: Knot detection performance: precision (left) and recall (right).

The QA panel analysis demonstrates the system’s capability to detect irregularities in stud placement and deviations in panel dimensions. For panels meeting quality standards, more than 95% of the points are classified as green, which can be considered an indication of acceptable quality.

The combined use of the Home Configurator as a digital twin, robotic panel assembly, and panel-specific installation guidance via unique QR codes has yielded significant efficiency gains during on-site construction. By generating a fully detailed 3D model of the house in the Home Configurator, all panel specifications, including stud positions, nail patterns, and service openings, are defined and verified before fabrication. These data are then directly transferred to the robotic assembly system, eliminating manual layout work and ensuring consistent panel quality. Once panels are fabricated, each is labeled with a QR code that, when scanned on site, provides installation crews with precise placement information and detailed instructions for integrating plumbing and electrical systems. This combination of pre-verified fabrication and real-time, panel-specific guidance has reduced the need for re-measurement, error correction, and coordination between trades. The field results show that this workflow delivers more than 70% reduction in the time required for structural framing compared to conventional construction methods, while also improving overall build precision and reducing downtime caused by miscommunication or missing information.

V. CONCLUSION

This paper has presented a robotic system that combines digital twin technology, automated panel assembly, and vision-based quality assurance into a seamless prefabrication pipeline. Architectural data from the Home Configurator transfer directly to robotic fabrication, enabling accurate, template-free production, while QR-coded panels provide crews with instant, location-specific installation guidance. By consolidating design, fabrication, QA, and on-site assembly into one continuous data flow, the system minimizes errors, shortens handovers, and ensures structural integrity through automated defect detection and real-time dimensional verification.

Validated on over 50 real-world panels, the framework achieved up to 70% faster framing, 30% lower costs, and markedly improved traceability. It empowers manufacturers to deliver custom designs without reprogramming and equips installers with precise, just-in-time instructions, boosting accuracy and coordination. As a scalable blueprint for Industry 5.0 construction, this approach closes the loop between digital design and physical assembly, driving the shift toward faster, more flexible, and more resilient building workflows.

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