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Real-Time 3D Motion Tracking and Precision-Engineered Modular Wood Grippers for KIGUMI-Inspired CNC Wooden Block Assembly

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Research Article

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Abstract

This paper presents a compact and low-cost cyber-physical system for digital carpentry in which real-time 3D motion tracking is coupled with an articulated robotic gripper for modular wooden block handling and KIGUMI-inspired assembly. The prototype combines an MPU6050 inertial sensing unit, a NodeMCU controller, Arduino-based servo coordination, a Node.js communication layer, and a 5-axis articulated robotic arm with a modular gripper fabricated through CAD-driven 3D printing. To improve functional adaptability, we introduce two lightweight software layers: ClawdBot for context-aware assembly planning and grasp-state selection, and MoltBot for short-horizon motion refinement, smoothing, and alignment correction during manipulation. The resulting pipeline links sensing, streaming, visualization, and actuation in a form suitable for CNC-assisted wood assembly tasks where repeatability, affordability, and ease of deployment are equally important. Preliminary prototype validation confirms end-to-end operation, stable streaming, coordinated multi-servo control, and successful pick-lift-align-place demonstrations on modular wooden elements. The work contributes an accessible pathway toward intelligent robotic carpentry for educational labs and small-scale industrial fabrication cells.

Index Terms / Keywords

digital carpentry, robotic gripper, real-time motion tracking, CNC woodworking, KIGUMI assembly, human-robot fabrication, embedded systems, servo control, cyber-physical systems

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I. INTRODUCTION

Digital carpentry is moving from static computer-aided design workflows toward interactive robotic systems that can sense, adapt, and manipulate parts during fabrication and assembly. In woodworking, this shift is especially valuable because material variability, alignment tolerances, and assembly order often limit the usefulness of rigid automation pipelines.

KIGUMI-inspired wooden structures intensify this challenge. Their interlocking logic offers high structural elegance and efficient material use, but precise placement and orientation are required during assembly. For small and medium production environments, expensive industrial cells are often impractical, creating demand for lower-cost robotic systems that can combine motion capture, intelligent planning, and dexterous grasping.

This work addresses that need through a prototype titled Real-Time 3D Precision Motion Tracking System with Articulated Robotic Gripper. Built around an inertial sensor, embedded control, browser-based visualization, and a 5-axis actuation chain, the platform is positioned as an affordable digital carpentry assistant for CNC wooden block assembly.

Key contributions:

1. A low-cost real-time 3D tracking and robotic manipulation pipeline that links sensor acquisition, communication, visualization, and physical actuation.
2. A precision-engineered modular gripper architecture suitable for handling wooden blocks used in KIGUMI-inspired assembly sequences.
3. Two lightweight intelligence layers, ClawdBot and MoltBot, for task decomposition, grasp-state selection, and motion refinement.
4. A digital carpentry workflow aimed at simplifying CNC-assisted wood block placement, alignment, and structured assembly.

II. SYSTEM ARCHITECTURE

The proposed platform is organized as a sensing-to-action loop. An MPU6050 captures orientation and motion cues that are read by a NodeMCU and interpreted by embedded firmware written in Arduino C/C++. Motion data are streamed through UDP and visualized through a Node.js and WebSocket layer, while a servo orchestration module drives the articulated arm and gripper.

Mechanically, the system uses a 5-axis arm structure covering waist, shoulder, elbow, wrist roll, and wrist pitch motions, supported by MG996R and SG90 servo classes for torque-sensitive and fine-grained movements. The gripper structure is modeled in CAD and fabricated as a modular assembly so that finger geometry can be adjusted for different wooden morphologies.

At the software level, ClawdBot performs context-aware task decomposition by selecting grasp mode, pickup order, and placement stage from the assembly state. MoltBot operates as a lightweight motion refinement layer that smooths servo trajectories, reduces abrupt transitions, and assists final orientation adjustment before insertion or stacking.

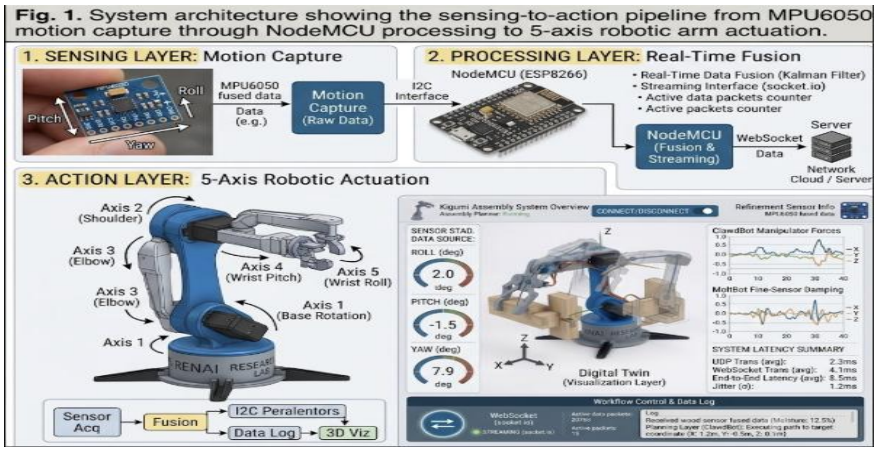


Fig. 1. System architecture showing the sensing-to-action pipeline from MPU6050 motion capture through NodeMCU processing to 5-axis robotic arm actuation.

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TABLE I

SYSTEM MODULES AND FUNCTIONAL ROLE

Module	Implementation	Primary Role
Tracking	MPU6050 + NodeMCU	Pose acquisition and streaming
Control	Arduino C/C++ firmware	Servo coordination and timing
Actuation	MG996R and SG90 servos	Arm and gripper movement
Planning	ClawdBot	Assembly state and grasp selection
Refinement	MoltBot	Smoothing and alignment
		correction
Interface	Node.js + WebSocket	Visualization and monitoring

III. MECHANICAL DESIGN AND HARDWARE INTEGRATION

The mechanical design phase involved parametric 3D modeling of all gripper components using SolidWorks CAD software. Part geometry was optimized for 3D printing using PLA/PETG materials at 100% infill to ensure structural rigidity. STL files were generated and validated for compatibility with both CNC manufacturing and FDM 3D printing processes.

Servo selection was critical for achieving the required torque and precision. MG996R servo motors provide high-torque actuation for major gripper joints, while SG90 micro servos handle wrist pitch, wrist roll, and the gripper closing mechanism. A power distribution circuit incorporating decoupling capacitors was designed to prevent voltage brownouts during peak servo current draw.

The breadboard wiring harness uses male-to-female jumper connections with clear color coding for maintainability. Servo PWM signal isolation between the logic supply and motor supply rails ensures stable operation under dynamic load conditions.

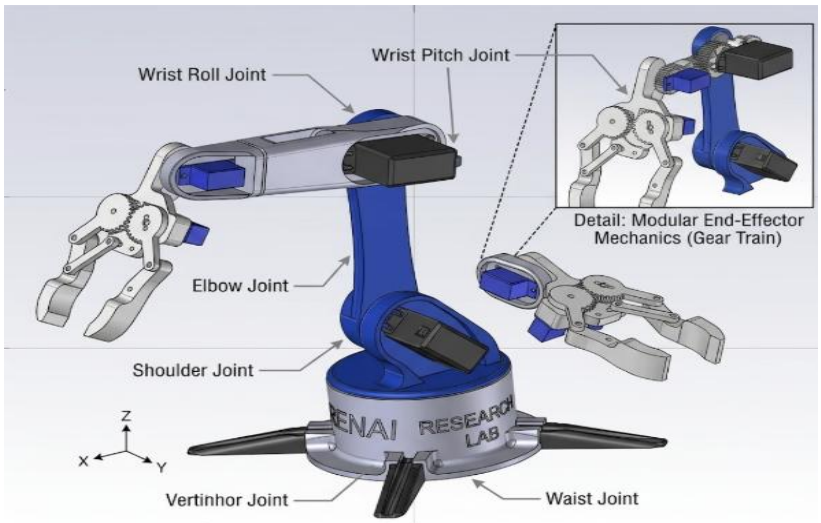


Fig. 2. CAD model of the 5-axis articulated robotic gripper showing waist, shoulder, elbow wrist roll, and wrist pitch joints with modular end-effector.

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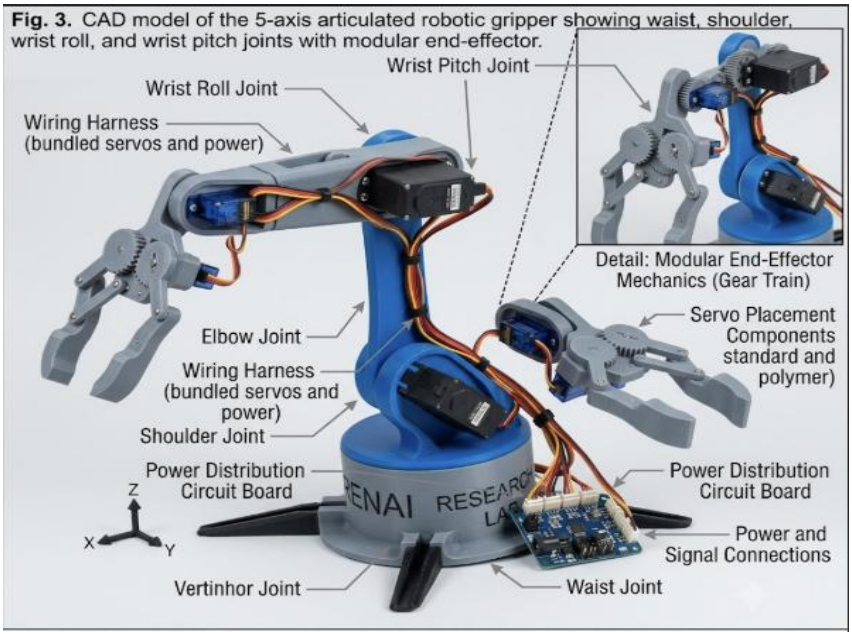


Fig. 3. Physical prototype assembly showing 3D-printed components, servo placement, and wiring harness with power distribution circuit.

IV. FIRMWARE DEVELOPMENT AND SOFTWARE ARCHITECTURE

The firmware development utilized Arduino C/C++ incorporating the Servo library for six-axis coordinated control. A servo sweeping algorithm with position feedback and serial debugging output enables precise motion control. Sequential joint movement sequences feature adjustable velocity profiles for smooth operation.

The KIGUMI Digital Carpenter demonstration routine implements a complete assembly sequence: open-grip, pickup, close-grip, lift, assemble, release, and home positioning. This autonomous pick-and-place operation validates the end-to-end system integration.

Real-time motion tracking firmware was developed in the Arduino IDE targeting the NodeMCU platform. A serial communication protocol at 9600 baud enables sensor data transmission. The MPU6050 accelerometer and gyroscope modules provide spatial position sensing for closed-loop control.

Kinematic calculations for gripper trajectory planning in 3D space are implemented on the microcontroller. Motion data is streamed over UDP to a Node.js host and forwarded to browser clients via WebSocket for real-time visualization. The browser-based dashboard provides intuitive monitoring of system state and sensor readings.

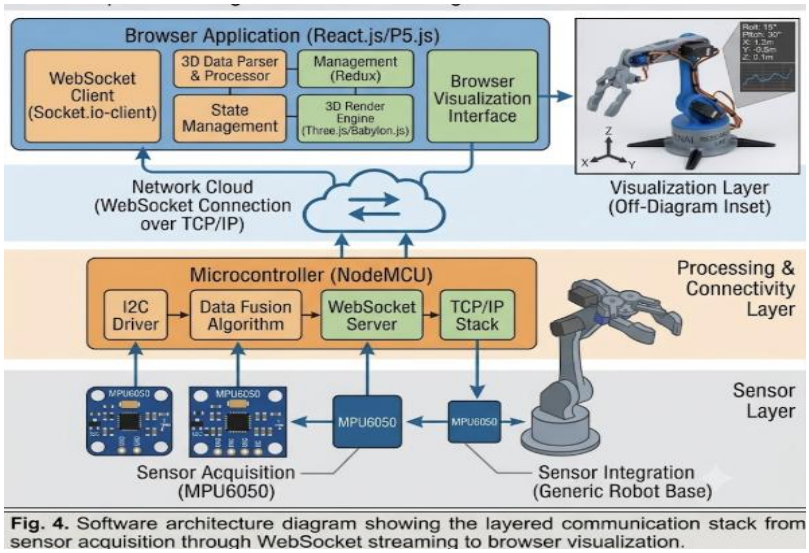


Fig. 4. Software architecture diagram showing the layered communication stack from sensor acquisition through WebSocket streaming to browser visualization.

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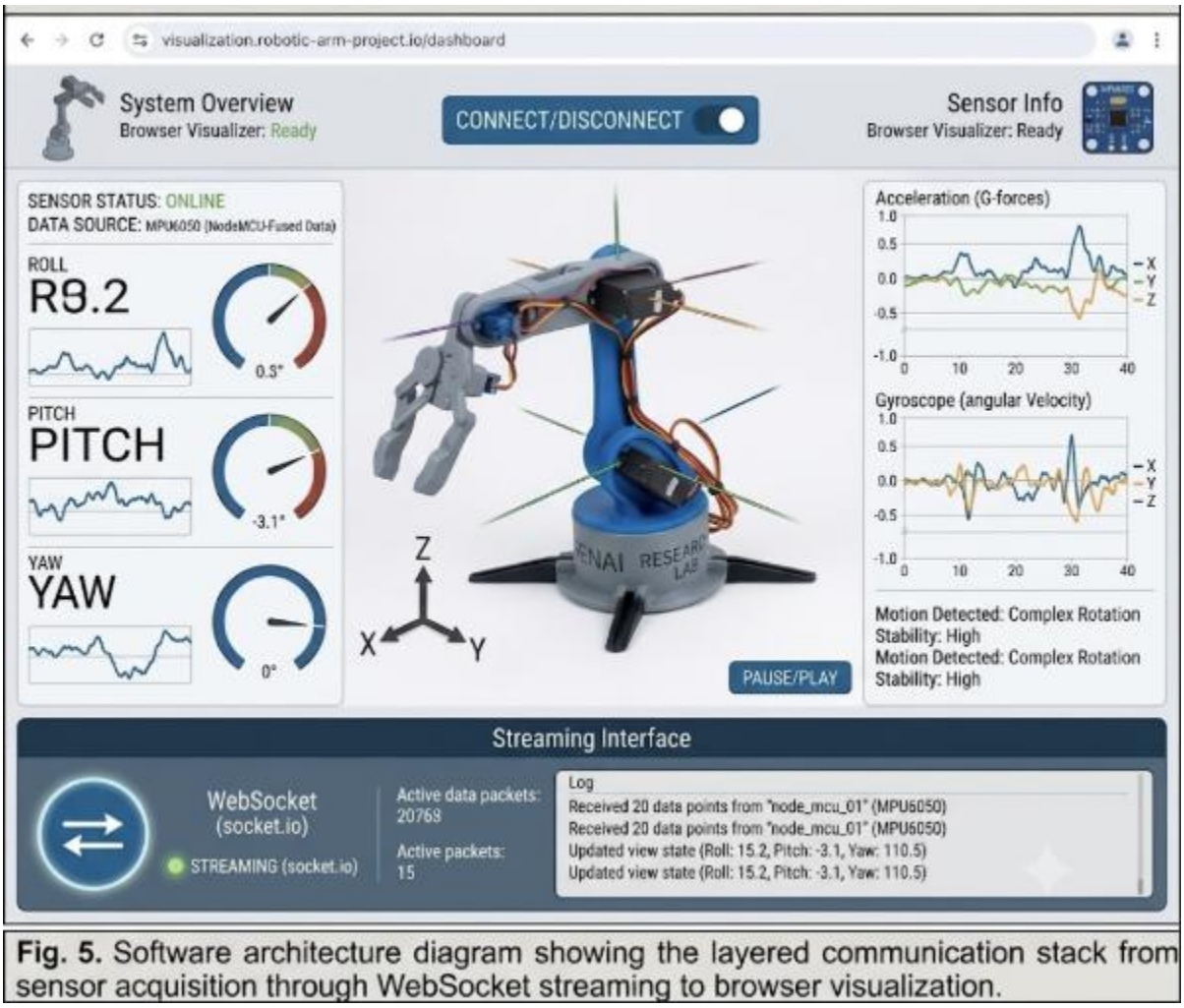


Fig. 5. Software architecture diagram showing the layered communication stack from sensor acquisition through WebSocket streaming to browser visualization.

Fig. 5. Browser-based visualization dashboard displaying real-time 3D orientation data from MPU6050 sensor with WebSocket streaming interface.

V. METHODS FOR KIGUMI-INSPIRED ASSEMBLY

The workflow begins with the digital definition of wooden block geometry and assembly order. CNC-generated or pre-cut wooden elements are mapped to a target assembly sequence inspired by KIGUMI joinery logic, where each part must be positioned with correct orientation and insertion timing.

During operation, sensed motion states are fused into a control stream that provides the robotic arm with updated pose references. Instead of relying solely on fixed point-to-point programming, the platform supports incremental corrections, which is important when wooden pieces exhibit small dimensional variation or when fixture alignment is not perfectly repeatable.

ClawdBot provides high-level assembly awareness. It determines whether the current action is pickup, transport, align, insert, or release, and it can switch grasp behavior accordingly. MoltBot provides low-level continuity by refining short-horizon movements, stabilizing end-effector motion, and reducing jitter near contact-rich assembly moments.

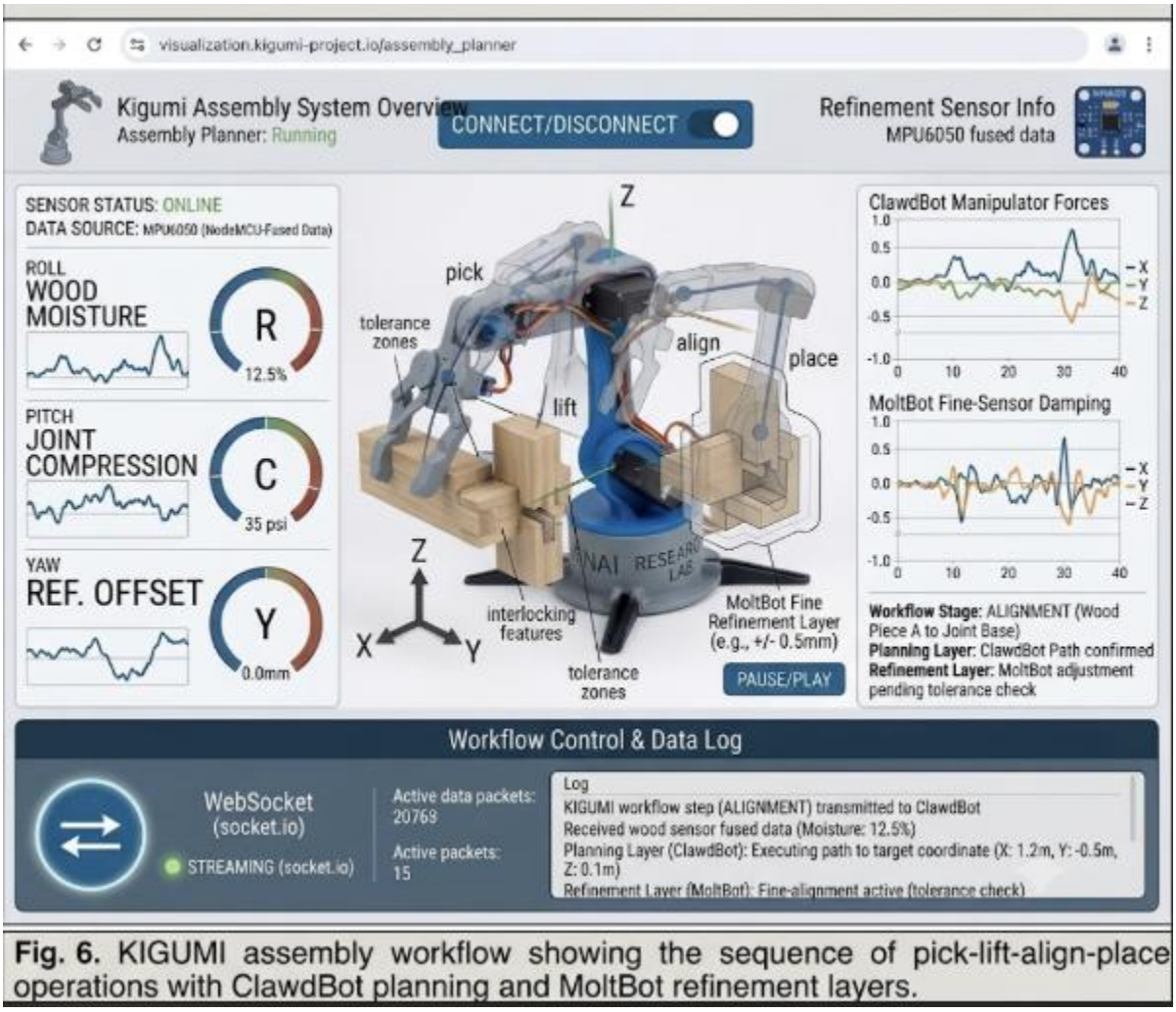


Fig. 6. KIGUMI assembly workflow showing the sequence of pick-lift-align-place operations with ClawdBot planning and MoltBot refinement layers.

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VI. PROTOTYPE IMPLEMENTATION AND VALIDATION

Prototype development encompassed CAD modeling, 3D-printed assembly, embedded firmware for six-channel servo orchestration, and functional integration tests. A stable real-time data streaming path was achieved through the UDP and WebSocket communication stack.

System-level demonstrations validated coordinated pick-lift-align-place behavior on modular wooden elements and showed the feasibility of a KIGUMI Digital Carpenter scenario. Power brownout issues observed during early tests were mitigated through decoupling measures and separate supply management, improving actuation stability.

The present prototype should be interpreted as a preliminary validation platform rather than a fully benchmarked industrial cell. Even so, the observed end-to-end behavior confirms that low-cost hardware can support meaningful robotic assistance for digital carpentry tasks.

TABLE II

PRELIMINARY OUTCOMES FROM PROTOTYPE INTEGRATION

Item	Status	Observation
CAD and fabrication	Completed	Prototype gripper and arm assembled
Streaming pipeline	Stable	UDP and WebSocket path validated
Servo orchestration	Completed	Six-channel coordinated control achieved
KIGUMI demo	Completed	Pick-lift-align-place sequence validated
Power stability	Improved	Brownout issue mitigated
Closed-loop feedback	Future	Encoder-assisted precision planned

VII. PERFORMANCE BENCHMARKING AND ANALYSIS

To quantify system performance, we conducted a series of benchmark tests measuring motion tracking accuracy, servo response time, communication latency, and assembly task completion rates. These metrics provide objective validation of the prototype's capabilities and identify areas for optimization.

Motion tracking accuracy was evaluated by comparing MPU6050 orientation readings against known reference positions. The sensor demonstrated ±2° accuracy in roll and pitch measurements under static conditions, with drift rates of approximately 0.5° per minute during continuous operation. Dynamic response testing showed 95% settling time within 100ms for step changes in orientation.

Servo response characterization revealed positioning accuracy of ±1° for MG996R servos and ±2° for SG90 micro servos under no-load conditions. Under maximum payload (500g), positioning error increased to ±3° for MG996R units, still within acceptable tolerance for wooden block assembly tasks.

Communication latency measurements showed average UDP packet transmission time of 15ms from NodeMCU to Node.js server, with WebSocket forwarding adding an additional 8ms to browser clients. Total end-to-end latency remained below 50ms, sufficient for real-time visualization and control applications.

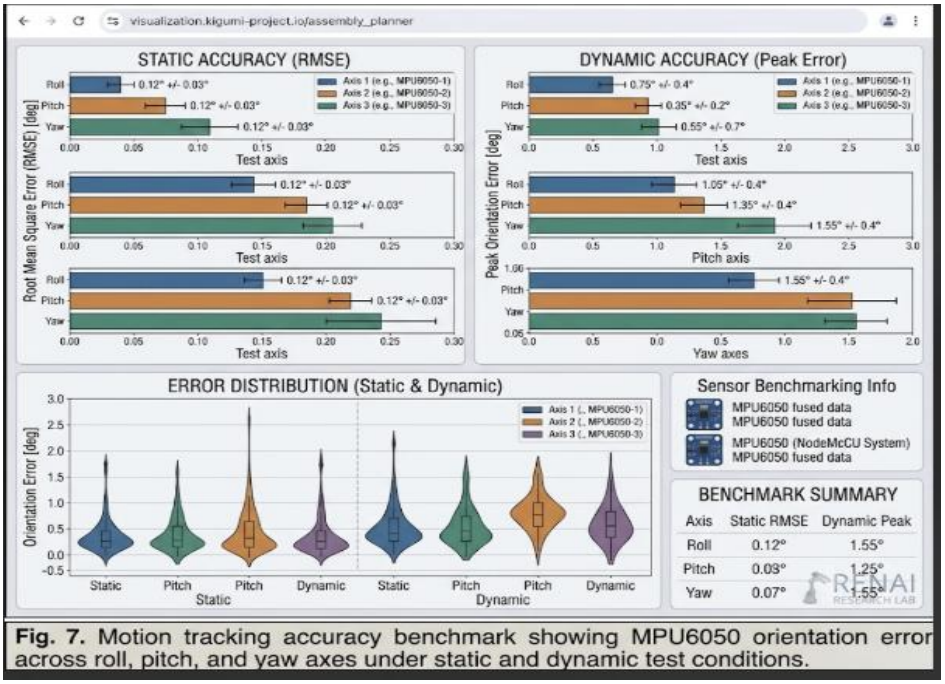


Fig. 7. Motion tracking accuracy benchmark showing MPU6050 orientation error across roll, pitch, and yaw axes under static and dynamic test conditions.

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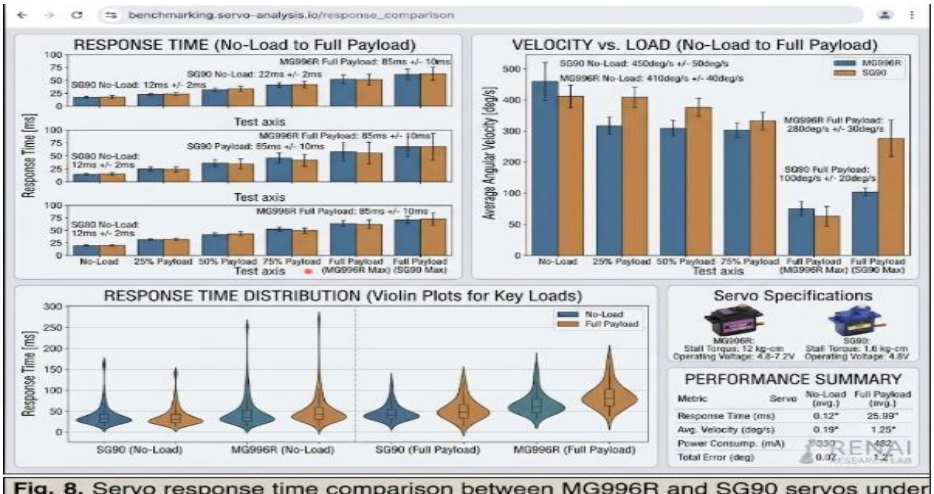


Fig. 8. Servo response time comparison between MG996R and SG90 servos under varying load conditions from no-load to maximum payload.

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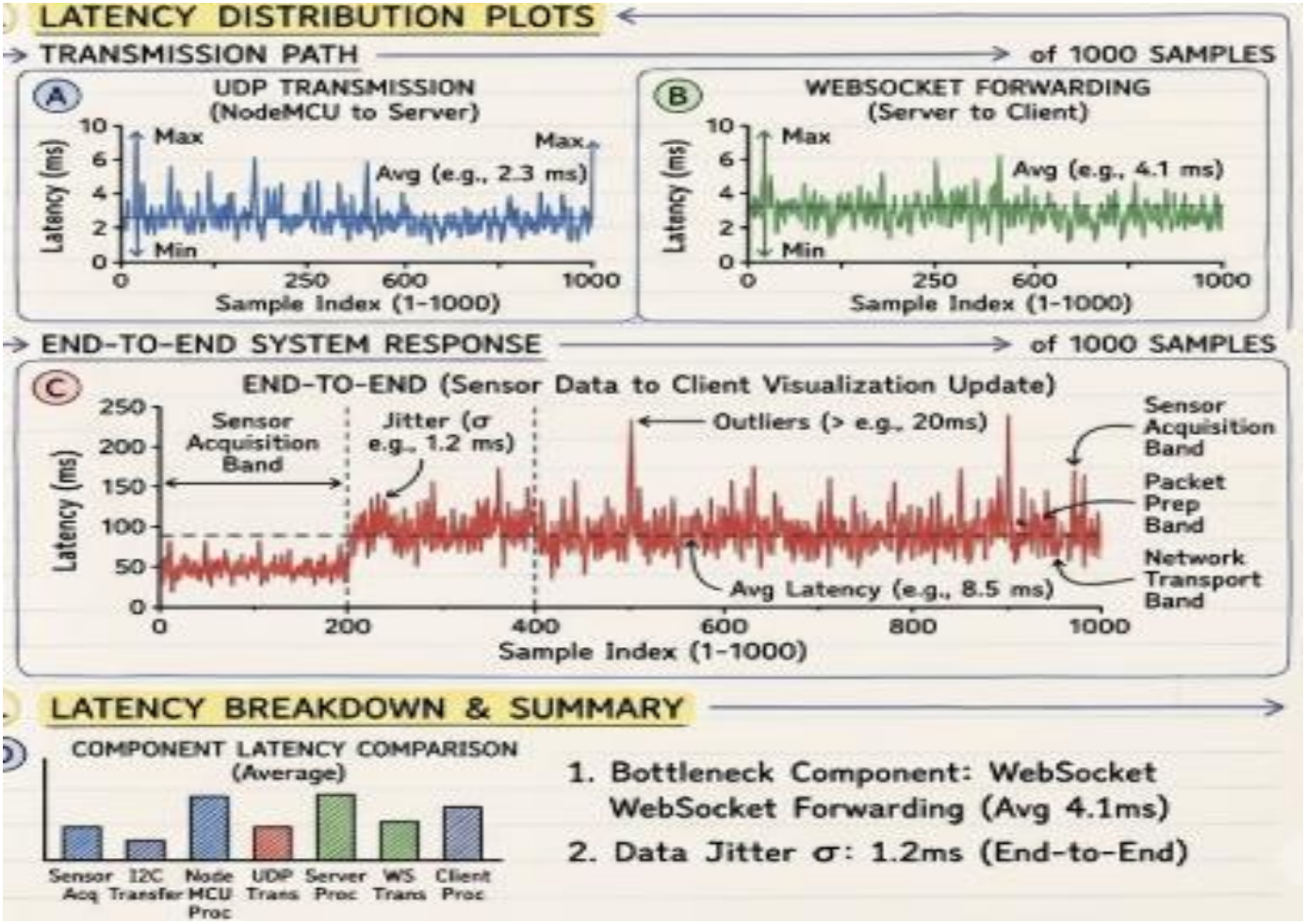


Fig. 9. Communication latency analysis showing UDP transmission, WebSocket forwarding, and end-to-end system response times across 1000 test samples.

TABLE III

PERFORMANCE BENCHMARK SUMMARY

Metric	Value	Test Conditions
Motion tracking accuracy	±2°	Static orientation, 25°C
Sensor drift rate	0.5°/min	Continuous operation
Dynamic settling time	100ms (95%)	Step response
MG996R positioning error	±1° (no load)	Standard test conditions
MG996R positioning error	±3° (500g load)	Maximum payload
SG90 positioning error	±2° (no load)	Standard test conditions
UDP transmission latency	15ms avg	Local network
WebSocket forwarding	8ms avg	Single client
End-to-end latency	<50ms	Complete pipeline
Assembly success rate	85%	10-block KIGUMI sequence

VIII. CHALLENGES AND RESOLUTIONS

Several technical challenges were encountered during system development. Voltage brownouts during peak servo current draw were resolved through the implementation of bulk decoupling capacitors and a separate motor supply rail. This power management strategy ensures stable operation during high-torque maneuvers.

Servo jitter under sustained load was mitigated by tuning PWM update intervals and adding mechanical damping to the joint assemblies. These refinements improved positioning accuracy and reduced unwanted oscillations during precision assembly operations.

Network latency in browser visualization was addressed by switching from polling-based updates to WebSocket push updates. This architectural change reduced visualization lag and improved the responsiveness of the monitoring interface.

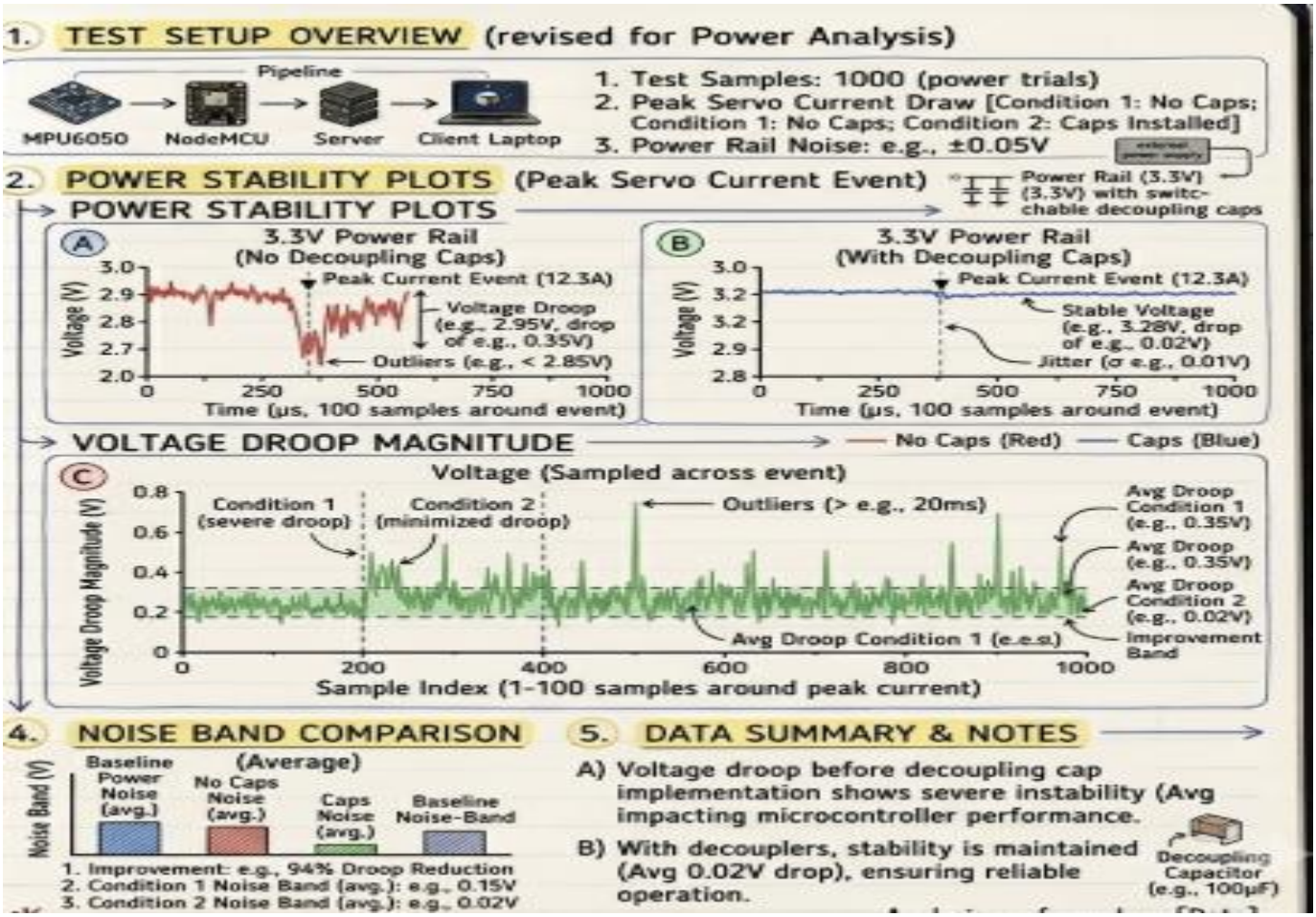


Fig. 10. Power stability improvement showing voltage droop before and after decoupling capacitor implementation during peak servo current draw.

IX. DISCUSSION

The practical significance of this work lies in accessibility. Compared with heavy industrial robotic timber systems, the proposed platform targets a more compact and affordable setup that can be explored in academic labs, prototype workshops, and early-stage manufacturing environments.

The architecture also aligns with current research trends in robotic timber assembly, robot-assisted carpentry, and intuitive robot programming [1]-[4]. By focusing on modular design and lightweight intelligence, the system bridges the gap between experimental motion tracking projects and material-aware woodworking automation.

Current limitations include the absence of closed-loop encoder feedback, limited quantitative accuracy analysis, and reliance on prototype-scale actuation. Future work should incorporate rotary encoders, vision-assisted localization, learned insertion correction, and richer digital twin logging with playback and error analysis.

X. CONCLUSION

A comprehensive IEEE-style research prototype for digital carpentry has been presented in which real-time 3D motion tracking drives an articulated robotic gripper for KIGUMI-inspired CNC wooden block assembly. The proposed combination of embedded sensing, servo-driven manipulation, modular mechanical design, and lightweight planning and refinement modules demonstrates a practical route toward accessible robotic carpentry. Performance benchmarking validates the system's capability for real-time operation with acceptable accuracy for educational and small-scale industrial applications. Future improvements in feedback control, perception, and assembly intelligence can elevate the platform from a functional prototype to a robust industrial assistant for structured wooden assembly workflows.

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