Modular Manipulator With Feedback Control

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***Abstract*—This paper presents the MODMAN – MODular robotic MANipulator, designed for adaptable build-to-task deployment in constrained and hazardous environments. To address mechanical joint play, torque deficits, and cabling wear, the platform integrates geometric polygon couplings, custom planetary gearboxes, and a decentralized ESP-NOW wireless architecture that reduces physical wiring to a three-wire power bus. Reconfigurable kinematics are resolved using an automated CAD-to-URDF pipeline paired with a MATLAB numerical inverse kinematics solver. Finally, an augmented reality interface on Microsoft HoloLens 2 provides real-time telemetry visualization and spatial zoning for safe pre-installation verification.**

***Index Terms*—modular robotics, joint rigidity, wireless control, kinematic reconfigurability, augmented reality**

I. Introduction

Industrial and scientific applications increasingly demand adaptable manipulators for confined or hazardous environments. Traditional rigid arms cannot reconfigure without costly hardware replacements and operational downtime. Modular reconfigurable robotics resolves this via a "build-to-task" strategy, allowing operators to dynamically alter kinematic chains using self-contained joint modules. However, physical implementation presents critical engineering trade-offs: maintaining joint rigidity to avoid end-effector inaccuracies, maximizing actuator torque density, solving dynamic kinematics on the fly, and eliminating wear on internal data cabling.

This paper presents the implementation of the MODMAN platform, featuring a multi-material structural design with polygon-joint couplings, custom planetary gearboxes, a decentralized wireless control architecture, an automated CAD-to-URDF kinematic pipeline, and a mixed-reality diagnostic interface [1].

II. Related Work

Modular reconfigurable manipulators have been widely investigated for space and flexible robotics, focusing on variable-DOF trajectory planning [2], [3] and automated on-the-fly kinematics generation [4], [5]. Concurrently, augmented reality (AR) interfaces have been integrated into human-robot collaboration to overlay telemetry, define spatial safety zones, and enable remote gesture control in hazardous environments. However, bridging theoretical reconfigurable kinematics with low-cost, physically robust, and wirelessly decentralized hardware remains an open engineering challenge.

III. Fundamental Principle and Contributions

The MODMAN platform is a modular, multi-DOF robotic manipulator consisting of a robust base and up to three physical joint modules. The architecture enables rapid physical disassembly and reassembly into varied kinematic topologies.

Mechanical coupling is achieved via a custom geometric polygon joint secured with a transverse locking pin, ensuring high torsional stiffness. Electrically, the platform utilizes a decentralized architecture. Each joint module contains its own stepper motor driver and an ESP32 microcontroller. Consequently, the physical arm requires only a 3-wire electrical bus (common ground, logic Vcc, and motor Vcc) that passes through the joints, thereby eliminating the need for data-routing wires. Joint coordination is achieved wirelessly using the low-latency ESP-NOW protocol. We introduce a multi-material structural design—combining PET-G load-bearing components with lightweight PLA enclosures—and integrate custom planetary gearboxes to resolve actuator torque limitations. To eliminate data cabling wear at moving joints, we implement a decentralized wireless control architecture that uses the low-latency ESP-NOW protocol. On the software side, we establish an automated CAD-to-URDF pipeline that generates kinematic models on the fly for a MATLAB-based numerical inverse kinematics [6]. Finally, we deploy a Microsoft HoloLens 2 augmented reality interface for live telemetry visualization, pre-installation spatial zoning, and remote gesture control.

IV. Mechanical Construction and Modularity

The physical development of the MODMAN platform progressed through three iterations to address structural, material, and torque constraints [1].