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The New Dexterity Modular, Dexterous, Anthropomorphic, Open-Source, Bimanual Manipulation Platform: Combining Adaptive and Hybrid Actuation Systems with Lockable Joints

Che-Ming Chang, Felipe Sanches, Geng Gao, and Minas Liarokapis

Abstract— **This work introduces the New Dexterity modular, dexterous, anthropomorphic, open-source, bimanual manipulation platform (OpenBMP) that is designed for research and rapid experimentation in robot grasping, dexterous manipulation, and bimanual manipulation. The platform combines adaptive and hybrid actuation systems with lockable joints, facilitating transitions between the execution of delicate and forceful tasks. Antagonistic tendon-driven elbows and inline actuator transmissions reduce the system's inertial mass while enhancing energy efficiency and overall performance. Leveraging 3D printing and carbon fiber reinforced manufacturing of core parts, the platform is easy to replicate and highly modular. This paper presents the details of the design, the actuation principles, and the experimental validation of the efficiency of the platform with the execution of complex teleoperation and telemanipulation tasks. The designs, the electronics, and the code are open-sourced to allow replication by others.**

I. INTRODUCTION

The field of robotics is witnessing substantial advancements in anthropomorphic robot manipulators, catering to diverse research and industrial applications [1]. These manipulators excel in automating repetitive or hazardous tasks, enhancing process efficiency, and minimizing errors. Versatile robotic manipulators can be found in wide-ranging applications in industry and commercial settings, homes, service sectors, and outdoor environments [2] [3] [4]. However, their limited flexibility and adaptability hinder customization for multi-application settings and diverse research applications. Modular robot manipulators allow for their joints and links to form various configurations, enabling the seamless extension of functionality by replacing arm units and/or end-effector modules. This approach has successfully been applied in industrial grippers, facilitating diverse manipulation tasks without extensive reconfiguration [5] [6]. While the modular approach proves effective for manipulation tasks, ensuring collaborative interactions with humans in dynamic workspaces necessitates careful consideration of safety aspects without compromising structural rigidity and functionality. Mechanisms like compliant shell structures and elastic linkages have been utilized to enhance manipulator versatility but often result in bulky exterior structures, compromising compactness and functionality.

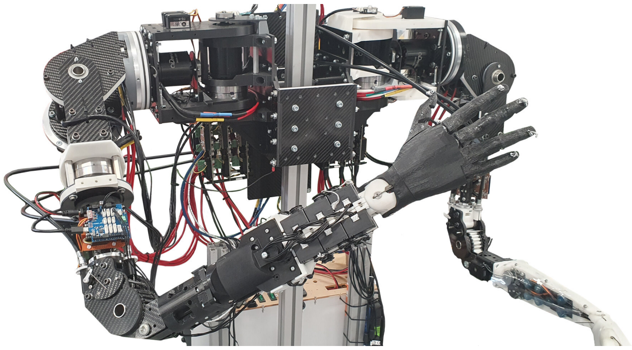

Fig. 1: The proposed modular, dexterous, anthropomorphic, open-source bimanual manipulation platform is designed for research and rapid experimentation in robot grasping, dexterous manipulation, and bimanual manipulation.

In this paper, we introduce the New Dexterity modular, dexterous, anthropomorphic, open-source, bimanual manipulation platform (OpenBMP) that combines lockable joints with adaptive and hybrid actuation systems for the development of the system components. The platform offers traditional configurations for the execution of traditional teleoperation tasks but also has the ability to quickly adapt to assistive and collaborative applications with the exchangeable forearm modules. The platform is designed for research and rapid experimentation in robot grasping, dexterous manipulation, and bimanual manipulation and is open-sourced to allow replication by other research groups.

II. RELATED WORK

A. Reconfigurable, Modular Manipulators

A common design approach for developing reconfigurable modular manipulators focuses on highly self contained motor joints such as the rapidly deployable reconfigurable modular manipulator system (RMMS) [7]. With highly integrated hardware and integrated coupling connectors, the joint modules could achieve a maximum torque of 270 Nm and weigh approximately 10.7 kg per unit. With similar torque output, lighter designs weighing 7.7 kg have been reported [8]. More recently, TRACLabs has developed a reconfigurable modular manipulator for NASA, featuring a fully modular 7-DOF robot arm with rotary joint and linkage modules [9]. The manipulator employs a universal mating adaptor to enable power and communication connectivity with additional modules, forming configurations ranging from 1 DoF

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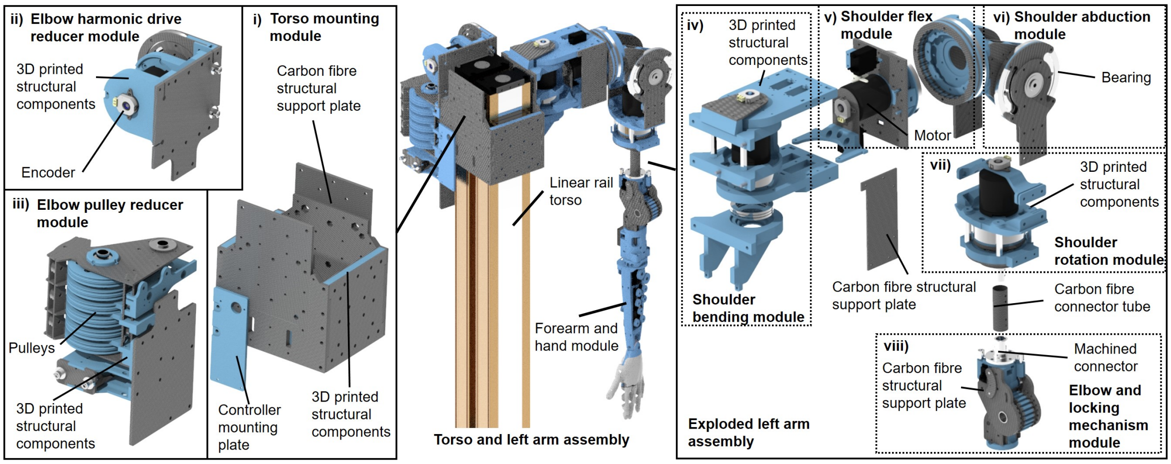

Fig. 2: Annotated exploded view of the: i) torso base assembly, ii) and iii) Bowden cable drive modules for the elbow, iv) to vii) shoulder modules, and viii) the elbow module and locking mechanism. The torso base consists of four carbon fibre-reinforced plates providing the basis and mounting point for the robot arms, control electronics, and elbow drive mechanism.

to N-DoFs. Each module contains its configuration, calibration, and park information in its memory, facilitating hot-swappable joints. Additionally, the final joint incorporates an auto detach device, enabling autonomous engagement with various end effectors or payloads. The xLink series of space rated modular robot manipulators from motiv space systems is designed to suit a wide range of on-orbit assembly and manipulation tasks [10]. The modular arms have enclosed actuator units that can be installed within connecting linkages of varying length. Commercial products such as the GLUON modular collaborative robotic arm and the MARA modular cobot from Acutronic robotics are desktop versions of industrial manipulators with lower weight and payload capacities. The 6 axis GLUON provides a peak payload of 1 kg while weighing approximately 2.5 kg [11]. The MARA cobot at 6 DoF has a rated payload capacity of 3 kg and weighs 21 kg [12]. Its T shaped modules can adapt to different types of linkage arms to reconfigure the manipulator. Servo based modular manipulators are often riddled with low payload capacities and complex wiring. The OpenMANIPULATOR-PRO series is a 6 DOF system with two rectangular tube linkage structures for connecting and reconfiguring the manipulator actuators. The system has a rated payload of 3 kg and weighs approximately 5.5 kg assembled with a reach of 645 mm [13]. The SES-PRO robot uses self contained smart servo units from Lynx motion's LSS-P range [14] housed in a rounded T-shaped metallic bracket, holding the strain wave reduction gears and smart actuator.

B. *Affordable and Open-Source Manipulators*

As robots begin to take on more and more tasks within unstructured environments such as hospitals, homes, and urban landscapes. The need for affordable robots will increase in order to fill roles within these settings. Affordable robot arms are a key component of this shift. In [15], the authors have designed a low-cost compliant robotic manipulator system composed of two arms equipped with parallel jaw grippers. Another low-cost robotic arm is a 6-axis 3D printed robotic arm designed for tasks such as additive and subtractive manufacturing processes with a single machine tool, and assembly type processes. The designs reported in [13], [16]–[18], offer cost-effective alternatives that promote accessibility for users and are often aimed at education. In [19], a fully open-sourced humanoid robot is developed, however, the arms of the robot lack the needed force and compliance in order to interact with humans or its environment. Another 3D printed robot arm is Reachy [20], a humanlike arm used as an experimentation platform for human-to-robot control strategies. Alternative methods from creating affordable robotics arms is the use of counterbalancing mechanisms to reduce the need for expensive high torque actuators [21].

III. DESIGN

A. *Modular Arm Hand Design*

The OpenBMP is equipped with a pair of modular, carbon fibre reinforced, 5 DoF mixed-drive manipulators with four axially driven joints and one tendon-driven joint in each arm. A 1:100 reduction harmonic drive is used in each direct axial drive joint. The Bowden cable tendon-driven elbows allow the actuating mechanism to be placed away from the joint, reducing the arm's inertial moments. Each upper arm shoulder unit joint is driven by a dual shaft brushless DC (BLDC) motor. The position feedback employs absolute encoders to provide compact, accurate, and fast position controls. Fig. 2 presents an exploded view outlining the various modules. The torso structure was designed to be mounted on a pair of opposing linear rails to access a larger reachable workspace similar to the variable torso of the New Dexterity ARoA humanoid described in [22]. The arm assembly, from torso base to the elbow, weighs 12.4 kg.

1) Shoulders: Each arm has a foldable shoulder joint. The ability to vary the orientation and distance between the two manipulators enables a much larger bimanual manipulation workspace. The modular design and tendon-driven elbow

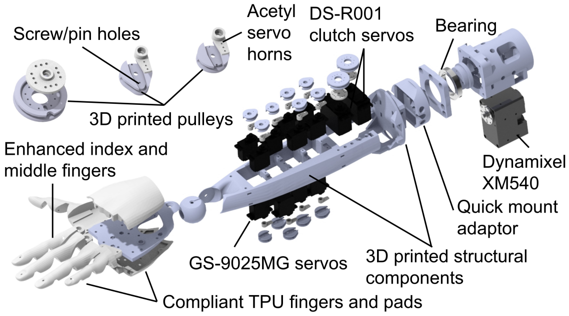

Fig. 3: Exploded view of the ASL forearm and hand module. The quick slot adaptor and actuator module are shown on the right, and the pulley designs are shown on the top left. The compliant index and middle fingers were modified to fit an adjustable elastic return system for finger abduction.

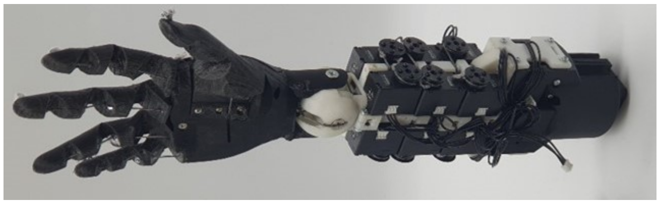

Fig. 4: The power grasp oriented forearm and hand module.

allow customization of arm length ratios. A raised shoulder abduction module can be used to facilitate different types of robotic configurations.

2) Joint locking: A specialized joint locking mechanism is used in both the shoulder and elbow flexion joints, mitigating motor stress during high-load manipulation tasks such as holding extended poses for long periods of time. The ratchet lock systems employed enable the joints to maintain their position with minimal energy expenditure, thereby reducing the overall torque exerted on the motors from the payload.

3) Modular, carbon fibre reinforced joints: The torso and bi-manual upper arm unit were constructed using 3D printed polylactic acid (PLA) high-strength filament parts, which were reinforced with carbon fibre composite plates in regions subjected to high loads. This choice of materials enables rapid prototyping and facilitates easy design modifications via Fused Deposition Modeling (FDM) 3D printing and waterjet cutting. The rigidity of the carbon fibre plates prevents structural deformation of the PLA parts. Furthermore, certain modules were structurally reinforced using aluminium standoffs, and a machined keyed shaft adapter drove each motor-harmonic drive module.

4) Bowden cable driven elbows: The system incorporates two types of reducer transmission mechanisms to demonstrate the versatility and capability of the platform. One is a directly coupled tendon drive onto the harmonic drive output with a total reduction of approximately 61.17. The other is an experimental pulley system routed around central idler wheels for compactness. The pulley system consists of an antagonistic 1:6 reduction pulley set with an output tendon driver reduction of 2.6 and a total reduction of approximately 15.6. Both transmission systems use Bowden cables for routing to the elbow joint and are fitted with in-line cable tensioners. The design enables easy exchange or modification of the elbow module without disassembling the shoulder modules. This allows for the replacement of Bowden cable sets through slotted in-line cable tensioners without requiring the disassembly of the robot.

B. Robotic Hand Designs

The system can integrate different forearm modules ranging from simple 3 DoF wrist to anthropomorphic wrist-hand units, and anthropomorphic hands with ASL signing capability and the ability to execute reliable power grasps.

1) American Sign Language (ASL) robot hand: The anthropomorphic hand module with dexterous signing features presented in Fig. 3 is an improved version of the TATUM arm hand unit [23]. The enhanced robotic hand incorporates 15 servos: 12 Goteck GS-9025MG servos for finger movements, 2 DS-R001 servos for the wrist, and a Dynamixel XM540 smart actuator for pronation/supination. Key improvements prioritize safety and reliability. Replacing FS5115M servos with DS-R001 clutch servos provides force-limited actuation and prevents back drive damages. The Dynamixel XM540 improves forearm rotation accuracy and is accompanied by a more dependable quick slot mounting adapter. Modifications to the index and middle fingers and the attachable pulleys on the acetyl servos horns expand the abduction range and enable adjustable joint return force via elastic tendons.

2) Power grasp oriented robot hand: The power grasp oriented, anthropomorphic hand features 12 Dynamixel XC330-T288-T smart actuators for finger motion and two Dynamixel XM430-W350 for wrist motions (See Fig. 4). These actuators have approximately 3.7 times more torque than the GS-9025MG servos and weigh 23 grams per unit. The rectangular casing allows the servos to be easily stacked and mounted to suit different configurations. The motors are stacked in a 4 by 3 configuration separated into a pair of mirrored 2 by 3 panels mounted on the forearm's structural base and are daisy-chained with exposed sides to facilitate individual programming and maintenance. Two Dynamixel XM430 actuators actuate the wrist, and the chassis of the actuators acts as the mounting point to the forearm rotation module. This hand weighs approximately 0.68 kg.

C. Control Interfaces

The forearm's control system interfaces via the ESP32-WROOM development board. This facilitates low-voltage systems with optional RS485, pulse width modulation, and TTL control communications. Six ODrive V3.6 control boards manage ten BLDC motors, with two motors per board except for the elbows. Each board has a power supply with circuit breakers and step-down buck converters to reduce input voltages and limit current (30-60V to 24V). Power sources include benchtop supplies from the mains or 54V battery packs for untethered operation. The ODrive controllers utilize cascaded position and velocity current

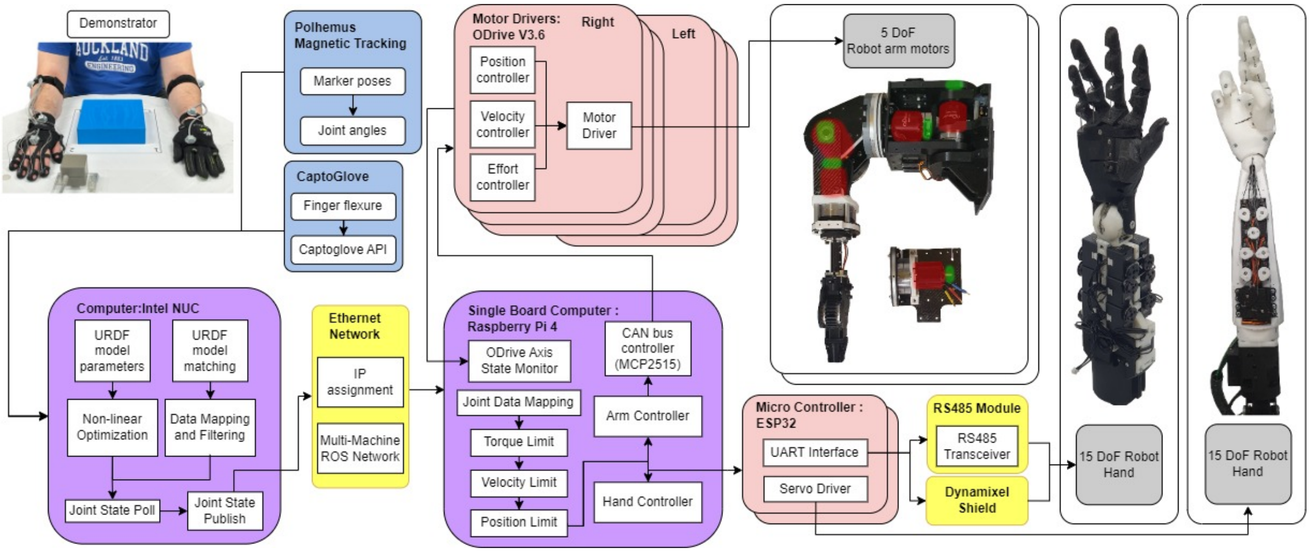

Fig. 5: Block diagram for the control of the arm-hand system. The system integrates different forearm modules for signing tASL messages and executing dexterous manipulation tasks.

loops, facilitating joints with configurable position, speed, and torque limits. The ODrive controllers interface with the ROS framework via the Controller Area Network (CAN) bus using the CANSimple protocol. A custom MCP2515 CAN bus transceiver connects the ODrive boards to a Raspberry Pi 4 (RPi4) via SPI. To mitigate electromagnetic interference, the RPi4 is encased in grounded aluminium. Interface with multiple AMT232B-V encoders via SPI necessitates a tri-state buffer and custom SPI cables constructed from CAT5e Ethernet cables. A custom interface adaptor board links the CANbus and encoders to each ODrive board. The RPi4 communicates with the main control computer (Intel NUC), over an Ethernet-based ROS network. The RPi4 runs the arm64 version of Ubuntu 20.04 LTS and ROS Noetic, interpreting, limiting, and transmitting received joint state commands and ensuring motor safety. Once the local USB ROS serial communication for the ESP32 is established, it can connect to other ROS network machines. An Intel NUC mini-computer hosts the vision-based decoding Mediapipe API, interfaces with Polhemus magnetic sensors, a nonlinear function solver for human-to-robot motion, and filters human motion data. The Universal Robotic Description Format (URDF) package defines the virtual model's parameters and software constraints, ensuring alignment with the virtual robot model's joint and design limits.

IV. CONTROL METHOD

A. *Overall Control Workflow*

The workflow for controlling the proposed bimanual manipulation platform is summarized in Fig. 5. A combination of the Polhemus magnetic motion capture systems and flexure sensors has been employed to capture high-fidelity human arm and hand motions for executing teleoperation and telemanipulation tasks with the proposed platform.

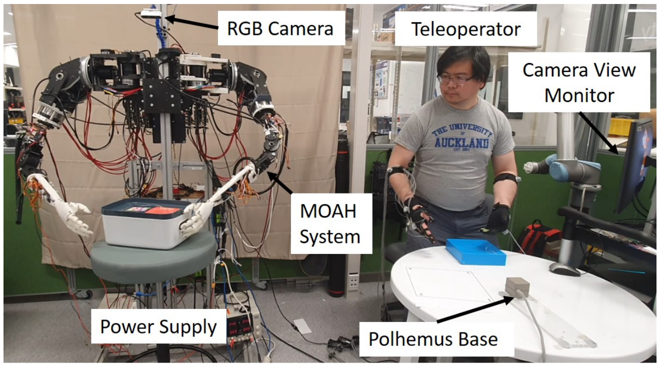

Fig. 6: Instances from one of the telemanipulation experiments showcasing the proposed bimanual robotic manipulation system setup. Polhemus and Captoglove data captures the human kinematics and maps the motion to the robot kinematics. The RGB camera provides visual feedback of the workspace to the teleoperator. Objects are placed on an adjustable stool within the bimanual manipulation workspace.

B. *Human to Robot Motion Mapping*

Human-to-robot motion mapping has been formulated as a constrained optimisation problem using the tracked human wrist position as a goal position and solving for the robot arm joints. This generates robot trajectories that can closely track the human trajectories similar to the work presented in [24]. Setting an appropriate elbow constraint allows the optimisation to derive humanlike configurations that closely resemble the human configurations despite the kinematic differences, respecting functional anthropomorphism.

V. EXPERIMENTS AND RESULTS

A series of bimanual tasks were performed to demonstrate the capability of OpenBMP. This includes a cooperative bimanual lifting task of a small box, a coordinated bimanual

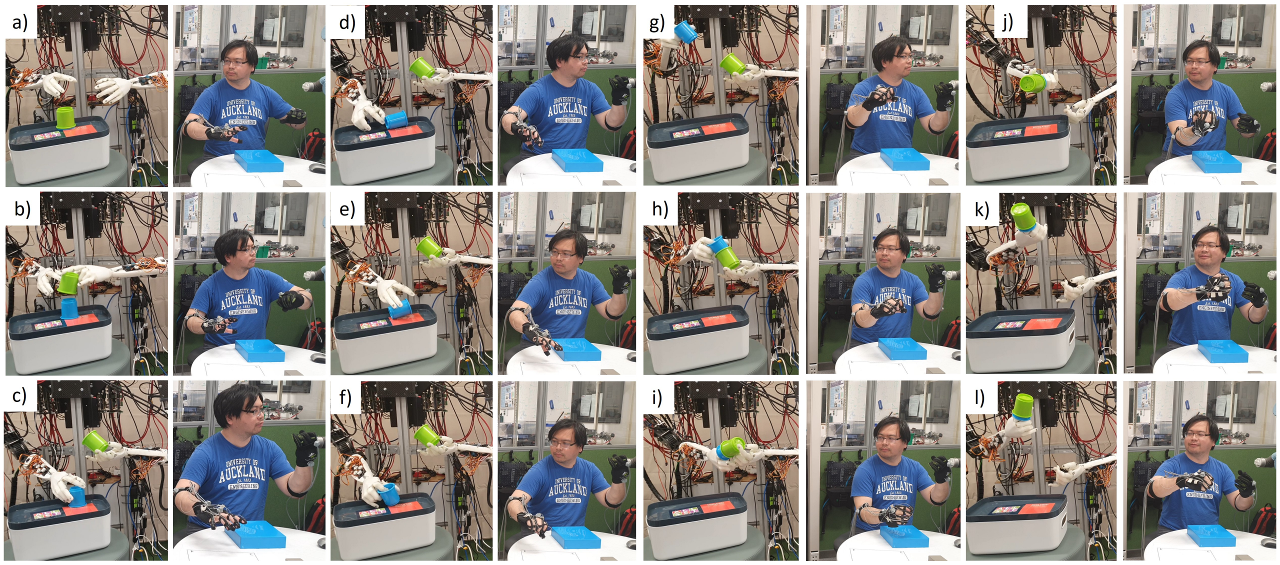

Fig. 7: Bimanual manipulation task of stacking cups. Subfigure a) and b) show the green cup being picked up by the left hand. Subfigures c), d), and e) show the right hand re-orienting the blue cup to an upright position for grasping, as shown in Subfigure f). Subfigure g) and h) show the blue cup being inserted into the green cup and Subfigures i), j), k), and l) show the stacked cups being transferred to the right hand and reoriented on the right hand.

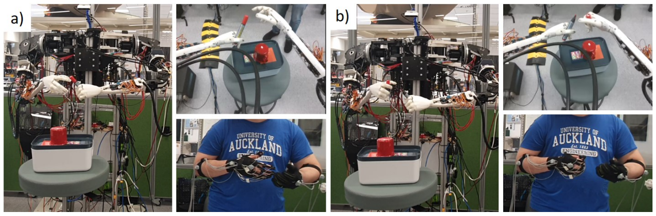

Fig. 8: Demonstration of telemanipulation based execution of pen lid removal task. Subfigure a) shows the pen being held in one hand, ready for lid removal and b) shows the lid being removed from the pen by the other hand.

task of removing a pen lid, a bimanual manipulation task of picking up and transferring the pen between the hands, and a complex bimanual manipulation task involving stacking and un-stacking of cups. The experimental setup is shown in Fig. 6, where the teleoperator has direct sight from the side and a top-down view from the monitor. The manipulated objects were placed on an elevated platform to allow better access by the teleoperator and to ensure that the manipulation task is executed within the bimanual workspace of the arms.

A. Characteristics

The proposed OpenBMP without the forearms costs approximately $12,000 USD in materials. The forearm units range between $450 to $1900 USD each. With a reach of approximately 935 mm, the design operates at a limited current of 10 A and is capable of payloads of 3 kg and 0.6 kg with the Dynamixel hand and the ASL hand configuration, respectively. The torque available from the elbow limits the payload, which showcases different reduction methods. Additionally, the hand's capabilities also severely limit the payload. Table I outlines the range of motion and the theoretical joint characteristics of the openBMP. The results of the experiments differed from the theoretical 6.8 kg and 1.75 kg capacities. The main factor attributing to the transmission loss is likely the additional friction acting on the Bowden cables as Dyneema ropes replaced the steel tendons. The elbow motor controllers were also set at limited speeds and were not tuned to loaded weight operations. However, by locking the joints, the joint position could be maintained beyond the motor payload capacity for the elbow.

TABLE I: Joint characteristics of the OpenBMP.

Joint Movement	Range of Motion (°)	Max Joint Torque (Nm) @ 70A/10A
Shoulder		
Protraction/Retraction	80/-45	386 / 55.14
Extension/Flexion	-180/180	386 / 55.14
Abduction/Adduction	180/-50	386 / 55.14
Internal/External Rot.	180/-180	386 / 55.14
Elbow		
Elbow Left Flexion	170	236.14 / 33.73
Elbow Right Flexion	170	60.22 /8.6
Pronation/Supination	90/-180	10.6 at 4.4A
Wrist - ASL Hand		
Extension/Flexion	-20/90	0.59 at 1.65 A
Abduction/Adduction	50/-30	0.59 at 1.65 A
Wrist - Dynamixel Hand		
Extension/Flexion	-60/75	4.1 at 2.3 A
Abduction/Adduction	45/-45	4.1 at 2.3A

B. Telemanipulation Experiments

The telemanipulation experiments involved pickuping up a plastic box with both arms and removing the cap of a pen with ease using bimanual manipulation capabilities, as depicted in Fig. 8. The teleoperator was able to pickup the pen and transfer it to the other hand using a power grasp. During task execution it is evident that the right hand positions the pen towards the center of the bimanual workspace and the left hand moves towards the moving target to grasp the pen. Finally, a task involving the pickup, re-orientation, and stacking of cups is demonstrated in Fig. 7. The left-hand first picks up the green stacked cup and rotates it to an upright position from Fig. 7 a) to b) with Fig. 7 c) to e) demonstrating how the right-hand uses the surface to re-orient the blue cup for pickup. Fig. 7 f) and g) show the bimanual motion of aligning the cups for insertion, and Fig. 7 h) and i) depict the bimanual coordinated local rotation of multiple in-hand objects that results in the transfer of the green cup into the blue cup held by the right hand.

C. Project Website

The video presenting the experimental validation of the efficiency of the proposed bimanual manipulation platform together with the open-source designs, specifications, and code can be found in HD quality at the following URL:

www.newdexterity.org/OpenBMP

VI. CONCLUSIONS

This paper introduced the New Dexterity modular, anthropomorphic bimanual manipulation platform. The OpenBMP is purpose-built for research and rapid experimentation in the domains of robot grasping, dexterous manipulation, and bimanual manipulation. It achieves this through a unique combination of adaptive and hybrid actuation systems with lockable joints, allowing seamless transitions between delicate and forceful tasks. The integration of antagonistic tendon-driven elbows and inline actuator transmissions not only reduces inertial mass but also enhances energy efficiency and overall system performance. The platform's design philosophy emphasizes ease of replication and high modularity, thanks to the utilization of 3D printing and carbon fiber reinforced manufacturing for core components. We have provided a comprehensive overview of the platform, including its design intricacies, actuation principles, and experimental validation, showcasing its efficacy in executing complex teleoperation and telemanipulation tasks. Importantly, we have embraced open-source principles by making the designs, electronics, and code freely available. This openness fosters collaboration and innovation, allowing others to replicate and build upon our work.

REFERENCES

[1] T. B. Insights, "Humanoid robot market share, demand, analysis, report 2032," last accessed 10 June 2023. [Online]. Available: https://www.thebrainyinsights.com/report/humanoid-robot-market-13319

[2] T. Yamamoto, T. Nishino, H. Kajima, M. Ohta, and K. Ikeda, "Human support robot (hsr)," in *ACM SIGGRAPH 2018 emerging technologies*, 2018, pp. 1–2.

[3] C. Borst, T. Wimbock, F. Schmidt, M. Fuchs, B. Brunner, F. Zacharias, P. R. Giordano, R. Konietschke, W. Sepp, S. Fuchs *et al.*, "Rollin'justin-mobile platform with variable base," in *2009 IEEE International Conference on Robotics and Automation*. IEEE, 2009, pp. 1597–1598.

[4] S. Zimmermann, R. Poranne, and S. Coros, "Go fetch!-dynamic grasps using boston dynamics spot with external robotic arm," in *2021 IEEE International Conference on Robotics and Automation (ICRA)*. IEEE, 2021, pp. 4488–4494.

[5] FESTO, "Adaptive gripper fingers dhas," last accessed 10 June 2023. [Online]. Available: https://www.festo.com/media/pim/048/D15000100122048.pdf

[6] ——, "Flex shape gripper | festo gb," last accessed 10 June 2023. [Online]. Available: https://www.festo.com/gb/en/e/about-festo/research-and-development/bionic-learning-network/highlights-from-2015-to-2017/flexshapegripper-id_33444

[7] C. J. Paredis, H. B. Brown, and P. K. Khosla, "A rapidly deployable manipulator system," *Robotics and Autonomous Systems*, vol. 21, no. 3, pp. 289–304, 1997.

[8] D. Schmitz, P. Khosla, and T. Kanade, "The cmu reconfigurable modular manipulator system," 1988.

[9] I. TRACLabs. Reconfigurable modular manipulator (rmm) - traclabs. Last accessed 10 June 2023. [Online]. Available: https://traclabs.com/projects/rmm/

[10] M. space systems. xlink space-rated modular robotic arm system. Last accessed 10 June 2023. [Online]. Available: https://motivss.com/products-capabilities/robotics/xlink/

[11] Mixos. Gluon | modular desktop collaborative robotic arm by sca - electronics-lab.com. Last accessed 10 June 2023. [Online]. Available: https://www.electronics-lab.com/gluon%E4%B8%A8modular-desktop-collaborative-robotic-arm-sca/

[12] A. Robotics. Robotic arm | the first modular articulated robotic arm | m-cobot. Last accessed 10 June 2023. [Online]. Available: https://acutronicrobotics.com/products/

[13] I. ROBOTIS. Open source robots - openmanipulator-p - robotis. Last accessed 10 June 2023. [Online]. Available: https://www.robotis.us/openmanipulator-p/

[14] L. motion. Ses-pro modular robot system - lynxmotion. Last accessed 10 July 2023. [Online]. Available: https://www.lynxmotion.com/ses-pro-modular-robot-system/

[15] D. V. Gealy, S. McKinley, B. Yi, P. Wu, P. R. Downey, G. Balke, A. Zhao, M. Guo, R. Thomasson, A. Sinclair *et al.*, "Quasi-direct drive for low-cost compliant robotic manipulation," in *2019 International Conference on Robotics and Automation (ICRA)*. IEEE, 2019, pp. 437–443.

[16] M. Lapeyre, P. Rouanet, J. Grizou, S. Nguyen, F. Depraetre, A. Le Falher, and P.-Y. Oudeyer, "Poppy project: open-source fabrication of 3d printed humanoid robot for science, education and art," in *Digital Intelligence 2014*, 2014, p. 6.

[17] S. Manzoor, R. U. Islam, A. Khalid, A. Samad, and J. Iqbal, "An open-source multi-dof articulated robotic educational platform for autonomous object manipulation," *Robotics and Computer-Integrated Manufacturing*, vol. 30, no. 3, pp. 351–362, 2014.

[18] A. Soriano, L. Marin, M. Valles, A. Valera, and P. Albertos, "Low cost platform for automatic control education based on open hardware." *IFAC Proceedings Volumes*, vol. 47, no. 3, pp. 9044–9050, 2014.

[19] G. Langevin, "Project -inmoov," last accessed 8 January 2019. [Online]. Available: http://inmoov.fr/project/

[20] S. Mick, M. Lapeyre, P. Rouanet, C. Halgand, J. Benois-Pineau, F. Paclet, D. Cattaert, P.-Y. Oudeyer, and A. de Rugy, "Reachy, a 3d-printed human-like robotic arm as a testbed for human-robot control strategies," *Frontiers in neurorobotics*, vol. 13, p. 65, 2019.

[21] H.-S. Kim and J.-B. Song, "Low-cost robot arm with 3-dof counterbalance mechanism," in *2013 IEEE International Conference on Robotics and Automation*. IEEE, 2013, pp. 4183–4188.

[22] G. Gorjup, C.-M. Chang, G. Gao, L. Gerez, A. Dwivedi, R. Yu, P. Jarvis, and M. Liarokapis, "The aroa platform: An autonomous robotic assistant with a reconfigurable torso system and dexterous manipulation capabilities," in *2021 IEEE/RSJ International Conference on Intelligent Robots and Systems (IROS)*. IEEE, 2021, pp. 4103–4110.

[23] C.-M. Chang, F. Sanches, G. Gao, S. Johnson, and M. Liarokapis, "An adaptive, affordable, humanlike arm hand system for deaf and deafblind communication with the american sign language," in *2022 IEEE/RSJ International Conference on Intelligent Robots and Systems (IROS)*. IEEE, 2022, pp. 871–878.

[24] M. Liarokapis, P. K. Artemiadis, and K. J. Kyriakopoulos, "Functional anthropomorphism for human to robot motion mapping," in *2012 IEEE RO-MAN: The 21st IEEE International Symposium on Robot and Human Interactive Communication*. IEEE, 2012, pp. 31–36.