FABRIC: FAbricating Bodily-Expressive Robots for Inclusive and Low-Cost Design

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***Abstract*— Sign language serves individuals with hearing impairments as a crucial communication mode operating through visual-manual means. While there has been established theory and agreement about embodiment in multiple fields, only limited research has deeply engaged to lower access to the physical body for spatial perception and engagement. Embodied robots are often cost-prohibitive, and existing open-source robot fabrication packages are limited in their ability to fully address communication nuances, typically running only on predefined programs. Reprogramming for broader bodily interactions, such as gestures in various domains (e.g., construction), is nearly impossible unless expertise precedes. We introduce FABRIC, an end-to-end toolkit for fabricating and programming bodily language for unique human-robot interactions. The toolkit includes a fully 3D-printable robot, designed for consumer-grade FDM machinery, that learns from demonstration (LfD) to capture and translate users' bodily expressions through its upper torso (arms and hands) movements. A visual programming interface enables appending or sequencing demonstrations from various sources, i.e., videos, cameras, and expandable word/phrase/sentence libraries.**

I. INTRODUCTION

Sign language plays a crucial role in communication using hand configuration, gestures, upper torso movements, postures, and facial expressions [1]. It conveys the message through a *visual-manual modality*. Sign language is acquired as a first language early in life, while others, including those without hearing impairments, learn it later as a second language [2]. Over 430 million people (5% of the global population) have hearing impairments, and nearly 1 billion young adults risk permanent hearing loss due to unsafe listening habits [3]. However, many lack motivation to learn sign language due to the long learning duration.

Physical embodiment enhances language expressivity beyond virtual avatars by fostering social presence and reinforcing social norms in physical spaces. Physical robots provide natural interaction by offering various pedagogical strategies [4], promoting more interactions [5], efficient language learning [6], and supplementing teachers [7]. However, the widespread deployment of sign language robots remains insufficient to meet the growing demand for embodied communication. High-fidelity sign language robots require intricate designs with high-DOF robotic arms and finger joints, demanding sophisticated kinematic programming for precise actuator control. While some prior research contributed to low-cost hand, wrist, and body production [8], [9], [10], relying on off-the-shelf robots [11] remains unaffordable for many individuals who require a physical agent. Also, sign language is culture-dependent, thus, a pre-codded system does not allow for customization and adaptation. Furthermore, both open-source and off-the-shelf robotic devices assume an understanding of the owned robotic system, posing barriers to average users to design human-robot interaction that adapts to the idiosyncratic needs. Three key challenges remain: first, fabricating sign language robots requires complex design and engineering, second, the lack of end-user toolkits for programming and reprogramming hinders versatile interaction design. Lastly, the technical proficiency gap between non-experts and robotics specialists makes it infeasible to afford physical sign language expressions in all regions, cultures, and contexts.

Our work draws inspiration from the end-user toolkits, their role in reducing barriers to accessing emerging technologies by using low-cost fabrication techniques [12], open-source electronics (e.g., Arduino), and end-user programming (e.g., Blockly [13]).

We introduce FABRIC, an end-to-end toolkit for low-cost fabrication of a robotic sign language body and the expressive programming of social interactions. Built on learning-from-demonstration (LfD), FABRIC captures bodily input from webcams or pre-recorded videos, translating pose estimations into kinematics for high-level authoring of robot behaviors. Much as previous end-user toolkits (e.g., Arduino, Blockly) have brought about many innovations in personal projects, FABRIC aims to democratize access for non-experts by seeking attention from those who are otherwise not offered an accessible platform for non-verbal interaction with robot body. A visual programming interface allows users to easily program custom interactions by drag-and-drop language modules. We validate FABRIC through quantitative analysis using the Sem-Lex benchmark dataset [14] and Mediapipe [15] to assess its coverage and accuracy in executing ASL signs.

The subsequent sections will outline prior works, sign language elements and kinematics, FABRIC toolkit design and iteration, interaction synthesis, user walkthrough, applications, and evaluation.

II. RELATED WORK

Physical embodiment in robots refers to their materialistic appearance and configuration, which is crucial for enhancing human-robot interaction [22]. Embodied robots foster greater social engagement, emotional expressiveness, and enjoyment compared to screen-based agents [23], particularly in sign language learning, where spatial movements are crucial [7].

This work was supported in part by the NSF, IIS-2340120.
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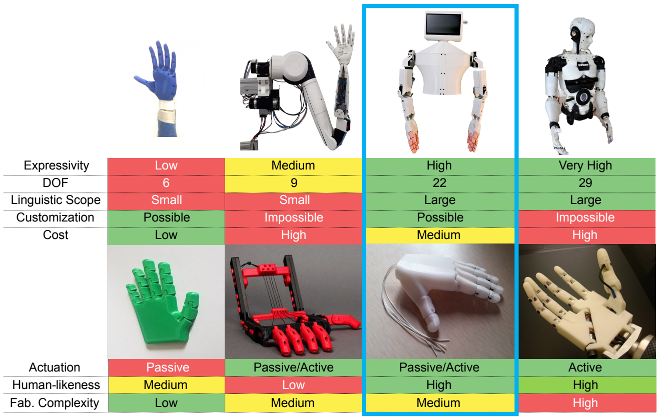


Expressivity	Low	Medium	High	Very High
DOF	6	9	22	29
Linguistic Scope	Small	Small	Large	Large
Customization	Possible	Impossible	Possible	Impossible
Cost	Low	High	Medium	High
Actuation	Passive	Passive/Active	Passive/Active	Active
Human-likeness	Medium	Low	High	High
Fab. Complexity	Low	Medium	Medium	High

Fig. 1. Situating FABRIC's capabilities and comparative benefits. (Top) Modified Ada robotic hand [16], TATUM robotic arm and hand [17], FABRIC and Inmoov robot [18]. (Bottom) Compatible robot hands with FABRIC robot body [19], [20], [21], [18]. FABRIC features low-cost, fully 3D printable bodies with large communication coverage.

Embodiment increases motivation, engagement, and performance during sign language learning [6], especially among children and infants with hearing impairments. Beyond off-the-shelf models like Nao and Robovie R3, custom-built robots such as InMoov [18], Igus [24], and the Poppy [25] project have been on the rise with 3D printable robot bodies. While it is one of the foremost and promising bodily solutions, limited degrees of freedom in SignBot [26] restricts the adaptability of various signs unless extensively re-engineered. Most sign language robots are pre-programmed with limited vocabularies [27], [26]. A gap also exists between highly dexterous, high-end sign language robots [27], [28] and those accessible through end-user fabrication.

The complexity of programming robotic systems has been a long-standing research question, leading to various end-user programming, including visual programming, deep learning [29], and learning from demonstration (LfD) [12]. To simplify action programming and design dexter interactions in robots, Hierarchy Temporal Memory (HTM), motion suites, spatial-temporal system have been employed [30]. LfD offers an intuitive way for novices to describe actions through demonstrations for robots to accumulate knowledge from movement primitives to perform tasks such as grasping, moving, releasing objects, and series of them to conduct more complex motions [31]. Although sensor-embedded gloves [32] enable new signs to be added, they only capture the handshape, missing crucial components of sign gestures involving arm, body, and head movement, all are not accessible to end-users. Nonetheless, recent advances in pose estimation offer granular human body poses with high accuracy using noninvasive, regular RGB cameras [15] for low-barrier programming of robot behaviors.

III. Sign Language Embodiment Knowledge Space

A. Elements of Sign Language

Sign language comprises five key elements: handshape, orientation, spatial location, movement, and non-manual expression [1]. Handshape defines finger configurations and

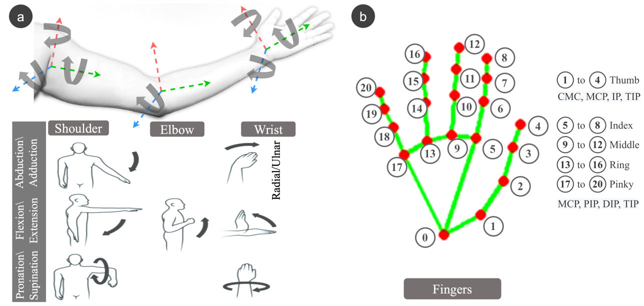


Fig. 2. Human arm (a) and finger (b) joints to realize sign languages.

orientation refers to the palm's direction in 3D space. Together, they form alphabets, numerals, and static signs. Spatial locations relate to body reference points (e.g., nose, chin, mouth), with transitions enabling word and sentence formation. Nonmanual expressions (e.g., facial and head gestures) convey mode, adjectives, and emotions.

B. Anatomy of Sign Language: Degrees of Freedom

In this section, we examine the involved joint movements for realizing the sign language elements.

Arm (Shoulder & Elbow): The arm supports and positions the hands for sign language expression. The shoulder provides 3-DOF via flexion/extension, abduction/adduction, and pronation/supination, and the elbow adds another through flexion and extension (Fig. 2a).

Hand (Fingers & Wrist): Each finger has three joints: the Metacarpophalangeal (MCP), Proximal Interphalangeal (PIP), and Distal Interphalangeal (DIP) joints, while the thumb has the Carpometacarpal (CMC), MCP, and Interphalangeal (IP) joints (Fig.2b). Wrist movements—flexion/extension, radial/ulnar deviation, and pronation/supination -add three DOFs for orientation.

Head Position and Facial Movements: Facial movements enhance sign language expressiveness. Eyebrows, eyes, mouth, cheeks, and jaw provide 1–3 DOF each, conveying nonmanual expressions.

C. Precision Requirements of DOF ASL Linguistic Units

Sign languages rely on iconicity and similar to spoken languages, sign language expressivity depends on context, cultural norms, and individual signing style. Signers draw from these layers to produce rich, dynamic, and context-sensitive expressions that mirror the depth & diversity of spoken language. In sign language, the need for precision and complexity increases as linguistic units are broken down from phrases to individual letters. This is partly because phrases are contextual, aiding interpretation, whereas individual letters often lack context and are presented in isolation.

IV. FABRIC Design & Configuration

FABRIC features an end-to-end pipeline, from motion capture to the fabrication of an expressive robot, with a programming toolkit for interaction design without domain expertise. Each robotic arm has 6 DOF, and each hand has 5 DOF, totaling 22 DOF. Users can 3D-print and assemble the

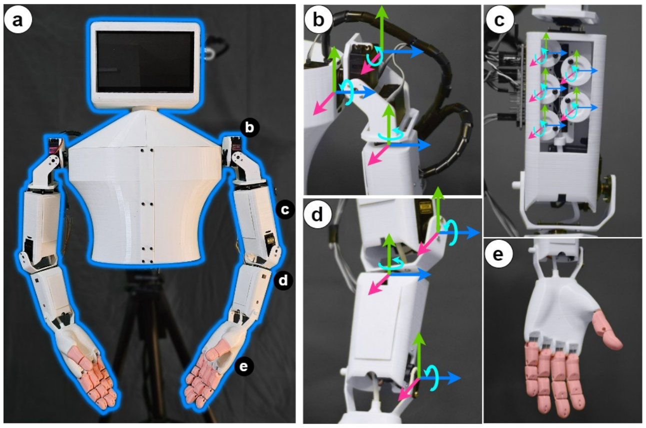
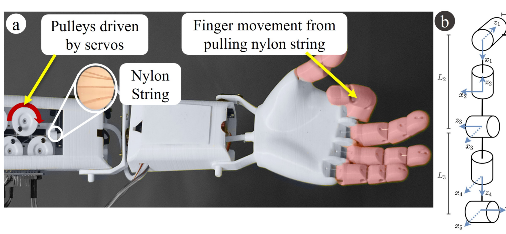


Fig. 3. Components of FABRIC robot, (a) assembled FABRIC, (b) shoulder joints, (c) finger movement servos mounted inside the upper arm, (d) elbow and wrist joint, (e) robotic hand.



	a_i	α_i	d_i	θ_i
1	0	90	$L_1 = 25$	ϑ_1^*
2	0	90	0	ϑ_2^*
3	$L_2 = 185$	90	0	ϑ_3^*
4	0	-90	0	ϑ_4^*
5	0	-90	0	ϑ_5^*
6	$L_3 = 120$	0	0	ϑ_6^*

Fig. 4. (a) Finger actuation mechanism with servo motors rotating the pulleys connected to the fingers. Flexion and extension movements in the fingers are executed when strings are pulled and relaxed. (b) Robotic Arm Joint DH Parameters. Units are in mm and angle in $degrees$. * *variable*.

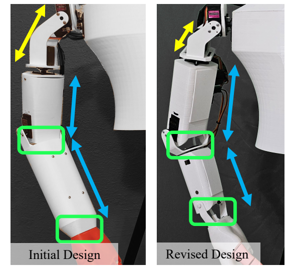
robot with off-the-shelf electronics. FABRIC's interface offers four ways to design interactions: (1) using pre-built ASL sets, (2) capturing demonstrations via webcam/smartphone, (3) converting expert videos, and (4) sequencing and conditioning actions. Demonstrations are automatically converted into kinematics and stored for sign language execution.

A. Anatomy of FABRIC

We prioritized ease of assembly and all hardware components, except for electronics and actuators, are 3D printable using a standard FDM 3D printer, allowing easy replacement for longevity. Fig. 3(a) illustrates the assembled FABRIC robot. The mechanical structure comprises four parts: robotic hands, arms, chest, and head.

1) Robotic Hand: We adopted the Flexy-hand design [21] for its necessary joints and full 3D printability, modifying it for servo-driven activation. Each fingers has three joints with TPU printed hinges (Fig. 3e), bending and relaxing with nylon threading (Fig. 4a). Nylon threads run through PTFE Bowden tubes, ensuring consistent length and preventing unintended movements, which connects to 3D-printed pulleys and a servo base inside the robot's bicep (Fig. 3c).

2) Robotic Arm: The latest FABRIC design features 6 DOF per arm (Fig. 3b-e): shoulder flexion/extension, abduction/adduction, pronation/supination, elbow flexion/extension, wrist flexion/extension, and pronation/supination. Each joint is a revolute type, as illustrated in Fig. 4b, driven by off-the-shelf servos and mounted using 3D-printed brackets, screws, or zip ties.



	Torque optimization	Reduced shoulder length
	Increase DOF	Enable palm rotation Enable wrist movement
	Movement balancing	1:1 length ratio between bicep & forearm Finger driver relocation

Fig. 5. Design iterations of the FABRIC robot for dimension optimization and addition of degrees of freedom to improve dexterity.

3) Chest: The robotic arms are mounted on a chest. To fit the chest into standard FDM printers, which are often limited by print volume, it is divided into two parts and can be easily glued together. The chest houses the electronics and power adapter while giving the robot its body presence for the hands' relative positioning around the chest, as needed for ASL *"Animal," "Love," "Sorry,"* etc.

4) Head: The FABRIC robot's head includes a 3D-printed shell for a 7-inch display that provides spatial reference for different signs. For example, ASL *"Understand," "Ooh,"* or *"Hair"* require hand positioning relative to the head.

5) Off-the-Shelf Electronics and Actuators: Numerous off-the-shelf miniaturized electronics kits arrived the market, as cheap as several dollars. We selected the ESP32 for its Arduino IDE compatibility, WiFi connectivity, and market popularity. An LM2596S DC-DC converter powers servo motors, while PCA9685 controllers simplify wiring. For actuation, we employ two types of low-cost servo motors. 14 lightweight MG90 servos control the fingers and the wrist, while four MG996R high-torque servos actuate the arms.

B. Optimizing Body Geometries for FDM 3D Printing

1) Adjudicating Degrees of Freedom: In sign language robotics, degrees of freedom (DOF) determine the range of signs a robot can perform. While fewer DOF simplify assembly for low-barrier, they limit sign variety. Initially, FABRIC had 4 DOF in the arm (Fig. 5-left), sufficient for basic numeric and alphabet signs but inadequate for broader sign language gestures. As expert feedback and Sem-Lex benchmark [14] analysis (See Evaluation) discloses the need for greater movement, 2 wrist DOF were added (Fig. 5-right), increasing sign execution by over 40%.

2) Weight Balancing for Fine Arm Movement: Weight distribution is critical for a humanoid robot's balance, particularly for fine motor control. Our initial design placed servo motors for finger control in the forearm, which added unwanted weight to the forearm resulting in wavy movement during gesture/language execution. Hence, we relocated the motors to the bicep (Fig. 5), reducing forearm weight, to improve stability and minimize failure and vibration.

3) Dimension Optimization: A robot's dimensions impact stability, energy use, aesthetics, and cost. A linear servo configuration (Fig. 6a-left) extended the forearm, increasing

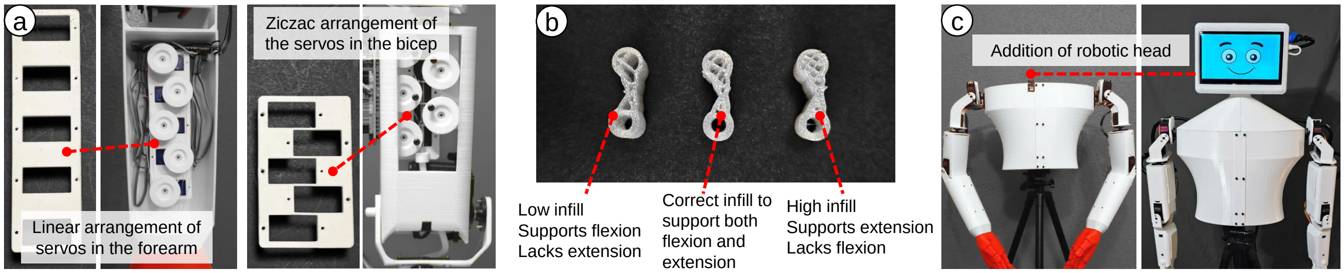


Fig. 6. Design iterations of the FABRIC body to improve articulation and expressivity, (a) servo motor arrangement and relocation for weight distribution and reduction in unnecessary space, (b) flexible hinge infill revision to support flexion and extension of the fingers, (c) addition of robotic head.

torque (τ) demands as distance (r) and weight-induced force (F) are related by $\tau = r \times F$, reducing speed and causing motor clamp failures. Thus, we finalized the zigzag arrangement (Fig. 6a-right), reducing forearm length with a near 1:1 upper arm-to-forearm ratio (Fig. 5) for balance.

4) Finger Hinge Fabrication: Flexible hinges enable flexion and extension in the fingers. The infill density of the hinge affects its metamaterial properties. Higher infill increases stiffness and extension support but strains servos to trigger flexion, while lower density eases flexion but reduces retraction. We tested infill from 8% to 12% and found this range balances flexion and extension for handshapes.

5) Robotic Head: In our initial robot design, we included articulation for sign language through the arms and hands but omitted a robotic head, crucial for enhancing expressiveness. Having sought SL experts' review on our initial design, we iterated with a 3D-printed robotic head using an off-the-shelf display (Fig. 6c-right) to show facial expressions through static or animated images.

6) Robotic Hand: A sign language robot hand requires articulation, active actuation, and a resemblance to the human hand. Various open-source 3D-printable options exist (Fig. 1) spanning from relatively simpler designs with limited articulation capacity to intricate configurations demanding complex fabrication. Balancing constraints, we selected the Flexy-hand design [21] for its full 3D printability, well-configured joints, scalability, and potentiality for active actuation. This choice enabled the design of wrist clamps and mountings to integrate them into the FABRIC robot.

C. Supporting Modular Fabrication and Assembly

The integration of off-the-shelf electronics into 3D-printed parts enables plug-and-play assembly using a commodity FDM 3D printer with a 0.15–0.2mm layer height. PLA is used for major parts, TPU is used for finger hinges. Most parts print without supports, except for intricate finger structures, which reduces complexity, time, and cost. The toolkit, including STL files or parts, is open-sourced *(https://github.com/abulalarabi/FABRIC)*.

D. Pose estimation through LfD and Execution

We use imitation-based learning from demonstration (LfD), estimating poses using Google's Mediapipe API [33] that provides 33 3D landmarks for body pose estimation and 21 landmarks for hand pose estimation. Yet, it lacks the

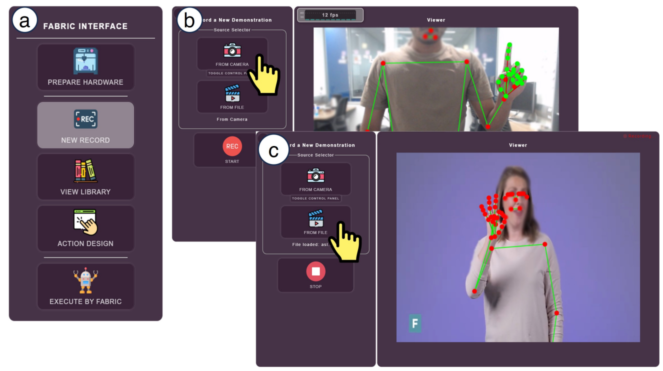


Fig. 7. (a) FABRIC user interface landing page. Users can record a new demonstration (b) using a webcam or (c) from a video file.

joint angles required for forward kinematics. Raw 3D pose data from a webcam or video file, including timestamps are captured, allowing the robot to record continuous movements beyond single frames. From each frame, 22 angle values are extracted using cosine formula. Movement-induced noise and pose estimation errors are compensated using a low-pass moving average filter. Human hand motion is highly agile. Contrarily, robot's actions are constrained by actuator speed and structural factors- weight, center of gravity, etc. To execute an action, angle values are down-sampled from the motion sequence, sent to the ESP32 via UART or WiFi, and parsed via servos with *servo easing* for smooth motions.

V. Interactive Program Synthesis

We developed a web-based interaction editor for end-users, compatible with modern browsers. The front end uses HTML and JavaScript with WebGL and Mediapipe library support, while the backend runs on Python Flask. The backend communicates with the ESP32 to send sequential motion commands to the robot. It is designed for simplicity and features three main options: *(i)* fabrication & assembly instructions, *(ii)* interaction design, and *(iii)* execution.

A. Authoring Schemes

1) Import Lexicons from Pre-built Library: FABRIC editor comes with a pre-built library that contains 22 alphabets, 10 ASL numbers, and 7 common gestures and emojis.

2) Capture and Execute: As sign language varies by region and culture, the robot needs to acquire new sets of signs. Thanks to our LfD scheme that enables FABRIC to incorporate new signs, breaking the barrier of predefined

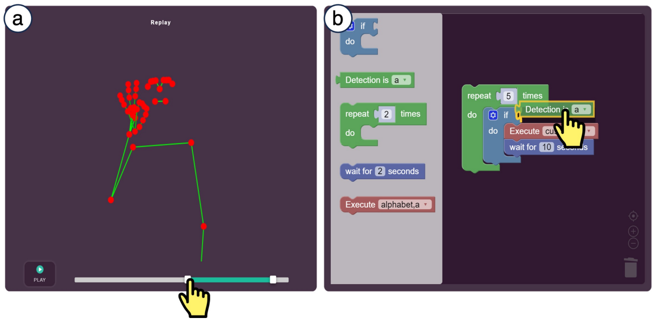


Fig. 8. (a) Cropping tool to remove unwanted movements. (b) Designing bi-directional interaction that the robot executes *Ok* emoji once the user successfully executes alphabet *A*, and repeats 5 times.

sets found in previous works. This is achieved by recording a signer's demonstration or fetching videos from SL dictionaries. FABRIC captures motion data from the new demonstration, adds it to the library, allowing the robot to execute the newly learned sign.

3) Visual Programming: FABRIC's interface features a drag-and-drop action sequencing and conditioning based on Blockly [13], an open-source library for visual programming. We developed five custom blocks: execution, conditional, repeat, detection, and delay. The execution block allows users to select an action from the library. The conditional block detects a sign (supporting alphabets and numerals from [34]) and triggers an action based on user input, enabling bi-directional interaction. Repeat and delay blocks enable repeated execution of actions or sequences and add necessary time gap in between executions respectively.

B. Walkthrough of Interaction Design in a Toolkit

From the FABRIC's interface, a user can take different paths, such as use the library or capture a demonstration.

1) Acquiring a Demonstration: FABRIC's authoring tool allows the user to expand the pre-built library. The user interface first lists all possible options (Fig. 7a), including *Record a New Demonstration*. It brings up a camera feed or a button to load a video file. The user can start the recording of their action with overlayed pose landmarks (Fig. 7b-c). Once the demonstration is done, the user can press the *Stop* button that brings up the editing window (Fig. 8a).

2) Editing Demonstration: Recording may include unnecessary movements, especially at the start and end. The editing mode allows users to crop these, leaving only the core demonstration. Once satisfied, users can save the recording as a JSON object in the library. Selecting the *Library* option from the landing page allows users to open a saved demonstration in the editor for replaying and cropping.

3) Sequencing Actions: Action Design lets a user create complex scenarios combining different actions and conditions. For example, users can drag an execution block, select "Alphabet A," add a delay, then add "Alphabet B," and nest them in a loop to repeat "A" and "B" five times (Fig. 8 b). Conditional blocks are useful for bidirectional communication, such as showing *"ok"* once the interaction opponent executes a corresponding sign. Actions or sequences can be saved, edited, remixed, and executed later.

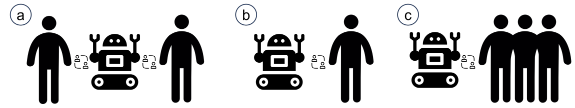


Fig. 9. FABRIC can afford Human-Robot Interaction schemes including (a) human-robot-human, (b) robot-human, and (c) robot-multiple humans.

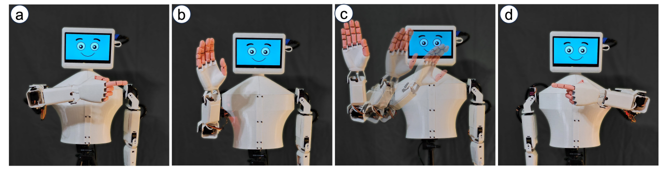


Fig. 10. FABRIC robot showing directional cues, such as (a) go right, (b) stop, (c) wave, (d) go left.

C. Executing Demonstration

To execute a sign from the library or saved sequences, the user can choose the *Execute* option that displays signs categorized by type and saved modules to deliver sentence-level and bidirectional communications.

VI. Affording Various Bodily Interactions

FABRIC has the potential to innovate sign language education through accessible fabrication and design of human-robot interaction. SL teachers can use it to create lessons (Fig. 9a), while learners (e.g., parents, deaf individuals) can use it as a personal coach (Fig. 9b). In public settings (e.g. conferences), FABRIC can address the shortage of interpreters and complement them in reducing fatigue, providing stay-in service to promote societal inclusive designs (Fig. 9c). In this section, we present various use-cases across users and contexts.

A. Gestural Communication

FABRIC platform can be utilized in multifaceted applications within the domain of non-verbal communication. Such as an autonomous robotic kiosk stationed at the forefront of various public venues, encompassing but not limited to public facilities, corporate workspaces, and healthcare establishments. Courteous waves or welcoming gestures from different cultures can be recorded through the user interface, allowing the robot to act as a hospitable greeter and engage in non-verbal communication, such as acknowledging someone's presence or giving directional cues (Fig. 10).

B. Embodied Emoji

Emojis convey emotions and tone in text, reducing ambiguity and language barriers and making communication more accessible across cultures [35]. With its articulated robotic arm and hand, FABRIC can effectuate tangible and physical renditions of emoji characters, akin to the expressive gestures found in sign language. For instance, a user can record *"call me"*, *"ok"*, *"love"*, etc. emojis on demand (Fig. 11), and let the FABRIC robot execute embodied emojis depending on the situation.

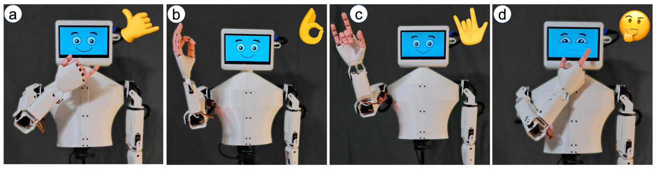


Fig. 11. Embodied emojis executed by FABRIC, (a) *call me* emoji, (b) *ok* emoji, (c) *i love you* emoji, and (d) *think* emoji.

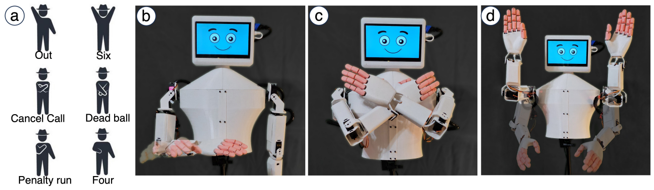


Fig. 12. (a) Different signs used by an umpire in a cricket game. (b)-(d) FABRIC robot performing different tasks of a cricket umpire: (b) declaring boundary *four*, (c) cancellation of a decision, (d) declaring boundary *six*.

C. Instructional Signals

In various environments embodied signs are crucial for regulation, coordination, and guidance, such as sports judges signaling rules, spotters and signers communicating excavation limits on noisy construction sites, and marshallers directing aircraft during taxiing and parking using standardized gestures. Fig. 12a shows cricket game umpire signals, while Fig. 12b–d illustrate FABRIC signaling a boundary, canceling a decision, or declaring a six. As computer-based umpiring advances, the robot can physically execute umpire decisions. While human safety personnel may fatigue, FABRIC can deter trespassers and emit warning signals, such as performing OSHA hand signs for safety awareness.

VII. Evaluation

A. Communication Coverage by FABRIC: Word & Phrase

Although all hand and arm poses can be recognized by the toolkit, due to hardware constraints, the physical robot's capability has limitations.

1) Test Settings: From the Sem-Lex benchmark dataset [14], we first check the visibility of relevant landmarks (elbow, wrist, hand). If sufficient, we compute vectors for the elbow-to-wrist, wrist-to-index, and wrist-to-pinky. We compute the normal vector of the wrist-index-pinky plane, project the elbow-to-wrist vector onto it, and subtract the perpendicular component to isolate radial and ulnar deviations. Finally, the angle between the adjusted vector and the wrist-to-index vector provides the radial/ulnar deviation sequence from the videos. A low-pass filter (window=5) reduces jitters from Mediapipe pose estimation. We compute the max-min difference in each sequence and apply a threshold to detect radial/ulnar deviation. For finger abduction/adduction, we use a similar method, analyzing angles at MCP and PIP joints.

2) Phrase/Word by Sem-Lex Benchmark: First, we inspected 11,000 videos, and 92.56% of videos are in the range of FABRIC-realizable words and phrases given its anatomy (N=10181), with only 7.53% videos containing the radial/ulnar movements in the wrist, such as *"Envelop", "Smoke", "Interaction"* or *"Socializing", "Go"*. Similarly,

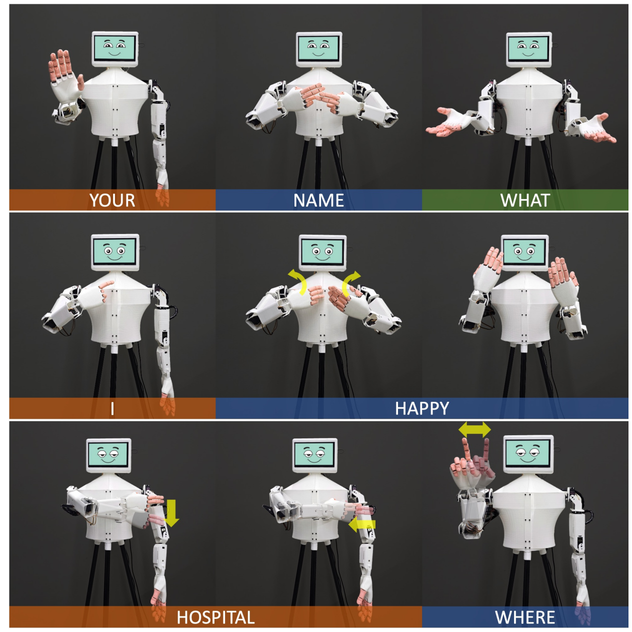


Fig. 13. FABRIC robot demonstrating *"What is your name?"*, *"I am happy"*, and *"Where is the hospital?"* in ASL.

90.17% of words and phrases can be executed using FABRIC, with 9.83% videos involved abduction/adduction in the fingers, such as *"Freedom", "Galaxy", "Group", "Hair"*. A mitigation strategy is substituting words with alternative signs or phrases. For instance, *"Freedom"* (requiring finger abduction/adduction) can be replaced with *"Liberty"*, which conveys a similar meaning with reduced movements. With hardware improvements, ball-socket joints could replace the current wrist joints to increase DOF. Using the Sem-Lex Benchmark, we constructed sentences with the help of a large language model (LLM). For instance, *"What is your name?"* is expressed in ASL as *"YOUR NAME WHAT"*, and *"Where is the hospital?"* becomes *"HOSPITAL WHERE"*. Thanks to the high dexterity of FABRIC, it is capable of producing such sentence structures (Fig. 13).

B. Communication Coverage by FABRIC: Alphabets

1) Test Settings: We first recorded ASL alphabets using the toolkit and executed them with the robot. We posed a camera in front of the robot to detect it's hand poses using the Mediapipe library. The hand poses are then passed through

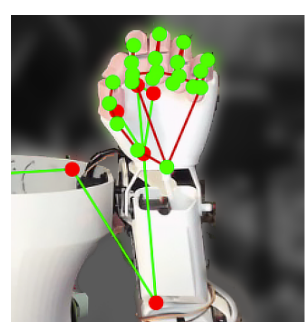


Fig. 14. FABRIC hand pose detection using Mediapipe.

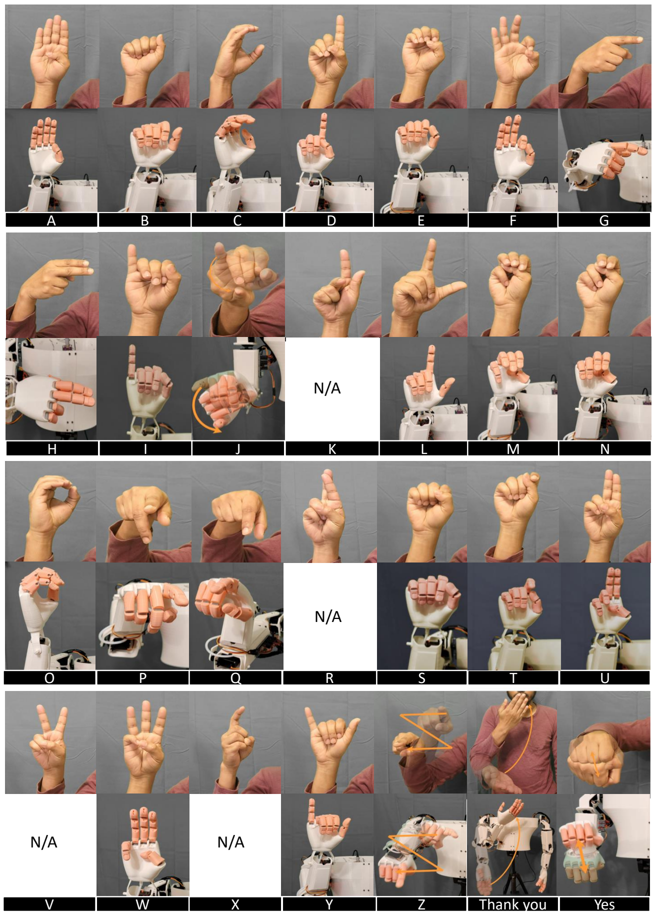


Fig. 15. ASL alphabets and phrases realized by Human ASL translator (top) and FABRIC (bottom). As the visual similarities of both in each case illustrate, FABRIC executes the majority of English alphabets and phrases to afford a wide range of communication in ASL.

a pre-trained model obtained from [34] that can detect static sign language alphabets. For instance, the alphabet *'Z'* requires arm movement, and hence the model can not detect it. We marked "success" if the pre-trained model recognized the sign language which is replayed by the FABRIC robot and performed qualitative assessments of the executed signs.

2) Results: The robot can realize 22 out of 26 alphabets covering around 85% ASL alphabets (Fig. 15). An example of FABRIC's hand pose detection is illustrated in Fig. 14. Trained on human hand data, the model [34] struggles with FABRIC's limitations (fixed MCP flexion and lack of radial-ulnar deviation), making some signs (e.g., *'P'*) undetectable. For *'H'* and *'Q'*, camera perspective adjustments were needed for detection. Although alphabets *'G'* and *'H'* require radial-ulnar deviation in the wrist, the robot can compensate for such movements with shoulder and elbow movements. Lacking opposable thumb movement (extension-hyperextension), the robot can not execute the alphabet *'K'* and *'X'*. Alphabets *'M'*, *'N'*, and *'P'* also require such movements to be fully expressive. Alphabets *'R'* and *'V'* require abduction-adduction movements in the fingers and hence the current FABRIC hardware can not execute these alphabets. Alphabet *'W'* also requires abduction-adduction to be fully expressive. All the numerals are in FABRIC coverage, yet

TABLE I

FABRIC BoM and Cost Breakdown in USD.

Component	**Quantity**	**Unit Price**	**Total**
ESP32 microcontroller	1	$10	$10
PCA9685 Servo Driver	2	$5	$10
LM2596S DC-DC Converter	1	$4	$4
MG996R Servos (arm)	8	$5	$40
SG90 Servos (finger/wrist)	14	$3	$42
PLA Filament	∼1.5 kg	$20/kg	$30
TPU Filament	∼0.25 kg	$30/kg	$8
Power Adapter (12V 10A)	1	$20	$20
Display (optional, for head)	1	$20–40	$30
Wires, headers, cables	—	—	$20
Screws, glue, zip ties	—	—	$10
PTFE Tube	1m	—	$5

the numeric *'10'* is properly expressed with ulnar deviation in the wrist. Adding radial-ulnar deviation, opposable thumb, and abduction-adduction movements would enable the robot to execute all sign languages, but significantly increase structural complexity and make assembly challenging.

C. Cost-Performance Comparison

We evaluate the fabrication efficiency of four selected Sign Language Embodiments introduced in Figure 1, chosen specifically for their compatibility with 3D printing. The actuators used across these robotic bodies range from off-the-shelf components to specialized units. To estimate costs, we referenced manufacturer market prices based on model numbers identified in the literature describing each embodiment. Table I details the bill of materials for FABRIC, with the total estimated cost at approximately $250. For comparison, we approximated the cost of the modified Ada robotic hand [16] at $460–$470, the TATUM robotic arm and hand [17] at $2500 (per hand), and the InMoov robot [18] at $2700. Compared to these, FABRIC provides significantly lower cost while maintaining high dexterity.

ADA robotic hand [16] and TATUM [17] lack articulated bodies and are limited to single-handed configurations, omitting spatial location critical to many signs. This restricts their ability to execute a wide range of sign language that involve two-handed coordination or positioning relative to the body, such as *"hospital"* or *"name."* We examined the mechanical configuration of existing embodiments compared ASL alphabet coverages. ADA covers approximately 66% of ASL alphabets, while TATUM reaches 88.5%; however, both fall short in capturing wide range of sentences and phrases. In contrast, InMoov [18] achieves a coverage of 85% in ASL alphabet, but its high fabrication complexity (characterized by a large number of mechanical parts & 3D printed components) poses a significant barrier. FABRIC trims down the cost significantly and balances performance to enable broader accessibility without compromising mechanical expressivity, positioning FABRIC as a uniquely affordable and inclusive solution for embodied sign language communication.

VIII. Conclusion

Sign language is critical for communication with the deaf community and the progression of robotics can enhance accessibility. While prior work highlights the importance of embodied robots for SL learning, end-users are yet to be introduced to an affordable and easy interaction method. FABRIC introduces a complete toolkit for fabricating and utilizing sign language robots ubiquitously by average users.

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