Real-Time Gesture Transmission with a Robotic Hand: Embodied Signals for Non-Verbal Remote Communication

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Abstract
This work explores how computer vision and robotics can support remote, gesture-based embodied signals for expressing presence and emotion in remote communication. We present an initial proof-of-concept in which users interact through robotic hands placed on their desks: one user's hand gestures are captured in real time by a camera, transmitted over a network, and reproduced by a robotic hand at the remote location. The prototype uses the InMoov robotic hand and MediaPipe Hands for gesture tracking across varied lighting conditions, viewing angles, and backgrounds. Our preliminary tests demonstrate that gestures can be reliably recognised and consistently reproduced through stable network communication. While still at an early stage, this project illustrates the potential of combining affordable robotics with computer vision to create accessible alternatives to voice communication and new forms of remote communication.

Keywords
robotic hand, gesture transmission, embodied signals, non-verbal communication, remote communication, computer vision,

1. Introduction

Communication is fundamental to human interaction, and while speech is the primary channel, non-verbal communication enriches and extends it. Hand gestures, in particular, represent one of the frequently used non-verbal modalities, capable of reinforcing, substituting, or even surpassing spoken words in expressiveness [1, 2, 3]. They can supplement speech to enhance meaning, or replace it entirely when verbal communication is not possible. In everyday life, people naturally employ a repertoire of gestures that expand the communicative capacity of language and provide a direct and often more expressive way of conveying thoughts and intentions.

These characteristics have long inspired research into gestures' role in human–computer interaction (HCI). Compared to traditional input devices, gestures support a more natural form of interaction, eliminating the barriers posed by keyboards, mice, or controllers [4]. Advances in computer vision, radar systems and similar technologies, have further accelerated this research by enabling robust real-time analysis of hand movements, allowing gesture recognition systems to be deployed in increasingly unconstrained environments. Gesture-based interaction has proven effective in a variety of domains, from immersive environments to assistive technologies [5].

Motivated by the communicative power of gestures and their technological feasibility, we set out to design a proof-of-concept prototype for remote non-verbal communication between individuals. By transmitting gestures through robotic embodiment, our project aims to extend hand gestures into new technological contexts for remote interaction. Similar to biofeedback remote signals such as breathing to foster empathy, awareness, and connectedness among individuals across distance [6], our approach highlights how gestural embodied signals can become a medium for expressing presence and emotion in remote communication [7].

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2. Related Work

This section focuses on two areas related to the paper: (i) hand gesture recognition, and (ii) embodied signals and biofeedback in remote communication.

2.1. Hand Gesture Recognition

Hand gesture recognition is generally divided into two basic categories: sensor-based and vision-based methods [8]. Each follows a different technical approach and presents advantages and limitations.

Sensor-based methods rely on wearable or ambient sensors. An example of the former are gloves that can integrate multiple sensors (e.g., flex, accelerometer, or tactile sensors) to capture fine-grained three-dimensional information about hand posture. These systems have demonstrated high recognition performance in areas such as sign language translation, virtual reality interaction, and assistive technologies, with accuracy often exceeding 90% [9, 10]. Their main drawback is the need for specialised equipment, which limits everyday usability.

Ambient sensors include, among others, electromyography (EMG) [11], Wi-Fi [12] and radars [5]. EMS records the electrical activity of muscles using electrodes placed on the skin. This enables detection of subtle hand motions and has achieved recognition rates above 80%, depending on the classifier (e.g., support vector machines, random forests) [13, 14]. However, the requirement for electrodes and calibration can reduce user comfort and accessibility. Wi-Fi and radar-based approaches use signal variations (e.g., Doppler shifts or changes in signal strength) to infer gestures. Systems such as WiSee [15] and Mudra [16] have reported recognition rates above 90% , showing promise for unobtrusive sensing. However, these methods remain highly dependent on environmental conditions and signal propagation quality.

Vision-based methods use cameras to capture gestures without requiring wearables. Advances in monocular, stereo, and depth-sensing technologies have enabled robust skeletal tracking and real-time gesture interpretation. Widely adopted platforms such as Microsoft Kinect, Leap Motion, and Intel RealSense illustrate the potential of camera-based approaches. While they provide a contactless interaction mode, their accuracy can be compromised by external factors such as lighting, occlusion, and background clutter [17]. Given that our prototype places robotic hands on users' desks during computer use, we selected a vision-based method, as standard laptops, as well as desktop computers, are typically equipped with cameras.

2.2. Embodied Signals and Biofeedback in Remote Communication

The integration of robotics and computer vision to transmit embodied signals for remote interaction is based on telerobotics and embodiment, particularly work on conveying expressive non-verbal cues [7, 18]. Telepresence robots are designed to make a remote operator feel perceptually co-located, and physical embodiment plays a crucial role in this process, shaping how collaborators perceive presence and social engagement.

Unlike virtual agents, social robots rely on physical embodiment to communicate non-verbal behaviours. For example, the MeBot platform [18] combined audio and video channels with expressive arm and head movements, demonstrating that adding gestural degrees of freedom improved participants' sense of involvement, cooperation, and enjoyment during interaction. Studies comparing different forms of embodiment suggest that physically embodied interactions are favoured over virtual ones and remote teleconference ones, with a co-located physical robot being perceived as both more watchful and more enjoyable than a remote physical robot or a simulated agent [7]. This work strongly indicates that telepresence systems benefit from allowing users to express non-verbal behaviour beyond audio and video, particularly in applications requiring deep engagement and cooperation.

Complementary to gesture-based embodiment, research in biofeedback has investigated how physiological signals can enhance emotional expression and connectedness in remote communication [6]. Biofeedback makes internal processes such as breathing perceptible, supporting interpersonal awareness and empathy. Breathing, in particular, has been explored as a communicative signal due to its strong links with emotional state, coordination, and social bonding at a distance. Extending these ideas, we set to use a robot hand to externalise gesture-based embodied communication at a distance.

3. Design and Implementation of the Prototype

The steps of the design and implementation involved selecting a computer vision (CV) framework, building a robotic hand, selecting a platform to control the hand movements, selecting gesture vocabulary for evaluation, defining communication workflow and writing the code for it. Each of these steps is presented in subsections below.

3.1. Tracking Gestures with Computer Vision

Computer vision (CV) is based on a range of techniques for extracting meaningful information from images and videos, from simple heuristics to advanced machine learning pipelines [19]. Similar to how humans first perceive basic shapes before interpreting a scene, CV systems detect edges and forms and then build higher-level representations [20]. In our prototype, this process begins with a real-time hand tracking. By continuously comparing successive frames from the camera, the prototype can detect motion and changes in gesture, allowing for accurate mapping of the user's hand movements to the robotic hand.

To implement this, we used MediaPipe Hands framework, a robust CV framework designed for high-precision hand detection. The framework identifies 21 landmarks on the hand to form a hand graph as visible in Figure 1. This allowed us robust estimation of finger positions and overall hand orientation across continuous video frames.

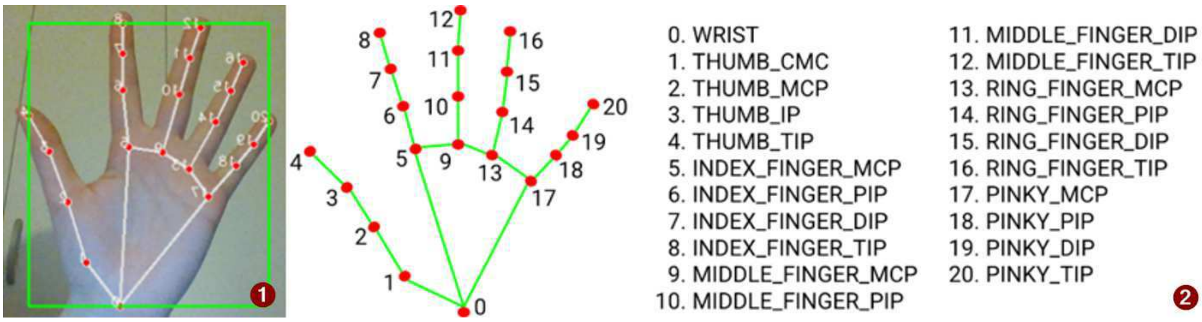

Figure 1: ① Hand landmarks detection. ② Hand landmarks detection guide, via Google AI for Developers [21].

3.2. Robotic Hand

For the robotic hand, we 3D-printed the right hand and wrist components of the InMoov robot [22]. InMoov, created by French sculptor Gaël Langevin, is an open-source humanoid robot released under a Creative Commons license, with freely accessible models and assembly guides. It has become a widely adopted platform for robotics education and prototyping, supporting integration of speech, vision, and sensing capabilities, which makes it highly adaptable for research and development.

For the purpose of this project, we restricted the implementation to the right hand of the robot since our focus was on hand gestures. Although the right hand was used, the left hand can easily be implemented as well. In addition, all the gestures selected (see next subsection) can be easily completed by both hands. At the time of construction, we used the available version of the hand model visible in Figure 2 ①, although newer 3D components were later released.

Assembly began with the fingers, each constructed from multiple knuckle elements to allow detailed articulation. Selected joints were glued or adjusted to ensure smooth closing, and the palm was subsequently added with additional parts for the thumb, ring, and little fingers. Printed cylinders served as connectors to provide full mobility. The fingers were actuated using five braided fishing lines of equal length, chosen for their strength and low elasticity.

The wrist, which houses a sixth servo for lateral palm movement (see Figure 2 ②), was then assembled. A connecting cylinder was positioned between palm and wrist to avoid obstructing the finger lines, which were threaded through dedicated channels to prevent tangling during rotation. The forearm was built from components designed to accommodate five servos, each equipped with a circular gear to secure the finger lines. After assembling the main structure, elastic sleeves and springs were added to protect and stabilise the lines. Each line was aligned with its corresponding servo as well as tightened and fixed with screws on the outer ring of the servo gear seen in Figure 2 ②. This ensured that rotating the servo left would tighten one line while releasing the opposing one and vice versa. This adjustment provided reliable finger motion.

Final steps included attaching palm covers, fingertip pieces, and labelling servo cables. The wrist and fingers were actuated using an Arduino Mega 2560 Rev3, controlling six servo motors. For stability, the assembled hand and Arduino board were mounted on a wooden base shown in Figure 2 ③. A demonstration of the working prototype is available at https://youtu.be/RLTetVgm4bI. The video also shows the speed of finger movements and prototype's latency without including the network.

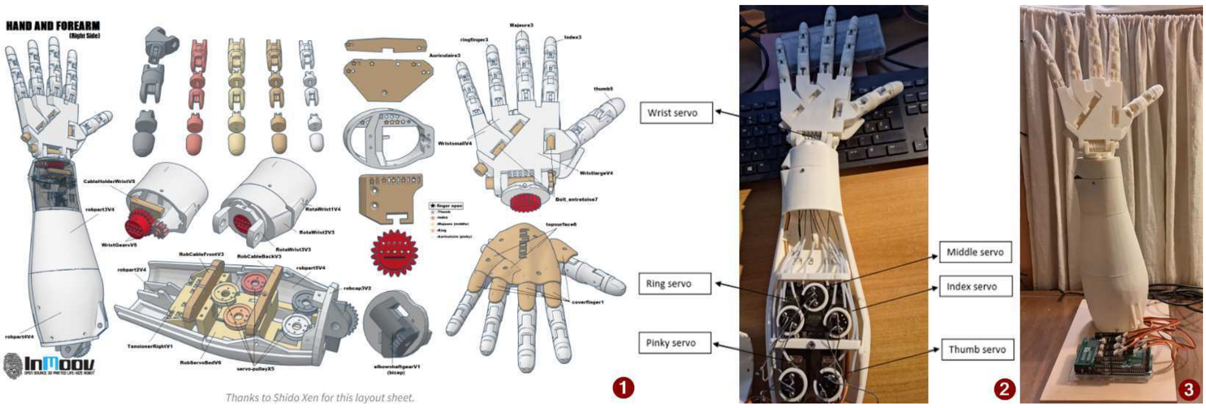

Figure 2: ① Hand and Forarm pieces from InMoov [22]. ② Assembled hand with connected lines to servos. ③ Whole hand mounted on the wooden board.

3.3. Arduino-Based Control System

The Arduino Mega 2560 Rev3 served as the central controller of the robotic hand, receiving hand gesture data via a WebSocket connection (described later) and converting them into predefined commands for six servo motors. Five of these servos actuated the lines, tightening or releasing them to open and close the fingers, while the sixth servo controlled lateral wrist movement.

To enable simultaneous control of the wrist and fingers, we integrated an Arduino ProtoShield, which provided six dedicated connection pins for the servo wires. Each connection included a ground, power, and PWM (pulse-width modulation) interface, which were matched to the corresponding servo. Specifically, the brown wire of each servo was linked to ground, the red wire to Vin (power), and the yellow wire to the PWM pin. Assigning each servo to a separate PWM channel allowed individual motor control.

The ProtoShield also simplified wiring and improved modularity by making servo connections detachable, allowing easy replacement if necessary. The Arduino board was powered via USB and generated PWM pulses to set servo angles. Standard timing values were used, with a 1 ms pulse corresponding to 0°, 1.5 ms to 90°, and 2 ms to 180°. To avoid overdriving the motors, the operational range was limited by 10°, such that relaxed fingers corresponded to 10° and fully closed fingers to 170°.

3.4. Code Implementation

We implemented three applications in Python. The first programme supporting communication between two remote systems, was implemented as a Python-based WebSocket server using Ngrok. The two

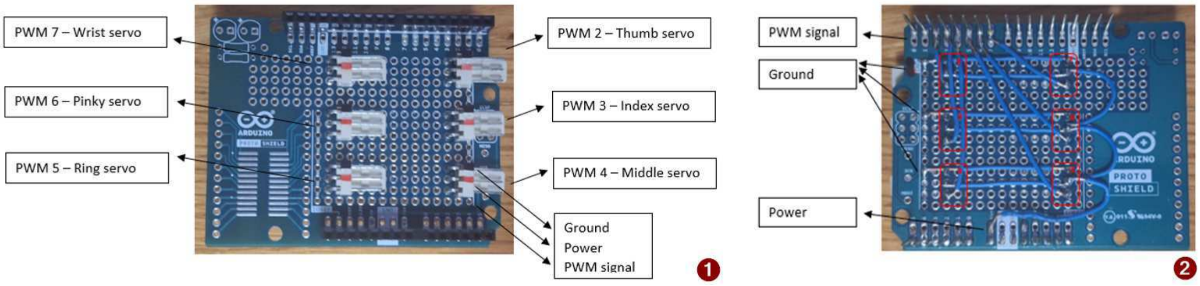

Figure 3: ① Front side of Arduino ProtoShield. ② Back side of Arduino ProtoShield.

systems are the client for detecting gestures and the server with the hand attached for executing gestures. The connection is secured with SSL encryption, ensuring safe data transfer. Once active, the server listens for incoming requests and, upon connection, creates a secure communication channel between two users. Gesture IDs detected on the client side are transmitted over this channel to the server, which then forwards them to the Arduino through a serial interface. Proper communication is maintained via a specified COM port and baud rate.

Next is the CV program that integrates the MediaPipe Hands library and OpenCV for real-time hand gesture recognition running on the client computer. When started, the program attempts to establish a WebSocket connection via Ngrok. If the request fails, an error is displayed. Otherwise, the camera is activated. A short countdown is presented to allow the user to position their right hand in a neutral position, after which the prototype begins tracking 21 hand landmarks and displays the recognised gesture in the corner of the interface.

And lastly we implemented the Arduino program, which first establishes serial communication at designed baud rate to receive data. It then attaches servos to Arduino pins 2, 3, 4, 5, and 6, and moves the fingers to the initial neutral open palm position with additional sixth servo on pin 7 that controls the wrist. The loop function continuously checks if data is available. When a new gesture ID is received, the program first validates whether it signals a valid gesture from a predefined set presented in the sext subsection. To ensure all servos move correctly and to prevent tangling of lines and fingers, the function uses a small delay after each finger or wrist movement.

3.5. Selected Hand Gestures and Their Meanings

Hand gestures range from movements that simply accompany speech rhythm to those that convey explicit meaning. Over time, many gestures have acquired socially recognised significance shaped by historical and cultural contexts [23]. As a result, gestures function not only as physical actions but also as communicative signals. While some gestures are understood almost universally, others remain closely tied to their cultural origins.

For the purpose of our proof-of-concept prototype we decided to select eight (8) distinct single-handed gestures that are widely recognised in Westers cultures. Hand gestures can otherwise be also two handed (e.g., forming a hand heart) or combined with other body parts (e.g., facepalm). The selected gestures, as detected by the computer vision framework, are illustrated in Figure 4. This set can be extended in future work. A description of each chosen gesture follows.

1.) Power - The clenched fist is a widely recognised symbol of resistance, power, and solidarity. Often used against oppression, it has appeared both as a physical gesture and in media graphics, becoming familiar worldwide through repeated historical use [24, 25].

2.) Trust - The open palm is used to signify many different meanings. But in our project, we have an open palm facing forward, which is used as a psychological and subconscious behaviour in body language to communicate trust, openness and compliance [26].

3.) Attention - Index finger pointing upwards can mean many things. In many Western countries it is

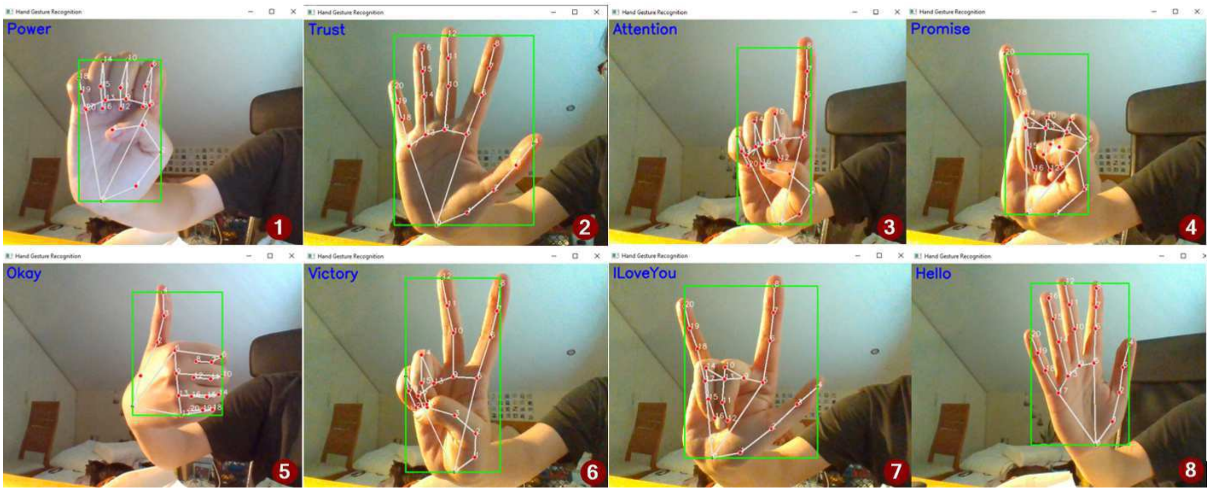

Figure 4: Selected gestures for our project: ① Power, ② Trust, ③ Attention, ④ Promise, ⑤ Okey, ⑥ Victory, ⑦ ILoveYou, and ⑧ Hello.

used for indicating direction, drawing attention, or signalling success or achievement. However, in the Middle East, holding up the index finger is considered rude and can be interpreted as an insult or a threat [27].

4.) Promise - The pinky promise, primarily used by children, involves interlocking pinkies to signify a commitment. Originating in Japan as "yubikiri", meaning "finger cut off", it was allegedly used by the Yakuza to test loyalty. A related tradition in Japan and China, the "red thread," ties couples' pinkies to symbolize their destiny. Overall, the gesture represents a promise that should never be broken [28].

5.) Okay - The thumbs-up gesture has a varied history. In ancient Rome, it was linked to gladiatorial judgments, while in medieval England it indicated readiness among archers. By the 20th century, it signaled "all is well" for World War I soldiers and pre-flight checks in World War II. Today, it is widely recognised as a positive sign of approval [29, 30].

6.) Victory - The V sign, or victory sign, is made by raising the index and middle fingers with the palm facing outwards. It symbolised victory in World War II, later represented peace during the 1960s hippie movement, and is used in Asia to convey cuteness in photos [31]. If the palm faces inward, the gesture may be offensive in some countries.

7.) ILoveYou - The American Sign Language "I love you" sign combines the thumb and index to form an "L" and lifts the little finger to form an "I." Known as "I-L-Y," it is a widely recognised symbol in the deaf community and has spread globally, also used to say goodbye or thank you [32].

8.) Hello - Waving, commonly used to greet or say goodbye, also serves to acknowledge presence, call for silence, or deny someone. Its origins trace back to the 18th century as a form of saluting, evolving from medieval knights lifting helmet guards to show identity and peaceful intent. By the 1780s, European armies formalised the salute, and waving became a standard way to address others, especially in military contexts [33].

3.6. Prototype Communication Workflow

To test functionality of communicating at a distance, two people are needed. For simplicity, only one-direction communication is described. Person-1 runs the CV program and performs hand gestures in front of a camera, while Person-2 runs the socket program on a computer connected to the Arduino via USB. Person-2 must start the socket program first to allow connection from Person-1. It then receives and enters the Ngrok URL to establish the connection. Both users receive an alert once connected. Next, gestures are being tracked in real time, recognised by the gesture module, and assigned one of eight gesture IDs. These IDs are transmitted via the WebSocket to the Arduino, which controls servos to move fingers accordingly. Small delays may occur due to sequential servo motion. Tracking ends when Person-1 presses “q”, stopping data transmission and closing the socket connection, notifying Person-2 that gesture tracking has finished.

As previously mentioned, we used MediaPipe Hands to track hand gestures. Table 1 shows the classification of eight gestures as well as a neutral position used for the initial interaction with the robotic hand. For the neutral position we selected an open palm, since this is the robotic hand’s default starting posture as well as position that indicates trust as one of the strong positive gestures in our set. Two things need to be noted. To classify the thumb as closed, its fingertip must be positioned below the nearest knuckle joint. For the waving gesture, the hand must repeatedly move left and right until the “Hello” gesture is displayed. This requirement was introduced to prevent false positives from incidental wrist movements.

Table 1
Gesture labels and their corresponding IDs

ID	Gesture	Label
0	Neutral	Neutral
1	Closed fist	Power
2	Open palm	Trust
3	Index up	Attention
4	Pinky up	Promise
5	Thumb up	Okay
6	Index and middle up	Victory
7	Thumb, index and little up	ILoveYou
8	Open palm, wrist moves left, right	Hello

After starting the CV program, a ten-second countdown allows the user to position their right hand in front of the camera in the neutral position, the same as the robotic hand. It is also important to note that hand tracking does not work if the left hand is in the frame. Once the requirements are met, landmarks appear, and gestures are tracked. Gestures are accepted only after two seconds to reduce false changes. The wrist can be rotated left or right, but rotation is limited to the opposite direction after a turn.

4. Testing and results

In this section we present evaluation of camera gesture tracking and testing gesture execution.

4.1. Camera Gesture Tracking

We performed a series of tests to evaluate prototype performance and identify its limitations. The first set of experiments examined the effect of lighting conditions, as illumination strongly influences the detection of all 21 hand landmarks. We then investigated how varying hand orientations affected recognition accuracy, identifying angles at which the program failed to track landmarks reliably. Lastly, we assessed the prototype’s robustness in cluttered environments by introducing multiple background objects.

The gesture recognition system demonstrated reliable performance across various lighting conditions, with failure occurring only in complete darkness. Recognition was also robust across different hand orientations, except when the hand was tilted sharply upwards. In extreme cases, such as fully vertical or horizontal orientations, the 21 landmarks overlapped and could not be distinguished, and these scenarios were excluded from the project scope. The system performed best against plain backgrounds but also managed cluttered scenes, provided the hand remained fully visible. For accurate detection, all 21 landmarks had to be unobstructed and free from occlusion by other objects.

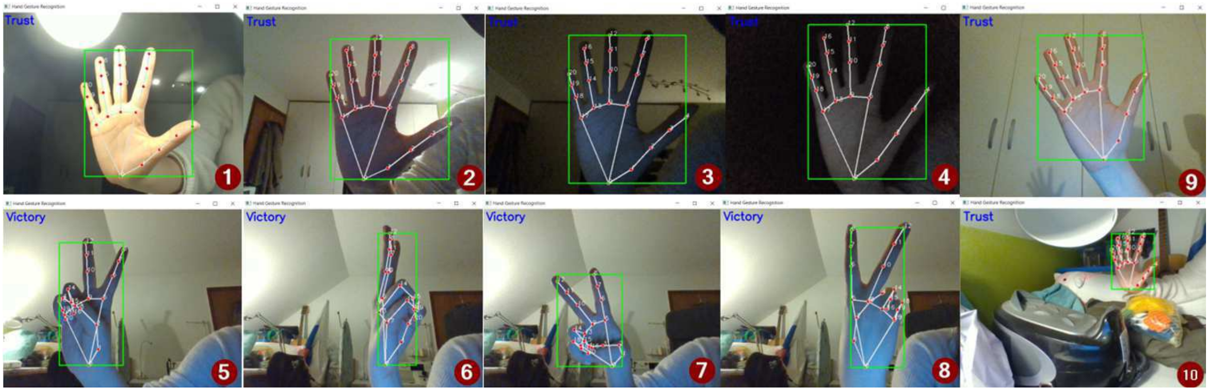

Figure 5: Gesture tracking in different lightning conditions, angles and backgrounds: ① Bright lighting, ② Normal lighting, ③ Dark conditions, ④ Only screen lighting, ⑤ Front view, ⑥ Side view, ⑦ Tilted downwards, ⑧ Turn backwards, ⑨ Plain background, ⑩ Cluttered background.

4.2. Testing Gesture Execution

The first step was to verify that the robotic hand correctly executes each predefined gesture ID, ensuring that the fingers aligned with the servo angles assigned to that gesture.

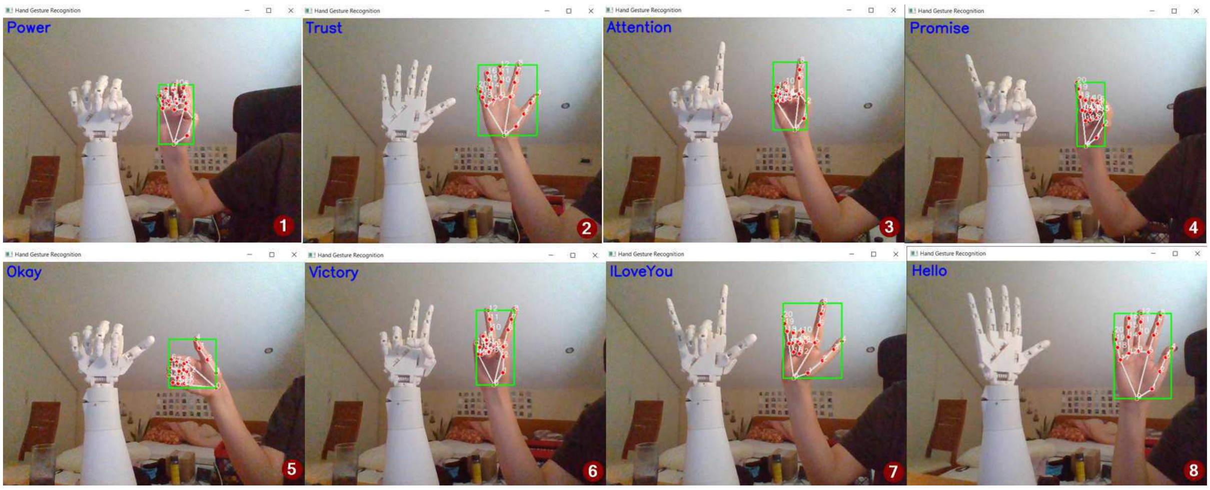

Figure 6: Testing hesture execution: ① Power, ② Trust, ③ Attention, ④ Promise, ⑤ Okey, ⑥ Victory, ⑦ ILoveYou, ⑧ Hello.

Testing showed that the robotic hand consistently executed predefined gestures, with both fingers and wrist moving to the correct positions. Servo response time was measured as the delay between transmitting a gesture ID and completing the motion sequence. Commands were executed within a few seconds, with minor delays resulting from the intentional sequential control of servos to prevent interference. Repeated trials confirmed reliable precision, as the hand consistently reached the expected positions. The only issues observed were small gaps caused by loosely connected servo lines when fingers were released, which were subsequently corrected.

5. Discussion, limitations and future work

While this work successfully demonstrates a real-time gesture transmission prototype, several limitations regarding the prototype's scope and cultural applicability must be addressed to ensure scalability and communicative effectiveness in diverse, real-world scenarios.

5.1. Gesture Vocabulary

The current proof-of-concept prototype supports a limited gesture vocabulary of eight distinct single-handed gestures primarily drawn from Western cultures. While this selection was sufficient to demonstrate the technical pipeline, it restricts the prototype's communicative potential and inclusivity. Gestures are shaped by historical and cultural norms. Some, such as waving or pointing, have relatively universal interpretations, while others are culture-specific and may be misunderstood or even offensive in different regions as explained in subsection 3.5. Relying on a small, Western-centric set introduces the risk of cultural ambiguity and limits the generalisability of the prototype.

Future work should explore customisable or extensible gesture sets, such as enabling users to define their own gestures relevant to their contexts. This would make the prototype adaptable to diverse cultural environments and specialised domains (e.g., technical fieldwork, sign languages, or task-specific commands). However, scaling the gesture vocabulary will also require careful management of actuators. The current prototype uses sequential control, requiring a small delay after each finger or wrist movement to prevent line tangling and servo interference. Although these commands are executed within a few seconds and the resulting delays are minor with the current eight gestures, larger or more complex gesture sets requiring simultaneous, multi-servo motion may present a challenge for the current prototype.

5.2. Evaluation

The present evaluation focused primarily on technical feasibility rather than human-centred performance. We report early metrics such as gesture recognition accuracy and servo response time, but have not yet conducted user studies to investigate how the prototype supports remote communication, user experience, social presence, or ease of interaction. Consequently, while the prototype demonstrates the technical feasibility of gesture-based robotic embodiment, its communicative effectiveness and usability in real-world scenarios remain unverified. Moreover, the evaluation is mostly qualitative and lacks end-to-end quantitative analysis (between two users) of key aspects such as (i) overall prototype latency from recognition to actuation over the network and different network connectivity, (ii) gesture recognition accuracy under challenging conditions over the network, and (iii) actuation repeatability or reliability over time. Future evaluations should combine technical metrics with human-subject experiments using validated scales for social presence, usability, and user experience.

5.3. Alternative approaches

This work would also benefit from comparative analysis with alternative modalities for remote gestural communication. Virtual avatars and wearable haptic devices are commonly explored to convey presence and intent in telecommunication contexts. Contrasting our robotic embodiment with these alternatives could clarify its unique advantages, such as providing visible, physically co-located gestures that can be understood without specialised hardware on the user's side. A clear articulation of when and why robotic embodiment outperforms purely virtual or haptic solutions would help guide future adoption and inform design trade-offs.

6. Conclusion

In this project, we successfully implemented a camera-based hand gesture tracking prototype that transmits gesture commands over a secure network to a robotic hand, which replicates the detected gestures. Testing under various conditions confirmed that the prototype performed reliably in nearly all scenarios. The results demonstrated real-time gesture recognition with high accuracy, with only a minor delays in robotic hand movement due to the intentional sequential operation of the servos to prevent interference during execution. During development we encountered several problems, such as twisting and stretching of the lines, excessive servo rotation, and others, which were progressively addressed and resolved. In the future we plan to evaluate the prototype in user studies to explore the effects of embodied signals for non-verbal remote communication.

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