

DESIGN AND VALIDATION OF A LOW-COST MODULAR HAPTIC GLOVE FOR HUMAN-ROBOT TEAMING*

Martin Økter¹ and Filippo Sanfilippo¹

¹Department of Engineering Sciences, University of Agder, 4879 Grimstad, Norway, e-mails: martin.b.okter@uia.no, filippo.sanfilippo@uia.no

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ABSTRACT

This paper presents the design and implementation of a low-cost, modular haptic glove for teleoperated robotic manipulation. The system integrates flex-based finger tracking, servo-driven force feedback, and ROS2-based communication to enable bidirectional interaction with a robotic manipulator. A dual-microcontroller architecture is employed to ensure stable sensing and wireless communication despite hardware constraints. The mechanical design is based on a modular linkage system with integrated compliance to provide controllable resistive feedback across four fingers. Hardware infrastructure, including custom PCBs and signal conditioning, is detailed to support reproducibility and scalability. Experimental validation demonstrates stable signal filtering, force-to-actuator mapping, and functional teleoperation performance at a 100 Hz update rate. The proposed architecture emphasises affordability and modular extensibility, providing an open research platform for teleoperation and haptic system experimentation. The project files are openly available: <https://github.com/Microttus/ice-haptic-gripper-system-cad>.

INTRODUCTION

Advances in digitalisation and teleoperation technologies have made it increasingly possible to interact with and control remote environments in real time. While video and virtual reality can replicate visual immersion effectively, realistic tactile interaction remains a challenge due to stringent real-time requirements and the complexity of reproducing the sense of touch. Overcoming these challenges is essential if teleoperation is to achieve the same efficiency as on-site operation.

Despite advancements in prosthetics and haptic systems, many solutions remain expensive and complex, limiting their accessibility. While progress has been made in replicating natural hand movements, the development of affordable, effective haptic devices remains underexplored.

This work addresses this gap by presenting the design and development of a low-cost, modular haptic glove. The glove is intended to provide realistic tactile feedback for teleoperated robotic manipulation, offering a flexible platform that can be adapted to a variety of use cases. By focusing on affordability and modular design, the system enables broader experimentation, faster iteration, and the potential for future commercialisation.

STATE OF THE ART

The human hand is an especially complex part of human biology, consisting of a range of different sensing capabilities, as well as being able to perform a huge range of movement patterns Santello et al. (2016). While interacting with an object, the human hand is capable of determining firmness, weight, surface texture, vibrations, and slip Ajoudani and Ajoudani (2016); Fu and Santello (2020). These sensor features are crucial for successfully handling everyday activities Cadoret and Smith (1996). As objects to be grasped are constantly present in our daily environment, they necessitate a diverse range of approaches to ensure an effective and successful grip.

A wide range of haptic glove systems has been proposed for teleoperation and virtual interaction Ozioko and Dahiya (2022). Rigid exoskeletal gloves and similar linkage-based mechanisms provide grounded force feedback with relatively high force fidelity but require external actuation units and complex mechanical transmission systems Ma and Ben-Tzvi (2015); Aiple and Schiele (2013). Magnetorheological brake-based gloves introduce controllable resistive forces through variable damping mechanisms, offering compact designs at the expense of limited force magnitude and added material costs Blake and Gurocak (2009). More recently, soft robotic and pneumatic gloves have been developed to improve comfort and compliance; however, they typically rely on pumps, valves, or tethered actuation, which increases system complexity and limits portability Peng et al. (2023); Jadhav et al. (2017). See Table 1 for a comparison of some available commercial gloves and glove frameworks proposed by

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research.

While these systems achieve higher force bandwidth or more anatomically distributed feedback, they often involve proprietary components, dedicated actuation hardware, or high manufacturing costs. In contrast, the present work adopts a servo-driven linkage architecture using commercially available components and an open-source control infrastructure. The design emphasises affordability, modular subsystem separation, and ease of replication rather than maximising force output or bandwidth. This trade-off positions the system as an accessible research platform rather than a high-end haptic device.

The human hand exhibits high biomechanical complexity and coordinated activation patterns, often described through postural synergies Santello et al. (2016) Santello et al. (1998). These findings motivate simplified actuation strategies in robotic and haptic hand design.

METHODOLOGY

Building on the state of the art and aiming to address the existing research gap, the following requirements have been established for the proposed system. Given its comprehensive nature, the system must be highly modular, allowing individual components to function as stand-alone units and enabling straightforward future expansion. Furthermore, it should serve as a research tool for studying the forces and motions involved in handling graspable objects. To support this, the framework must include robust capabilities for extensive data collection and analysis.

The system requirements include: (i) a lightweight and simple structure, (ii) the capability of realising the measurement of driving force and position, (iii) the capability of realising soft and precise force feedback, (iv) a large workspace without causing harm to the operator, (v) a modular design facilitating partial or extensive use, (vi) the capability of collecting data from the system.

Framework design

As modular design is set as one of the requirements, a corresponding design framework is proposed. As shown in Figure 1, the hand position is collected using a webcam and a ROS2 node that analyses the picture. A position is collected and published on a topic for the robot arm node to retrieve. The new position is processed by the robot arm node and sent to the robot for actuation. As the UR5 robot

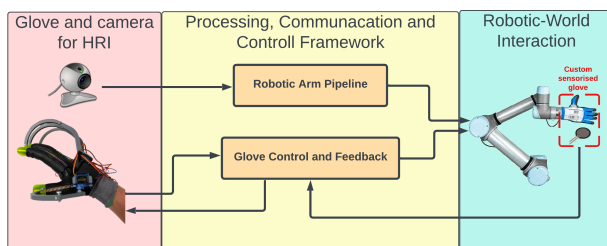


Figure 1: Overview of the proposed framework

arm is included as a library Lindvig et al. (2025), minimal effort is required to change the components related to machine-specific code. Hence, different robotic arms can be used with the same code, provided there is a C++ API for control available.

Furthermore, the "IceTeslaGlove" node is used to collect data from both the force sensor pads attached to the robotic arm and the position of the operator's hand. These data are processed in such a way that appropriate feedback can be provided to the glove for the operator. In addition, the current grip state of the operator is processed and sent to the "haptic_gripper_system" node. This node has the robotic hand implementation and is responsible for establishing communication with the hand using RS485. This is achieved through the use of a custom ROS2 package, which implements the qbrobotic Soft Hand API. Moreover, a force estimate based on the current drawn and the current position of the hand is published. This creates an additional optional data point for force feedback calculation. Consequently, a more precise force estimate becomes feasible.

Microcontroller

Due to the decision to use microROS for the microcontroller integration within the ROS2 system, the selection of microcontrollers is considerably limited. From the GitHub documentation of the micro_ros_arduino package, the two most advanced Arduino boards are indicated: the Portenta H7 and the Nano RP2040. The third and fourth generations of the Teensy board are also listed as officially supported micro ros (2024), and the ESP32 Dev Module.

Working with biomechanics and wearable technology, the update frequency is extremely important. As a benchmark, an update frequency of at least 1 kHz is needed for the user not to experience the device as "sluggish" or having a delayed response. The dilemma, as described by Sherman et al. Sherman and Craig (2018) is creating complex systems that are lightweight for a high update frequency, ideally up to 1,000 Hz. As the aim of the project is to make the operator feel the object as if it is actually in their hand, the smooth operation of the hardware is extremely important. The decision regarding the microcontroller is therefore strongly dependent on the core frequency of the microcontroller.

MicroROS is able to communicate with a ROS2 environment via either Wi-Fi or Ethernet. Since wearable devices should be minimally invasive to the user's workspace, a wireless connection is preferred. Wi-Fi add-on boards are available but would require more cables and pose challenges for mounting. Integrated Wi-Fi connections are therefore strongly preferred.

In table 2 a comparison of the most relevant microcontrollers that are supported either officially or by the community through microROS for Arduino is presented. There are several possibilities; however, for the specific application intended to operate the ROS topics, integrated Wi-Fi is beneficial. The TinyPICO board was already in local storage; in addition, the predecessor to the system,

Table 1: Comparison of selected commercial and research haptic gloves

System/Author	Actuation type	Design focus
SenseGlove	Tendon	Cable-driven haptic glove using tendon-based force feedback and integrated motion sensing to provide high-fidelity finger tracking and realistic grasp interaction in VR and teleoperation contexts.
Ma and Ben-Tzvi (2015)	Linkage	Cable-driven, worm-gear five-finger haptic glove providing compact, self-contained force feedback with optimized workspace and force transmission.
CyberGrasp	Tendon	Tendon-driven exoskeleton haptic glove with limited native bandwidth and stiffness, later enhanced through a high-frequency control backend enabling improved teleoperation performance and custom controller implementation.
Blake and Gurocak (2009)	Linage	Magnetorheological (MR) brake-based haptic glove enabling compact, self-contained force feedback without remote actuators, improving portability and stiffness rendering.
Peng et al. (2023)	Linkage	Linkage-based exoskeleton haptic glove with integrated force sensing and impedance control, enabling lightweight, flexible force feedback for teleoperation.
Jadhav et al. (2017)	Pneumatic	Soft robotic haptic glove actuated by McKibben muscles, providing compliant kinesthetic force feedback for immersive virtual interaction.
HaptX	Pneumatic	Pneumatic haptic glove using microfluidic actuators to deliver high-resolution tactile and force feedback for highly immersive virtual interaction.
TeslaGlove	Mixed	Electromechanical haptic glove combining motion capture with vibrotactile and force feedback actuators for immersive VR and training applications.

the IceThimble, was constructed on this platform. As a result, several hours of testing for implementation were saved during the testing phase.

During the build process, an issue with the TinyPICO was discovered, as it would disconnect the ADC (Analogue to Digital Converter) whenever the Wi-Fi module was activated. This necessitated the addition of another microcontroller to facilitate communication via I2C. The Seed Studio XIAO SAMD21 was selected for this purpose, given its small footprint, cost-effectiveness, and the fact that no Wi-Fi capability was required.

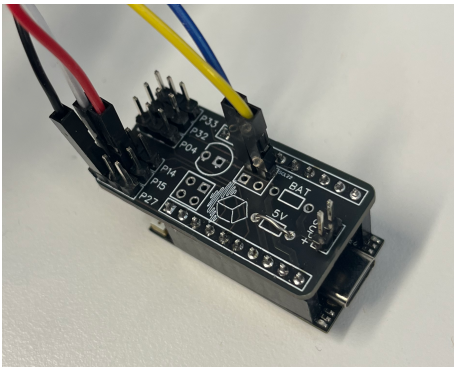


Figure 2: Utility PCB top view with Microcontroller

Hardware Infrastructure

To support the modular architecture, a custom utility printed circuit board (PCB) was designed to simplify wiring, reduce loose connections, and provide reliable power distribution. The board follows a “hat” design that connects directly to the TinyPICO microcontroller, rerouting selected pins while exposing others for sensors and actuators. Six dedicated servo connectors were integrated, each routed to a common power line and ground layer, sized to handle the current draw of multiple small servos (up to 6 A combined). Thermal considerations were taken into account during the layout, ensuring safe operation under continuous load.

To enhance robustness, the PCB was designed with distinct supply options for the microcontroller and the actuators. This prevents high-current transients from resetting the controller while still allowing both to share a supply when needed, e.g., for wearable use. Additional headers were provided for I²C expansion and optional peripherals, as well as pads for a status LED.

A second PCB was developed to handle analogue signals from the flex sensors and force pads. This was necessary because the TinyPICO’s ADC becomes unreliable when Wi-Fi is active, making it unsuitable for simultaneous sensing and communication. The solution was to delegate sensing to a Seeeduino XIAO board, which provided stable analogue readings and communicated with the TinyPICO over I²C.

The analogue PCB provided 5V rails and integrated

Table 2: A comparison of relevant microcontrollers

Microcontroller	Chip	Frequency	Price	Footprint	Capabilities
Arduino Portenta H7	M7 Core + M4 Core	480 MHz + 240 MHz	Expensive	Large	Wi-Fi Bluetooth Battery Connector
Arduino Nano RP2040 Connect	RP2040	133 MHz	Medium	Medium	Wi-Fi Bluetooth Python support
Teensy 4.1	M7 Core	600 MHz	Medium	Medium	Ethernet Partly Python
Teensy 3.6 (Not recommended)	M4 Core	180 MHz	Medium	Medium	
ESP 32 Dev Module	ESP32	80-240 MHz	Cheap +	Small	Wifi Bluetooth
TinyPICO ESP32	ESP32	240 MHz	Medium -	Medium	Wi-Fi Bluetooth Battery pin
Seed Studio XIAO SAMD21	SAMD21	48 MHz	Cheap	Small	MicroPython
Seed Studio XIAO RP2040	RP2040	133 MHz	Medium	Small	MicroPython

pull-down resistors for stable flex sensor operation. While the prototype was implemented on perfboard, the layout demonstrated the feasibility of a dedicated sensor board, and future iterations could employ professionally manufactured PCBs for improved reliability.

By separating high-current actuation from analogue sensing, the system achieved stable operation despite the limitations of low-cost microcontrollers. The modular PCBs also support future scalability, as additional sensors or actuators can be added without major rewiring. Full hardware files and schematics are made openly available on GitHub for reproducibility.

Glove mechanical design

A key principle of the design is modularity, ensuring that sensing and actuation subsystems can operate independently or together as part of a complete system. The glove integrates finger position sensors for tracking and an optional actuation plate for providing haptic feedback. This



Figure 3: The sensorised glove and feedback device

approach allows the core sensing to function on its own, while the feedback module can be attached when force interaction is required (Fig. 3). The long-term objective is to extend this modular platform with additional sensors and actuators to support more complex teleoperation tasks.

Finger Position Tracking

Several sensing strategies were evaluated for finger tracking. Camera-based methods such as MediaPipe Google (2024) and Leap Motion ultraleap (2024) offer high accuracy but suffer from occlusion, limited workspace, and poor robustness once actuators or gloves are attached, as also noted in related work Lelox93 (2024); Wang et al. (2021). These limitations rendered vision-based tracking unsuitable for the intended one-to-one teleoperation.

Instead, flex sensors were selected as a low-cost and robust solution. Each sensor was placed across the two proximal finger joints to ensure reliable detection of flexion patterns. Although their output is nonlinear and user-dependent, the sensors provide sufficient resolution for the targeted tasks, while remaining highly affordable and easy to integrate. Pull-down resistors were included to stabilise the analogue signals.

To secure the sensors, they were mounted directly onto a low-cost glove using adhesive. The inner link can be moved independently and will often initiate the movement of the full finger movement. The flex sensor must, therefore, be affixed in such a manner that the movement of the inner link is assured to be detected.

During testing, a critical limitation of the TinyPICO microcontroller was discovered: its ADC became unreliable when Wi-Fi was enabled, preventing simultaneous sensing and ROS2 communication. To resolve this, a dual-microcontroller solution was implemented. One controller

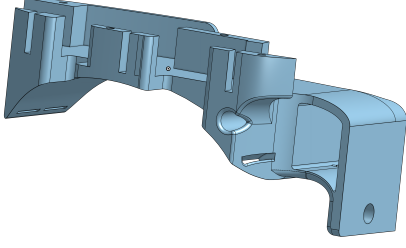


Figure 4: Render of the wrist plate

was dedicated to sensor readings, while the other handled communication. The two exchanged data over I²C with a latency of 4 ms, resulting in a stable update rate of 100 Hz. While below the 1 kHz target often cited for seamless haptics, this proved sufficient for responsive control in early prototypes.

This modular separation also makes the glove flexible: the sensing subsystem can operate independently of ROS or provide feed-forward input directly to the haptic feedback system, enabling responsiveness in future iterations.

The Haptic feedback device is based on a single actuated link system. As the possibility for how to design such a device is vast, the design best aligned with the underlying philosophy is the mechanical hinge approach. Multiple potential actuation designs were evaluated. Geared DC motors with encoders can offer accurate positional control; however, they necessitate custom drivers and more complex control strategies. For this prototype, 9 g servomotors were selected as a simpler alternative, providing sufficient torque, integrated position control, and ease of integration.

The main drawback of the servo approach is the large footprint. As palmar abduction is the main target, no more than 5 servos are necessary for full control. For further development, radial abduction could also be a useful addition, and in such case DC motors should be reevaluated due to the more compact mechanical integration. Due to the footprint of the servos, it is deemed difficult to add full five-finger support. For the first iteration, only four fingers have feedback, but the system is scaled for up to six.

The servos were mounted on a wrist plate secured to the user with straps around the palm and wrist (Fig. 4). The top of the plate secures the first three servos, while a bridge over the thumb accommodates natural abduction and demonstrates a path for adding further degrees of freedom, such as radial abduction. Each servo drives a linkage system that follows the finger's trajectory and applies resistive forces. The linkage geometry was optimized to cover the full range of fingertip motion. Both links introduce an additional bend, the first a 50 degree angle in the middle and the second one a circular design of approximately 100 mm radius. This design keeps the link away from colliding with the fingers, including full grip closure, while remaining compact.

In figure 5 the theoretical effective reachable area that the links may encompass is illustrated atop an image of the device. It is evident that all potential finger positions

are included, accommodating not only longer fingers than those depicted in the image but also a full grip. At the fingertip, a TPU thimble serves as the user interface. TPU was chosen for its flexibility, which allows a secure but comfortable fit and provides additional grip due to its surface texture.

To stabilise the device and improve tolerance to calibration differences, springs with approximately 400 N/m stiffness were integrated into the linkage. These springs introduce a compliance that enhances safety, provides a more natural feel, and allows the software controller to adjust resistance without risking excessive rigidity.

All CAD models and a bill of materials needed to replicate the project are openly available on GitHub in the repository: <https://github.com/Microttus/ice-haptic-gripper-system-cad>

An IMU module was integrated into the glove to extend control beyond finger movements by enabling wrist rotation during teleoperation. The IMU data were posted to a ROS2 Twist topic using MicroROS, allowing the robotic arm to replicate wrist orientation. Both accelerometer and gyroscope values were transmitted, and a complementary filter was applied to fuse the signals. The filter, shown in Equation 1, combines the stable but drifting gyroscope readings with the noisy but drift-free accelerometer measurements, where Θ_{un} are the less reliable values, Θ_{re} are the more reliable values, and α is the weighting factor. From these fused measurements, the roll and pitch orientations were calculated as in Equation 2, and a low-pass filter was used to suppress high-frequency noise.

The IMU node was designed to be accessed directly by another computer on the ROS network. MicroROS introduced instability in cross-computer communication, causing unreliable data transfer. Due to communication instability and safety considerations, the IMU subsystem was disabled during final experiments.

$$\Theta = \Theta_{un}1 - \alpha + \Theta_{re}\alpha \quad (1)$$

$$\phi = -\tan^{-1} \left(\frac{a_y}{a_z} \right) \quad (2)$$

$$\theta = -\tan^{-1} \left(\frac{a_x}{\sqrt{a_y^2 + a_z^2}} \right) \quad (3)$$

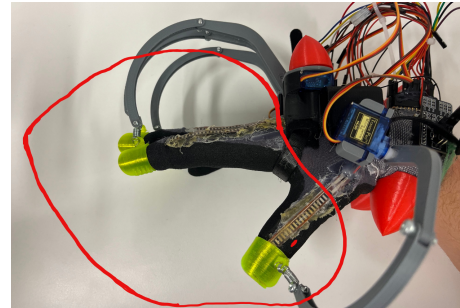


Figure 5: Work area of the haptic glove

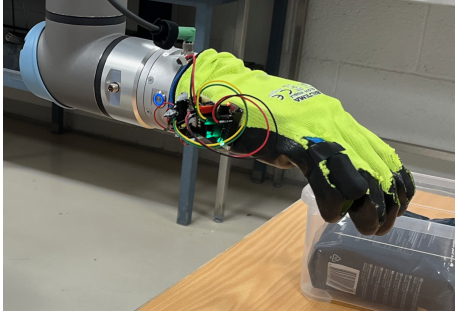


Figure 6: qbrobotic SoftHand Research with additional sensorised glove

Instrumentation of the hand

The qbrobotics Soft Hand Research provides limited sensor feedback in its standard configuration, motivating the addition of external sensors for improved force measurement. To avoid invasive modifications that could void the warranty of this costly device, force-sensitive resistors (FSRs, SEN-09375, SparkFun) were integrated into a thin over-glove (Fig. 6). The sensors were positioned on the inner gripping surfaces while the associated electronics were mounted externally on the back of the hand. This approach allowed additional sensing without altering the original hardware.

The over-glove was adapted from a low-cost work glove, modified to fit over the Soft Hand without saturating the FSRs. Small slits were cut in the back of the fingers to relieve excess pressure, ensuring that the sensors could measure grip forces within their operating range. While effective, the approach had some drawbacks: the FSRs reduced surface friction, exposed wiring was fragile and prone to noise, and sensor placement occasionally interfered with object grasping.

As with the finger-position sensors, the TinyPICO platform's ADC limitations required the use of a Seeeduino XIAO for analog signal acquisition. The signals were transmitted via I²C to the TinyPICO, which then published them to ROS2. The electronics and battery were attached externally to the glove, forming a self-contained module for force sensing.

EXPERIMENTAL VALIDATION

To validate the logic of the feed-forward loop, the received 8-bit force signal, the filtered force signal and the calculated servo signal are plotted. In Figure 7 the signals for the thumb are shown and in Figure 8 for the index finger. As the thumb, middle, and ring fingers have their servos attached such that the signal is inverted, the blue line is simply opposite to the measured force. For the index finger, the lines can be seen clearly following each other. The raw force indicated with yellow line have most reach and also most noise. The orange is the filtered force signal, which clearly has fewer oscillations and can also be observed to have a little less reach. The blue line is

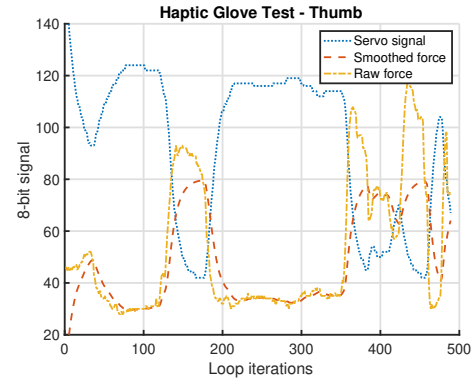


Figure 7: Comparison of received force signal, filtered signal and calculated servo position for thumb

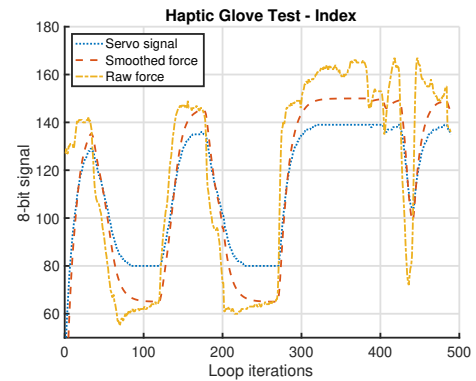


Figure 8: Comparison of received force signal, filtered signal and calculated servo position for index finger

the force signal mapped to the servo range and can be observed with little to no noise as a second filtering is used, and with maximum and minimum according to the servo range.

DISCUSSION

Preliminary functional tests were conducted to assess mechanical fit and signal stability.

Mechanical Design

The wrist plate was tested on users with hand sizes ranging from small to large. A secure fit is critical: if the plate slides on the palm, actuator forces are absorbed by the wrist instead of the fingers, thereby reducing haptic effectiveness and causing discomfort. Although the plate edges were smoothed, pressure against the palm could still be uncomfortable under high loads. The curvature of the plate, combined with two Velcro straps around the palm, provides a stable fit across all tested users.

The linkage system proved to be reliable and adaptable. Prior studies, such as Peng et al. (2023), showed that link designs can restrict finger workspace. To address this, the first link was given an additional bend, which improved finger mobility for most users. Even participants with longer fingers were not obstructed in their

ability to grasp everyday objects. A longer link would solve the issue for larger hands but reduce resolution for shorter fingers, underscoring the need for a compromise when designing for diverse users.

The thimbles also highlighted variability across users. While the selected size fits most hands, some users experienced a tight fit, while others experienced a loose fit. Since the thimbles are attached by screws, multiple sizes can be offered and easily swapped. This modularity avoids permanent attachment, which is important because the servos briefly move to their maximum position at startup. However, users with thinner fingers sometimes experienced the thimbles sliding off during use, requiring repositioning. The incorporated springs provide mechanical compliance that could be quantified through the spring constant, enhancing control and improving comfort.

The springs also introduced slight freedom of motion around the third link, allowing the fingers to move more naturally. However, because the flex sensors already exhibited precision limitations, this added movement increased detection latency. A fully integrated impedance design could resolve this trade-off but may also introduce new challenges at the prototype stage.

The current glove provides actuation for four fingers, excluding the little finger. Although full five-finger feedback would increase completeness, the four-finger configuration was sufficient for the evaluated teleoperation tasks.

The mechanical design remains sensitive to user variability, as fixed link geometries and discrete thimble sizes cannot fully accommodate differences in hand size, leading to suboptimal fit and inconsistent force transmission. Additionally, trade-offs between comfort and performance persist, where mechanical compliance improves safety but reduces sensing accuracy and increases latency. Finally, the system's structural and functional limitations, including partial finger actuation and minor linkage looseness, constrain overall dexterity and precision.

Sensors

Finger position was measured using flex sensors glued to the glove. These sensors change resistance with bending angle, providing a relatively linear correlation between finger flexion and output value, as confirmed in the position test. This allowed a direct mapping between sensor values and servo actuation, effectively representing the degree of grasp. Since each finger has three joints, and the available flex sensors only covered two proximal joints, the system could not detect distal joint movement. As a result, users who naturally relied more on the outer joints experienced reduced tracking fidelity. Longer flex sensors covering all three joints would provide a more general solution.

Flex sensors also proved highly user-dependent, with offsets introduced by finger thickness and length. This made calibration necessary for each operator. While a single-user setup could be calibrated once and remain functional, shared use required repeated recalibration, limiting practicality.

For future expansion to radial abduction, flex sensors are insufficient, as they cannot measure both axes of motion. A possible solution, inspired by the EFFG approach Peng et al. (2023), would be to integrate force sensing sensors. By measuring applied forces, an impedance controller could adjust the servo to maintain or modulate resistance. This would allow more general tuning across users but introduces challenges of noise susceptibility, cost, and mechanical integration.

In addition to position sensing, force-sensitive resistors (FSRs) were used to measure finger-object interaction forces. However, these sensors proved to be the weakest element of the system in terms of durability. The flexible leads extending from the sensing pads were repeatedly bent during finger contraction, leading to frequent cable breakage, causing complications for extended testing.

From the impedance tests, the FSRs were found to be non-linear and limited in range. They responded to initial loads of approximately 60 g but quickly saturated above approximately 150 g, making them unsuitable for the accurate measurement of larger forces. More robust and accurate sensors would improve reliability, but this improvement would come at a higher cost and increased integration complexity. A possible enhancement would involve sensor fusion, which would combine individual FSRs with the Soft Hand's motor current estimates to produce more reliable force feedback.

The sensing system is limited by restricted motion capture and user dependency, as flex sensors only measure proximal joints and require per-user calibration. Additionally, sensing accuracy is constrained by hardware limitations, where flex sensors cannot capture multi-axis motion and the non-linear properties of the FSRs, and they exhibit low durability under repeated use. Together, these factors reduce robustness and scalability, indicating that more advanced sensing modalities or sensor fusion approaches are required for reliable operation.

Actuators

For the glove itself, 9 g servo motors were used to provide haptic feedback. These actuators responded rapidly, with only 5 ms delay required for full command execution, making them effective in the feed-forward configuration. However, the servos also exhibited durability issues. When requested to move beyond feasible limits, due to poor calibration, excessive operator force, or high control gains, the internal position controller continued to drive the motor, causing the plastic gears to strip. In such cases, the servo required replacement, followed by recalibration of the affected finger.

This failure mode shows the need for improved mechanical coupling between the actuator and the finger link, i.e., introducing compliance or slack to absorb excessive forces. Additionally, the glove-mounted servos are prone to mechanical failure under excessive loads, highlighting insufficient protection against overdriving and poor tolerance to calibration errors.

CONCLUSION

This paper presents the design of a low-cost, modular haptic glove for teleoperated robotic manipulation. The system successfully demonstrates the feasibility of providing realistic force feedback with inexpensive components, validated through initial experiments. While challenges remain, particularly in sensor durability and calibration, the modular and open design enables rapid iteration and broader use as a research platform. Future work will focus on improving robustness, refining control algorithms, and expanding evaluation to more complex teleoperation scenarios, supporting further exploration of human–robot interaction through affordable haptic devices.

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