A Pneumatic Glove with Closed-Loop Control and Bidirectional Actuation for Real-Time Pose Synchronization

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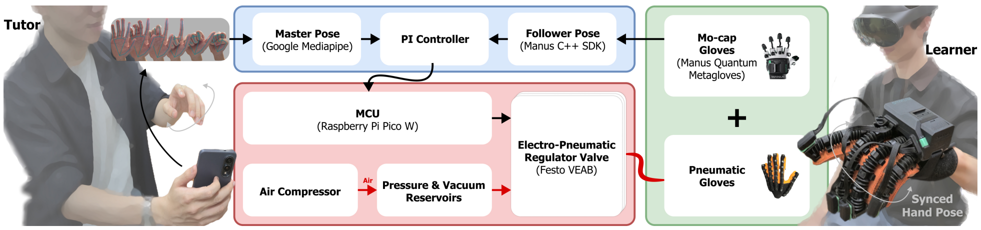

Figure 1: System architecture and workflow for the proposed hand-pose synchronization system. The color-coded subsystems are: pneumatic & electronic hardware (red), Middleware program (blue), and glove interface with motion capture capability (green).

Abstract

Soft pneumatic gloves provide lightweight, intrinsically safe haptic feedback, but such systems are often constrained by bulky pneumatic hardware and limited controllability. We present a compact and responsive pneumatic glove system enabled by positive-negative actuation capability. This bidirectional actuation is achieved using a single pneumatic unit, resulting in a system that is compact enough to fit within a desktop-sized form factor. The glove integrates soft actuators with commercial motion capture systems for hand pose tracking, enabling precise operation via closed-loop control. A modular middleware supports flexible operation with diverse hand pose sources, such as vision-based hand pose estimations from RGB cameras, HMDs, and depth sensors. This versatile yet compact platform extends the applicability of pneumatic gloves beyond rehabilitation to domains that require fast and responsive feedback, such as immersive remote training in VR.

Index Terms: Haptic interfaces, soft robotics, data gloves, closed loop systems

1 Introduction

Soft pneumatic gloves have attracted significant attention due to their mechanical simplicity, intrinsic safety, and user comfort [3, 6, 4]. However, they have not been regarded as suitable for fine tasks, as these advantages come at the cost of reduced motion precision and actuation speed due to inherent mechanical compliance [1]. In addition, although the end effector of soft gloves is lightweight, accompanying pneumatic hardware usually requires a fine-tuned configuration of industrial-grade pneumatic control components, resulting in a bulky and heavy system that produces audible noise. These limitations hinder the adoption of such systems beyond specialized contexts like medical rehabilitation and industry-scale facilities, in everyday applications like consumer VR, gaming, and personal training.

To circumvent this, researchers have explored the use of both positive and negative pressure sources in combination to enhance control bandwidth and responsiveness [3]. Moreover, Caasenbrood et al. [2] proposed a modular pneumatic hardware framework tailored to soft-robotic applications. They standardized the component configuration within a single compact enclosure, reducing system footprint and simplifying assembly. We believe that these advances extend the availability and operability of pneumatic systems to the extent that they can be deployed in broader application domains, particularly in human-computer interaction and haptics.

Building on these advances, we propose a pneumatic actuation system for real-time hand pose synchronization. For precise pose control, we further explore controllability by performing closed-loop PID control on hand flexion/extension. External bare hand pose sensing via computer vision algorithms serves as the ground truth (Figure 1 Left). The challenge that arises here is that the tracking performance of pneumatically actuated hands is significantly degraded in computer vision-based pose estimation due to the attached actuation components (Figure 1 Right). By implementing glove operation in tandem with motion capture gloves, we demonstrate how pneumatically controlled gloves can function as a real-time haptic interface for reliably transmitting hand poses. To ensure reasonable uptime, pneumatic systems often rely on large, heavy-duty air compressors, which are impractical for portable use. Instead, we employ a single compact compressor that achieves a low-footprint system design with minimum operation while providing sufficient pressure and vacuum, enabled by a dedicated control strategy with optimized pneumatic circuit design. We propose a modular software framework that supports pose tracking and analysis, feedback control, and digital command coordination. Our system can synchronize hand poses between master and follower agents [5] with low latency, thereby enabling immersive virtual training between the remote agents.

2 System Architecture

2.1 Pneumatic and Electronic Hardware

2.1.1 Pressure Regulation

Electro-pneumatic regulator valves (Festo VEAB) control target pressure values in the range of $+100$ to -100 kPa, directly supplying air to the pneumatic bellows attached to the gloves (Figure 1 Right). Our early prototypes, which relied on conventional positive-pressure-only regulators, suffered from slow finger extension because the bellows had to vent passively. A MCU (Raspberry Pi Pico W) receives digital setpoints given by middleware control loop and generates logic-level signals that are amplified by a cus-

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tom DAC-amp circuit to the analog voltage levels (0-10 V) required by the regulator valves.

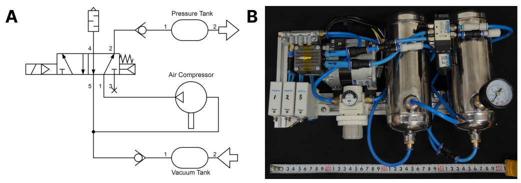

Figure 2: (A) Pneumatic system diagram showing a single compressor that supplies both positive and negative pressure. (B) Photograph of the assembled hardware. The complete system fits into a compact 400×200×150 mm volume.

2.1.2 Reservoir Charging System and Strategy

Given that the bellow-type soft actuators require only a small volume of air and operate at low instantaneous flow rates, the use of a conventional large-scale compressor is unnecessary. To minimize the system footprint and facilitate installation, a compact BLDC-driven rocking-piston compressor (model 30RNS-ED) is employed. As shown from Figure 2 A, this single pressure source unit is electronically controlled to supply both positive and negative pressure reservoirs, dynamically switching between pressurization and suction using a 5-way/2-mode solenoid valve. It can supply pressure up to $+650$ kPa and vacuum down to -65 kPa. Additionally, reservoir tanks are introduced for each air source to improve operational stability, compared to directly coupling of the source unit with the regulator valves. Overall, the system occupies just 45% of the volume (12L) and 30% of the mass (4.53kg) of a comparable commercial compressor, allowing portable tabletop deployment.

We have designed a pneumatic circuit with dual-reservoir system for bidirectional finger motion control. The positive pressure reservoir can store a sufficient amount of compressed air, which is then decompressed via a manual pressure regulator to match the operating pressure requirement of the regulator ($+200$ kPa). Unlike the positive pressure reservoir, the vacuum reservoir was depleted after just a few extension operations in our tests. Therefore, to avoid fluctuations in negative pressure during rapid glove operation, the pneumatic unit is normally connected to the negative pressure reservoir and is switched to the positive pressure reservoir only during flexion operations. This strategy aims to maintain the maximum negative pressure (-65 kPa) in the vacuum reservoir. Moreover, pneumatic check valves like diodes are installed between the reservoirs and the pneumatic unit to minimize air flow leakage while not charging.

2.2 Haptic Glove with Pose Sensing Capability

With the increasing demand for rehabilitation, mass-produced soft robotic gloves [3] incorporate pneumatic bellow actuators that operate under both positive and negative pressure for flexion and extension. Building upon the commercial product (ML-113) (Figure 1), we designed a 3D-printed mounting part that allows the attachment of the sensor module of the mocap glove (Manus Quantum Metaglove) to the tips of each finger along with the bellow actuators.

2.3 Modular Software Framework

As the backbone of the system functionality, middleware software was developed and deployed on a single-board computer unit (LattePanda 3 Delta) embedded into the system.

2.3.1 Pose Tracking and Analysis

The tracking module receives a 15-DOF finger joint position set (i.e., three joints per finger) from the Manus Quantum Metagloves via its proprietary C++ SDK. Owing to the modular architecture, we can capture data from other devices such as a USB camera or an Android device. The analysis module employs the Google Mediapipe Hand to estimate 3D landmarks and derive equivalent joint angles from different tracking sources. The joint angles of each finger are averaged to produce a 5×1 vector, representing per-finger flexion. This platform-independent analysis enables consistent closed-loop control across any combination of input devices. In summary, the degree of flexion can be used for either the target pose (master; any hand tracking module) or the measured pose (follower; the mocap tracking module) to compute the per-finger pose errors.

2.3.2 PID Control

The control system computes per-finger pressure commands using a proportional–integral (PI) controller. The derivative term is neglected due to inherent damping characteristics of pressure dynamics. Using the difference between the target pose vector θ_{tar} and the measured pose vector θ_{meas}, voltage command signals to the regulator valve are calculated using the standard PI control law. Using empirically obtained optimal gains, the measured end-to-end latency of the system from target pose update to the point where the tracking error stabilizes within ±5% is 173 ms. The corresponding sampling rates for input and control streams are: Manus Quantum Metaglove (120 Hz), the middleware with USB camera input (26 Hz), and finally the middleware with combined camera, Manus data glove, and serial communication (20 Hz).

3 Demonstration

The proposed system will be demonstrated in a virtual training scenario, showcasing real-time hand pose synchronization between a master (tutor) and a follower (learner) to facilitate imitation-based skill transfer. On the tutor side, a dedicated smartphone application performs on-device monocular 3D hand tracking and streams the target pose to the middleware for control. The middleware computes and transmits pressure commands to the pneumatic system based on the output of the PI control scheme. The learner's glove responds in real time, allowing the audience to observe how the learner's hand dynamically tracks the tutor's hand pose, thereby demonstrating the system's potential for remote skill training.

4 Conclusion

We have introduced a compact, bidirectionally actuated pneumatic glove that enables real-time pose tracking without complex mechanical parts. By combining a compressor, pressure reservoirs, and electro-pneumatic regulators, the proposed system achieves precise and responsive pose guidance for remote skill transfer.

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