PAL-HAND.Q: A Handheld Device for Bidirectional and Multimodal Haptic Interaction

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Abstract. This paper presents the design of a novel handheld device, named PAL-HAND.Q, that enables bidirectional and multimodal haptic interaction with a remote control unit. This device can receive inputs from the user and render both kinesthetic and tactile feedback on his fingers. This is achieved through a unique combination of deformable membranes filled with pressurized fluid and mini vibrating motors. These elements work in synergy with an integrated electro-pneumatic system which is used to control the kinesthetic feedback. These characteristics result in a compact, lightweight, and versatile device, that can be used, for instance, in rehabilitation, alternative forms of communication, and augmented/virtual reality scenarios. In conclusion, an early prototype is realized, and a few practical aspects are discussed as well.

Keywords: haptics, multimodal haptic feedback, hand rehabilitation, alternative communication, telemedicine.

1 Introduction

Compact, integrated haptic devices hold significant potential for diverse applications, such as hand rehabilitation, augmented/virtual reality, and telemedicine. Specifically, the crucial role that haptic systems could have in rehabilitation practices has been highlighted in the 2022 annual report of the *International Federation of Robotics* (IFR) [1]. According to the IFR classification, such systems fall under the AP63 category (*Medical robotics: rehabilitation and non-invasive therapy*). Moreover, the use of robotic systems for telepresence and alternative forms of communication is covered by the AP69 class (*Other robots for medical applications*).

A haptic device was initially identified as a system that could use the sense of touch for a two-way physical interaction with the user (Fig. 1). Subsequently, the definition of haptic signal also included the exchange of forces between the user and the device [2]. Besides, in recent years handheld and wearable devices have become increasingly popular as opposed to grounded devices. This is motivated by clear advantages in terms of portability, ease of movement, and ample workspace.

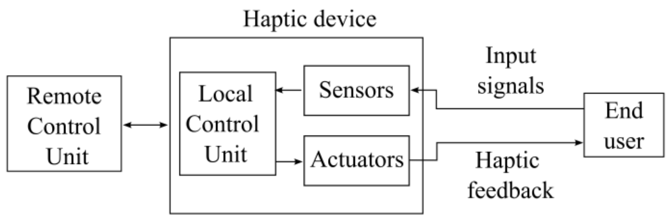

Fig. 1. A haptic device reads signals coming from the user and returns one or more feedback through a specific actuation system. A local control unit manages this interface and communicates with a remote control unit.

Haptic feedback can be rendered exploiting the sense of touch (tactile feedback) and/or imposing forces (kinesthetic feedback). Tactile feedback consists of a mechanical vibration or a localized pressure applied to one or more fingers, and it is typically used to simulate the contact with an object [3]. Kinesthetic feedback, i.e. the imposition of a force on the kinematic chain of the finger, is used for shape rendering in augmented/virtual reality [4-6] rehabilitation purposes, or alternative forms of communication. The possibility of providing kinesthetic feedback is the most powerful and exploitable functionality, and for this reason, it is a major object of study.

Kinesthetic feedback can be rendered using rigid actuators (fluidic or electromechanical), in direct contact with one or more distal phalanges of the hand [7]. The main drawback of such solutions lies in their large size and weight, and the difficulty of adapting to patients with different hand sizes.

To overcome these limitations, alternative solutions involve the interposition of a cable transmission between an electric motor and the end of the finger [8]. Alternatively, the modern paradigm of *soft robotics* is used to create actuators, joints, or entire kinematic chains that are compliant and adaptable to the geometry of the fingers. For example, the use of a soft fluid actuator mounted on a single finger, which extends along its entire length, has been investigated. Moreover, mixed structures consisting of a series of soft actuated joints and rigid parts have been proposed [9]. Deformable membranes or bellows distributed on the external shell of the device have been used as well [10]. These deformable elements are generally in contact with the distal phalanges of one or more fingers. Nevertheless, such devices always include an external auxiliary system, fluidic and electrical, for control and power supply.

Finally, wearable devices with similar deformable membranes, but decidedly smaller, have been used to provide tactile feedback through localized pressure forces [11]. In this case, a delocalized and fixed source of pressurized air/fluid is needed, or this can be mounted on a vest worn by the user.

As mentioned above, haptic devices can be used as human-machine interfaces in various contexts. These devices would benefit significantly if bidirectional and multimodal haptic interaction is made possible. For example, this can be exploited to develop alternative forms of communication, which bedridden patients can use. Moreover, new rehabilitation practices can be achieved, by integrating multiple haptic stimuli with augmented and virtual reality scenarios (gamification). Another interesting application is providing an enhanced musical experience, i.e. vibrotactile listening.

In this paper, a compact handheld haptic device that allows bidirectional and multi-modal interaction is presented. A set of design requirements is first identified, then the functional architecture of the device is introduced. At last, an early prototype is realized, showing the feasibility of the proposed design. Unlike the other solutions mentioned above, the device can track eleven degrees of freedom of the user's hand, i.e. pose of the hand and position of each finger, while being compact, lightweight, and portable.

2 PAL-HAND.Q: Concept and Design

Despite haptic systems for medical and augmented/virtual reality applications have received increasing attention, there still exists a gap between the world of research and the final consumer [12]. As a matter of fact, only a few clinically tested commercial haptic devices are available now. This gap arises mainly from the complexity of dealing with multiple design objectives and constraints, including:

1. ability to track the movement of the hand that holds the device;
2. capacity to provide a multimodal haptic feedback signal, i.e. combining signals of different nature;
3. creation of a compact, light and comfortable geometry, easily adaptable to various anthropometric dimensions of the hand;
4. presence of a low consumption and preferably integrated electrical power supply;
5. communication with remote control center, preferably via wireless.

Herein, a compact haptic system that addresses these complexities is presented. As shown in Fig. 2, the functional architecture of PAL-HAND.Q consists of the following elements:

- a graspable device, inside which there are all the regulation, sensing, control and communication devices;
- five deformable membranes in contact with each finger;
- ERM (Eccentric Rotating Mass) mini vibrating motors to provide tactile feedback;
- electro-pneumatic system to control the kinesthetic feedback. It comprises auxiliary reservoirs, pressure transducers, 2/2 digital valves, and check valves;
- on board control unit, i.e. microcontroller and integrated electronics;
- IMU (Inertial Measurement Unit) to track position and orientation of the device;
- wireless communication unit to connect with a remote control center;
- integrated electrical supply.

Moreover, no physical connections with additional external units are required. At the same time, PAL-HAND.Q shows high versatility, being able to render both kinesthetic and tactile feedback, while receiving multiple input signals from the user.

2.1 Functional Design

The deformable membranes are the core element of PAL-HAND.Q, serving as interface for user interaction. These elements are connected to an integrated electro-pneumatic

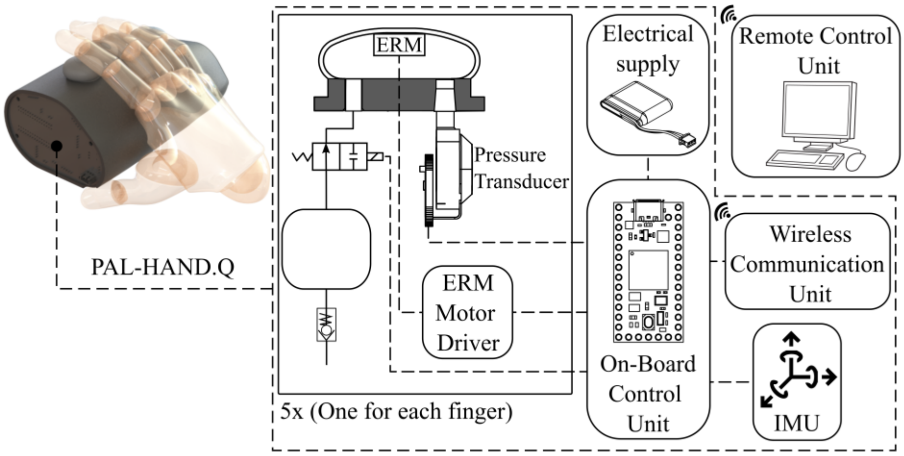

Fig. 2. Functional architecture of PAL-HAND.Q. The user interacts with a remote center by means of five deformable membranes (one for each finger), which measure the imposed deformation and return multimodal feedback (force and/or tactile feedback). An onboard control unit reads the signal coming from the pressure transducer and from IMU inertial sensor for tracking the motion of the hand, and allows wireless communication with a remote control unit.

system, whose primary function is to change the level of the force feedback. This principle was already demonstrated in [13] and herein is resumed. The geometry of the membrane is retrieved as well.

The underlying idea is to either isolate the volume inside the membrane or connect it to an auxiliary volume V_R by switching a 2/2 digital valve (Fig. 3). In the former case, the volume of air is the one enclosed by the membrane (denoted as V_M), whereas in the latter case, the total volume is $V_M + V_R$. By imposing a deformation y_s to the membrane, the trapped air undergoes a compression, thus resulting in a pressure increase.

The absolute pressure in the chamber as a function of deformation can be estimated using the standard compression rule:

$$P(y_s) = P_{C,i}\left(\frac{V_{C,i}}{V_{C,i}-\Delta V(y_s)}\right)^{\gamma} \tag{1}$$

where $V_{C,i}$ is initial volume of the chamber (either $V_{M,i}$ or $V_{M,i} + V_R$), $P_{C,i}$ is the initial absolute pressure, $\Delta V(y_s)$ is the volume change and γ is the adiabatic index (γ = 1.4). Then, the feedback force is:

$$F(y_s) = p(y_s)\,A(y_s) \tag{2}$$

being $p = P - P_{atm}$ the relative pressure and $A(y_s)$ the contact area. The theoretic feedback force, estimated through Eq. 2 for the two working conditions (high and low stiffness), is depicted in Fig. 3.

According to the notion of *just noticeable difference* coming from the ISO Standard for ergonomics of human-system interaction [14], a minimum difference between the forces rendered in the two working conditions is needed for the user to distinguish them. Specifically, the relative discrimination threshold is fixed at about 7%. Furthermore, it

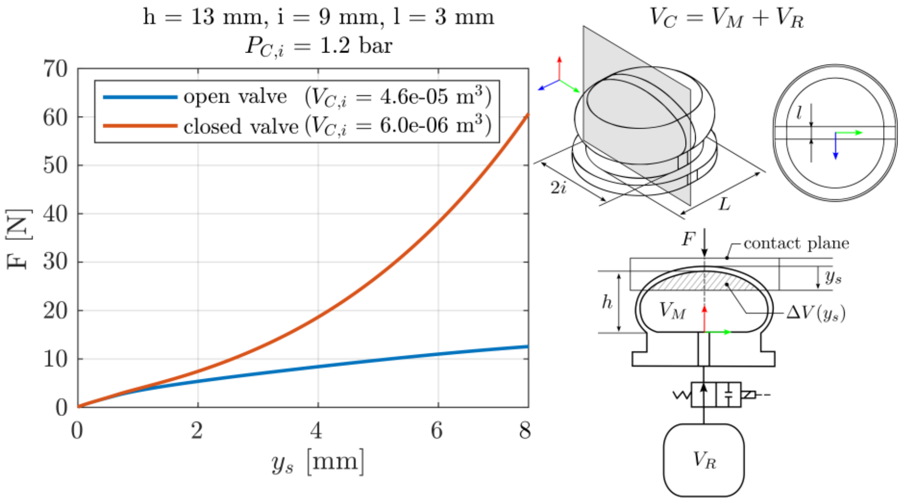

Fig. 3. Theoretic feedback force as a function of membrane compression y_s, for two working conditions: open valve (low stiffness, initial volume $V_{C,i} = V_{M,i} + V_R$) and closed valve (high stiffness, initial volume $V_{C,i} = V_{M,i}$). Please notice the representation of volumes V_M and V_R is not to scale.

should be noted that for small forces the threshold goes up since there also exists a minimum threshold in absolute terms. Therefore, a minimum deformation stroke of the membrane is required to clearly distinguish the difference in the kinesthetic feedback when switching the digital valve. Moreover, this difference becomes more detectable as long as the deformation increases. Thus, strokes of several millimeters are desirable.

The electro-pneumatic system also comprises pressure transducers to enable continuous reading of the deformation imposed by the user on the interface membrane. This enables one to independently read the position of each finger. Then, the combination of this feature and the use of systems for tracking the trajectory of the hand (i.e. IMU) provides a total reading of eleven degrees of freedom of the user's hand. The combination of all these input signals makes the device versatile and suitable for multiple applications. As an example, it enables the development of interactive forms of rehabilitation, where the user is asked to carry out tasks of grasping and manipulating objects in a virtual or augmented environment.

The vibration signal is generated using ERM mini vibrating motors. This functionality can be exploited, for example, to make the user perceive the grip of a solid object in an augmented reality environment or to allow the therapist to communicate remotely with the patient. A key aspect lies in transmitting the vibration signal specifically on the individual finger, thus avoiding the diffusion of the vibration in an uncontrolled and indistinguishable form. In other words, the position of the vibrating motor is crucial and must be carefully selected. Eventually, it has been noticed that integrating the ERM motor inside the membrane (see Figs. 2 and 4) helps prevent the vibration being transmitted to the rigid case.

Lastly, the independence from physical connections with the external environment is achieved through:

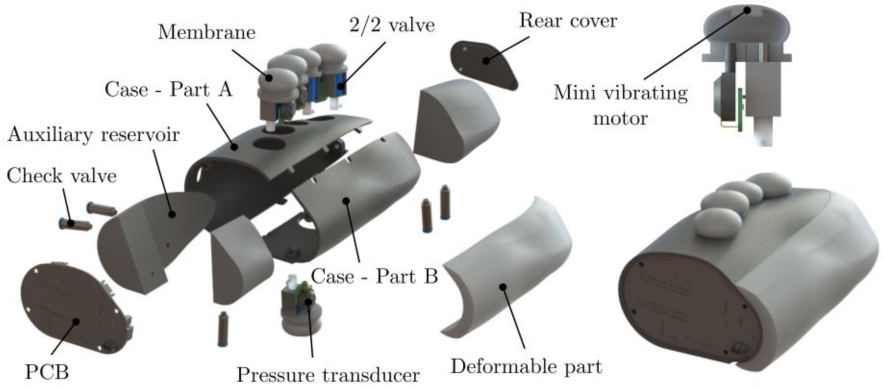

Fig. 4. Exploded view of PAL-HAND.Q (the battery pack is not represented)

1. auxiliary volumes that can be filled with compressed air before operation. During this set-up phase, it is also possible to choose a pressure level suitable for the application;
2. integrated electronics for power supply and control of the device.

As regards electrical components, these must be small-sized and low-consumption. For instance, a BLE (Bluetooth Low Energy) module for wireless communication with the remote control center was chosen. Moreover, if on one hand the use of a discrete control of the force feedback limits the sensations that the user can perceive, it allows a notable reduction in size as well as considerable energy savings.

The resulting design of PAL-HAND.Q is shown in Fig. 4. It can be noted that an optional deformable part can be added to the case to increase ergonomics and provide a better grip. Lastly a custom PCB (Printed Circuit Board) has been realized to govern the power and control commands of the handheld device.

3 Prototyping

The feasibility and the effectiveness of the proposed design is demonstrated through an early prototype (Fig. 5). The deformable membranes are made of TPU 60A and 3D printed using a low-cost desktop printer (Ultimaker S5), while the case and auxiliary volumes are made of PLA. Subsequently, the tightness of the 3D-printed pneumatic components has been tested. In particular:

– auxiliary volumes were tested at 130 kPa, and no leakages were detected;
– membranes were tested at 50 kPa, and leakages below 100 Pa were detected over a 30-minute interval.

A microcontroller (Arduino® Nano 33 BLE) that integrates an IMU sensor and a wireless communication unit is used as onboard control unit. Miniaturized 3/2 digital valves, adjusted to serve as 2/2 digital valves (0520F, www.fspump.cn), with a drive current of

Fig. 5. Early prototype of PAL-HAND.Q

Table 1. Summary of PAL-HAND.Q's technical specifications

Size (L×W×H)	160×120×100 mm
Weight (without/with battery pack)	200 g / 400 g
Membrane deformation stroke	10 mm
Set-up relative pressure	20 to 50 kPa
Estimated autonomy	~ 30 min

200 mA each and 24 Vdc voltage supply, are used to control the kinesthetic feedback. The vibration is generated by mini coin ERMs (FIT0774, DFRobot), similar to those used in mobile phones and watches. Additional technical specifications of the prototype are listed in Table 1.

A few practical considerations can be derived from the prototype:

1. when grasping the device, the hand's aperture affects finger prehension and the force that one can exert on the deformable membranes. Therefore, to improve user experience, alternative geometries of the case could be studied. For example, a dumbbell-like case might result in a more natural and ergonomic hand posture, as well as in a more balanced device;
2. the vibration of the ERMs is well localized on the fingertip and is not transmitted to the rigid case;
3. the distinction between the two levels of feedback force can be improved, especially when operating at low pressures. To this end, increasing the deformation stroke of the deformable membranes could be useful;
4. sometimes it can happen to squeeze a membrane involuntarily when pressing another one. This is especially true for the ring finger and little finger. Hence, one could consider having a single membrane for these fingers, thus losing one degree of freedom, but increasing device effectiveness.

4 Conclusions

The paper addressed the design of a handheld haptic device suitable for medical and augmented/virtual reality applications. The integration complexities that typically affect these devices have been solved through an innovative combination of deformable membranes and mini vibrating motors. The result is a compact device, able to render both kinesthetic and tactile feedback on all fingers of the hand. The use of an integrated electro-pneumatic system, combined with an IMU inertial sensor and a wireless communication module, allows the device to be used without external physical connections. The feasibility of the proposed design was demonstrated through an early prototype. Future work will focus on improving the device ergonomics, for instance studying alternative case geometries that can be easily adapted to the hands of different users. Further improvements of this work will also regard the development of use cases, related to virtual reality environments or alternative forms of communication. In this way, the suitability of the haptic device in some use scenarios will be assessed.

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