# Design and Integration of a Dexterous Interface with Hybrid Haptic Feedback

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Keywords: Force Feedback Interface, Haptics, Dexterous, Virtual Reality.

Abstract: Haptic interfaces allow natural physical interactions with virtual environments. By measuring the user's movements and providing force feedback, they recreate a physical sense of presence in the virtual world, thus improving the user's immersion. These characteristics led to their adoption in various VR applications, e.g. fitting, training or ergonomic studies. Until recently however, most of the commercially available systems were equipped with a handle which constraints the simulated movements to the manipulation of tools having a shape similar to the handgrip. More dexterous devices which do not constraint the hand's posture are required to allow for the simulation of more various grasps and fine manipulation. Such interfaces are currently the subject of intense research, with new products arrived recently on the market. Some of these devices allow generic force feedback on the fingers thanks to multidirectional actuation. They remain however complex and cumbersome. To overcome this limitation, some other devices limit the number of actuators. More compact solutions can be obtained this way, but force feedback is limited to only few directions. In this paper, we present a different approach. By combining force and local pseudo-force feedback, we aim at allowing a rich and multidirectional haptic feedback in a light and compact fashion. This paper presents an innovative haptic glove implementing such hybrid haptic feedback developed for interactions with digital mock-ups, with details on its main components and its integration in a VR application.

## 1 INTRODUCTION

A haptic interface is an (often small) interactive robot usually equipped with one or several end-effectors manipulated by a user. Its sensors allow measuring the user's movements which are in turn used to control the displacements of an avatar in a virtual environment. When the user's avatar is subject to an external force, generated e.g. when it contacts a virtual object, the device's actuators provide a force feedback which improves the user immersion by reproducing a physical sense of presence in the virtual world.

Such devices are designed so as to offer as less resistance as possible to the user when moving in free space, hence naturally following his or her movements, and at the same time to be powerful and stiff enough to render realistic forces when required. This capability to allow natural interactions by gesture with force feedback in virtual environments led to their adoption in various VR applications like for example fitting (i.e. verification of the possibility to assemble complex systems by reproducing the required user and parts movements in VR), training in VR or ergonomic studies (Perret et al., 2013) (Arnaldi et al. 2018).

Until recently, however, most of the commercially available haptic interfaces were still equipped with a handle fixed on the end-effector of the robot (Massie and Salisbury, 1994) (Conti and Khatib, 2005). This simple solution is well suited when simulating an operation performed with a given tool, for example a scalpel or a drill in surgery or a screwdriver in a virtual factory. However, they limit the user's dexterity and are less adapted when manual manipulation is required or when several tools with

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Gosselin, F., Andriot, C., Keith, F., Louveau, F., Briantais, G. and Chambaud, P.
Design and Integration of a Dexterous Interface with Hybrid Haptic Feedback.
DOI: 10.5220/0009831204550463
In *Proceedings of the 17th International Conference on Informatics in Control, Automation and Robotics (ICINCO 2020)*, pages 455-463
ISBN: 978-989-758-442-8

different shapes are used successively. In this case, a dexterous interface is required.

The design of a dexterous haptic interface is however an extremely difficult task as the hand is one of the most complex part of the human body. It has a large number of moving bodies and joints which produce complex and coupled movements when grasping and manipulating objects in many possible ways (Feix et al., 2009). Moreover, its morphology and dimensions vary greatly between individuals, and can even differ between the left and right hands for the same person. Finally, it is highly sensitive to force and haptic information. As a consequence, despite continuous efforts in the field, no haptic interface to date allows natural interactions in VR with the full dexterity and sensitivity of the human hand. Different approaches have been proposed in the literature to tackle this issue (see for example recent reviews in (Heo et al., 2012) (Pacchierotti et al., 2017) (Perret and Vander Poorten, 2018)):

- Wearable devices and thimbles are very simple systems that (at least for some of them) almost preserve the hand dexterity. They can give a compelling illusion of some of the phenomena occurring when one touches a virtual object, considering e.g. its shape or texture. However, they cannot block the fingers when grasping an object, thus limiting the realism of the interaction as the real world hand configuration may not be respected.
- At the opposite end of the spectrum, exoskeletons have links and joints similar to the hand, and (in their most complete and complex form) they are attached to all the phalanges on which they can independently apply forces. They theoretically allow simulating all types of grasps. Their joints must however therefore be roughly aligned with the fingers' ones, which in turn calls for a user-specific design or at least tuning. This is not convenient for a universal VR device that can be used by different users. Also, they are complex and bulky.
- Haptic gloves appear in between these two extremes. They allow accurately measuring the hand movements but usually only provide uni-directional force feedback on the hand closure, either using traditional motors and cables as in (Nilsson et al., 2012) or more innovative solutions like for example electrostatic brakes as in (Hinchet et al., 2018). Hence they do not allow simulating the forces occurring when touching the environment in any arbitrary direction. Also, like clothing, they must fit the user's size and are not universal.
- Fingertip devices also lie in between these two extremes in terms of complexity. Contrary to exoskeletons, they are linked to the user's hand only at the level of the palm and distal phalanges. As a consequence, they do not allow simulating power grasps but, despite being restricted to the simulation of precision grasps, they can more easily fit different users and their design is much simpler. When considering applications mainly focused on precise manipulation, they constitute an interesting solution.

This short review demonstrates the interest of dexterous fingertip interfaces. Such devices are indeed subject to intense developments at the moment, with a lot of products recently arrived on the market or announced, like e.g. Dexta Robotics Dexmo (www.dextarobotics.com), Senseglove DK1.2 (www.senseglove.com) or Haption HGlove (www.haption.com/fr/products-fr/hglove-fr.html). These interfaces feature between 3 and 5 fingers, which corresponds to what is required for the majority of dexterous interactions (Gonzalez et al., 2014). Indeed, this later reference shows that we mainly use the distal phalanx of the thumb, index, middle and ring finger, and the exterior side of the index when interacting with our environment (these areas are sufficient to simulate more than 50% of the tasks performed in the daily life). A four fingers (and even more a five fingers) interface remains however complex and potentially cumbersome and heavy. As a consequence, most of the four or five fingers devices only integrate 1 actuator per finger (e.g. Dexmo), acting only against hand closure, and eventually complemented with a tactile actuator (e.g. Senseglove). This solution allows for a more simple and compact design. It does not, however, allow rendering the forces occurring in other directions. Therefore, multi-degrees of freedom (DoF) miniature robots allowing multi-directional force feedback are needed for each finger. This solution theoretically allows a realistic rendering of any force on the fingertips (in a first approximation, a single finger can apply almost only forces on the environment, torques being generated by a combined use of several fingers, and only 3D force feedback is required at the fingertips). The Haption HGlove is the sole commercially available solution allowing such 3D force feedback on the fingertips. It is however restricted to three fingers. Addressing four or five fingers would probably lead to a more complex, cumbersome and heavy solution which would affect the user's ability to make abstraction of the interface. Preserving a natural interaction is however of particular importance for fine manipulation, i.e. when grasping and precisely manipulating small objects.

In this paper, we present a hybrid haptic glove that introduces several innovations intended to tackle these limitations. More specifically:

- in order to obtain a compelling illusion of a multi-directional force feedback in a lighter and more compact fashion than with existing devices, we propose to combine an under-actuated fingertip device used to render normal forces on the distal phalanges with thimble like local skin deformation systems positioned under the fingertips to render tangential forces,
- to allow for the simulation of the majority of the targeted activities, we implement this principle on four fingers,
- to allow for the realization of different grasp types without constraining the fingers' movements, a redundant and partially coupled architecture is chosen for each finger's robot,
- links dimensions and shapes are further optimised to get a light and compact design and to avoid fingers-robots collisions,
- finally, low cost optical sensors are introduced to measure the movements of the fingers.

Further details on these elements are given in the following section.

# 2 DESIGN AND IMPLEMENTATION OF A HYBRID HAPTIC GLOVE

## 2.1 Design Rationale

The dextrous hybrid haptic feedback interface presented in this paper was developed to address industrial applications, with a first use case focused on the maintenance of the battery of electric cars, and more specifically on training the technicians in charge of this task. The whole task (i.e. battery disassembly) duration being much too long (in the order of a few hours) to be completely simulated, we focused our attention on some critical steps like the disassembly of the on-board computing unit and some internal cables and connectors. These tasks are performed with both hands using different tools (T-shaped wrench, clamp,…) or directly with the fingers. In most cases, only the fingertips are involved, and almost only the tips of the thumb, index, middle and ring. To allow for the simulation of these tasks, we decided to develop two four fingers fingertip haptic devices, one for the left hand and the other for the right hand. The other technical design drivers are those classically used for the design of dexterous haptic interfaces as summarized in (Gonzalez et al., 2014): no restriction of fingers' movements, multi-DoF haptic feedback on the fingertips, force feedback in the order of 10N, control stiffness of about 5000N/m. Another constraint was to develop a solution that is compact and simple enough to be used by non-specialists.

## 2.2 Overview of the System

The interface developed to answer the above-mentioned specifications is illustrated in Figure 1. It is composed of four robots, each of them being associated with a finger. These robots are linked to a common basis fixed on the palm. The basis also serves as a support for motion capture passive targets that, in association with external cameras, allow tracking the hand movements (the robots' sensors being in charge of the measurement of the movements of the fingers). It is further connected to a controller in charge of the management of the different sensors' signals and of the control of the actuators.

Figure 1: Hybrid haptic feedback glove.

## 2.3 Hybrid Haptic Feedback Principle

As mentioned before, designing a 4 fingers device with 3 DoF force feedback on each finger would result in a complex and bulky system. Fortunately, local tangential skin deformation systems as for example in (Girard et al., 2016) can, to some extent, give the illusion of force feedback to the user yet without large actuators. Building on this observation, we propose to implement a solution combining large actuators able to provide (bi-directional) force feedback in the direction of the finger flexion-extension (that is roughly normal to the fingerpad), and local skin deformation systems using small actuators able to provide a pseudo force feedback in the other directions (i.e. tangential to the finger pulp).

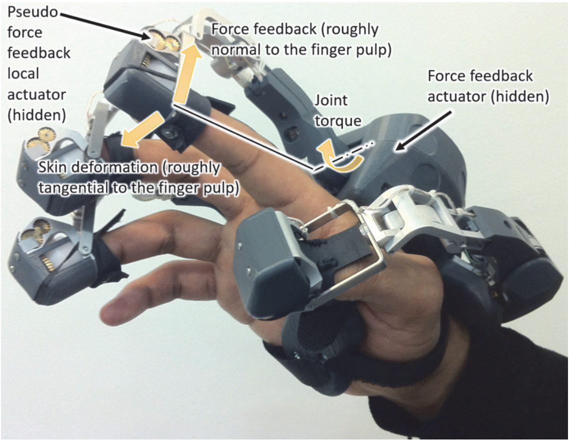


Figure 2: Hybrid haptic feedback principle.

The logic behind this choice is the following:

- the hand closing force is a function of the movements of the fingers and it has to be finely regulated when grasping a rigid or soft object if one wants to prevent slippage or break (if the object is fragile),
- the forces in the other directions mainly result from global hand movements (and only little from movements of the fingers relative to the palm) which produce local skin deformation under an external load.

This approach is different from usual solutions proposed to limit the weight of dextrous haptic interfaces. It does not replace force feedback produced by heavy robotic structures with pseudo-force haptic feedback rendered by wearable interfaces or thimbles. It neither proposes to implement tactile feedback in addition to force feedback (as for example on the Senseglove) in order to increase the force bandwidth. Here, the pseudo force does not replace nor come in addition to the force feedback. As illustrated in Figure 2, it complements it, both acting in different directions.

## 2.4 Kinematics

It is of primary importance that dexterous haptic interfaces allow free movements of the fingers. This prevents the use of fully coupled architectures introducing fixed synergies between links as it would constrain the hand closure movement to follow a given and fixed trajectory. Yet the device should also remain compact. This prevents using parallelogram structures as for example in (Gosselin et al., 2005), or their serial 2 links equivalent as implemented e.g. on the Dexmo, as such structures protrude excessively from the plane of the palm when the hand is opened.

To allow for free fingers' movements yet guaranteeing a compact design, we developed a redundant and partially coupled architecture composed of 7 links (plus the rotating drum of the local pseudo force feedback system, see Figure 3). The same solution is used for all fingers, except an additional joint and link for the thumb (this supplementary DoF allows to cope with the thumb's internal rotation appearing when the hand is closed).

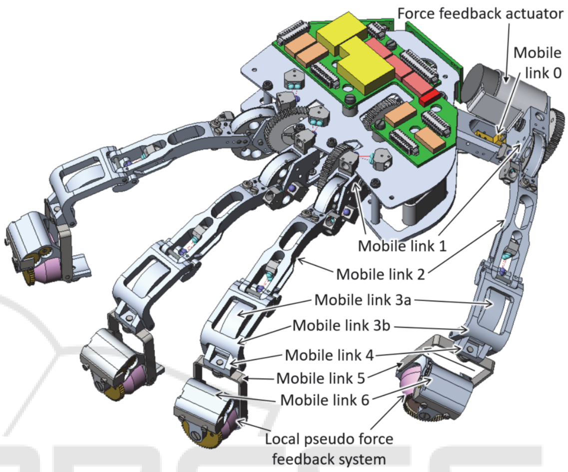


Figure 3: Redundant and partially coupled robots' architecture.

The kinematic structure of the index, middle and ring fingers' robots is illustrated in Figure 4 (corresponding to links 1 to 6, an additional joint being added between links 0 and 1 for the thumb):

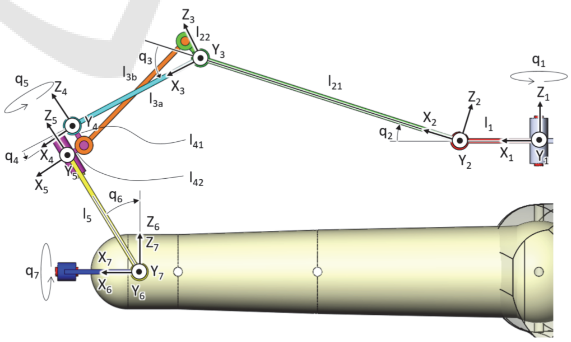

Figure 4: Kinematic model of the robots. A frame $R_i=(O_i,X_i,Y_i,Z_i)$ is associated with each link, with its origin positioned on the joint axis, $q_i$ is the rotation around joint $_i$, and $l_i$ (resp. $l_{i1}$, $l_{i2}$) designates the length of link i (resp. of different parts of link i).

With these notations, the kinematic model of the index, middle and ring robots can be written as follows:

$$T_{01}=trans(X_0,d_x).trans(Y_0,d_y).rot(Z_0,q_1) \quad (1)$$

$$T_{12}=trans(X_1,l_1).rot(Y_1,q_2) \quad (2)$$

$$T_{23}=trans(X_2,l_{21}).rot(Y_2,q_3) \quad (3)$$

$$T_{34}=trans(X_3,l_{3a}).rot(Y_3,q_4) \quad (4)$$

$$T_{45}=trans(Z_4,-l_{41}).trans(X_4,l_{42}).rot(Z_4,q_5) \quad (5)$$

$$T_{56}=trans(Z_5,-l_5).rot(Y_5,q_6) \quad (6)$$

$$T_{67}=rot(X_6,q_7) \quad (7)$$

Another transformation is required for the thumb. Equation (1) is then replaced with the following equations :

$$T_{b0}=trans(X_0,d_x).trans(Y_0,d_y).trans(Z_0,d_z).rot(Z_0,q_{zb0}).rot(X_b,q_{xb0}) \quad (8)$$

$$T_{01}=trans(Z_0,l_0).rot(Z_0,q_1) \quad (9)$$

Link 1 moves in abduction-adduction while the other links allow finger flexion-extension. The links 2, 3a, 3b and 4 form an inverted parallelogram which allows the robot to remain close to the finger in its entire workspace as shown in Figure 5 (contrary to parallelograms which protrude excessively from the plane of the palm when the hand is opened).

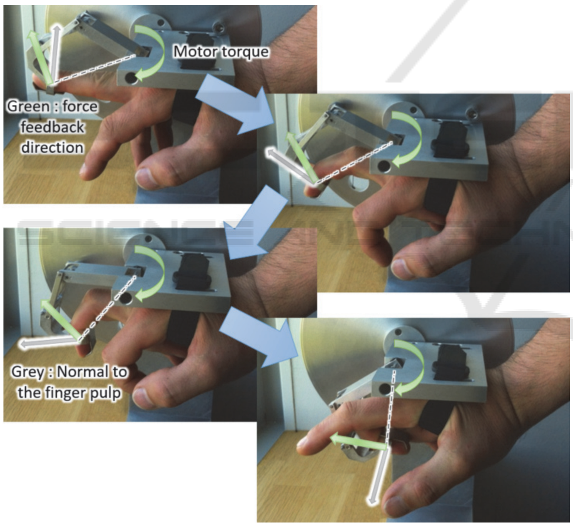


Figure 5: Ability of the proposed architecture to remain close to the finger (image made with a mock-up of the proposed architecture).

Pivot joints are added at the end of this structure to allow for the fingertip to rotate freely when the user closes his or her hand.

The placement of the robots relative to the palm, the joints' range of motion and the links' dimensions were further optimized in order to allow free movements of the fingers over their entire workspace. The resulting dimensions ensure the kinematic compatibility of the robots with the movements of human fingers for a medium sized male adult (Hansen et al., 2018). It also allows closing the hand in different ways associated with different grasp types as shown in Figure 6.

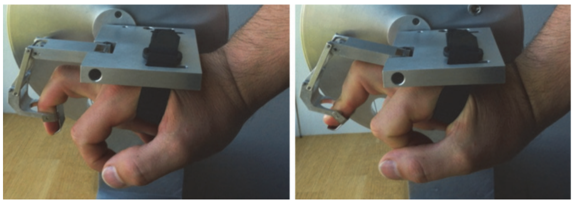

Figure 6: Ability to follow different hand closing trajectories.

It is worth mentioning that, unlike gloves and exoskeletons whose dimensions are adapted to the size of the user, fingertip devices can accommodate different hand sizes. Our device can therefore be used by various medium-sized users (for smaller and larger people, we intend in the future to develop several glove sizes to cope with significantly smaller or larger hands).

Its main limitation is that, due to under-actuation, the force feedback direction is not fully controlled. As shown in Figure 5, it is not always normal to the finger pulp. When the hand is fully closed, it does no more constrain the finger that can move freely. Still, the force is roughly normal to the finger pulp in the majority of the robot's range of motion.

## 2.5 Actuation

Figures 7 and 8 give additional details on the force feedback actuator (Figure 7) and local pseudo force actuation system (Figure 8).

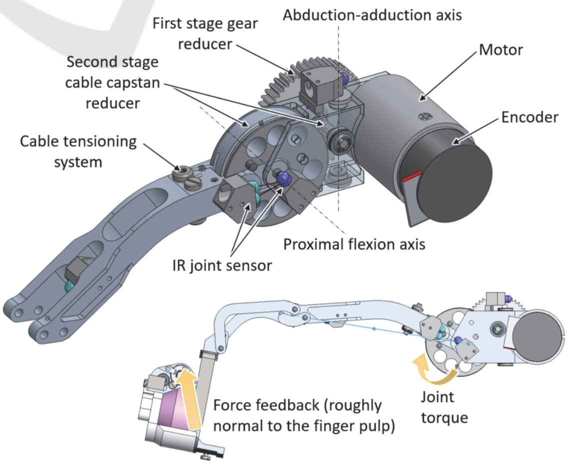


Figure 7: Force feedback actuator used to render forces on the proximal flexion axis.

The force feedback actuator was designed to be highly transparent and backdriveable yet compact and light. After the study of different combinations of actuators and reducers, we selected a Maxon DC motor (ref. REmax21 221028) and a two stages reducer combining a first stage gear reducer and a second stage miniature cable capstan reducer. Such combination ensures that, even if backlash occurs in the gear reducer, its amplitude is downscaled at the output of the cable capstan reducer, making if almost negligible in practice. This solution allows generating a continuous joint torque equal to 0.342Nm and a peak joint torque of 0.974Nm on the proximal flexion joint. The distance between this joint and the fingertip varying between 59.9mm and 111.7mm in the workspace of the robot (about 75mm when the hand is fully opened), this corresponds to a continuous force capacity varying between 3N and 5.7N and a peak force varying between 8.7N and 16.2N (4.5N continuous and 13N peak when the hand is fully opened). This is in line with our specifications.

The motor is further equipped with a 512ppt magneto-optical encoder (ref. Maxon MR 201940). After interpolation, this corresponds to a resolution between 0.18 and 0.34mm in the workspace of the robot. Finally, taking into account the maximum speed of the actuators, we can guarantee that the fingers can move at speeds up to 0.6 to 1.2m/s.

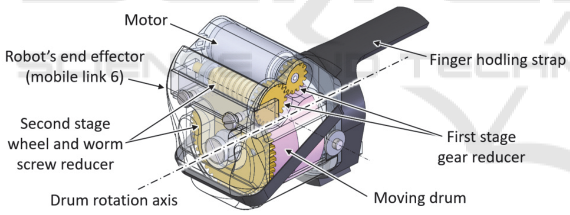


Figure 8: Local pseudo-force actuation system.

The pseudo force actuation system is composed of a miniature Maxon DC motor (ref. RE8 347727) associated with a two stages reducer combining a first stage gear reducer and a second stage wheel and worm screw reducer. It allows generating a maximum continuous (resp. peak) torque of 0.0196Nm (resp. 0.0308Nm) that produces a rotation of a moving drum placed below the distal part of the fingertip pulp (whose proximal part is supported by a dedicated support machined on the end effector, see Figure 9). This torque corresponds to a maximum continuous (resp. peak) tangential force of 1.96N (resp. 3.08N) for the index, middle and ring and 1.57N (resp. 2.47N) for the thumb (the thumb's drum has a larger diameter). This is theoretically sufficient to deform the pulp a few millimetres (Gleeson et al., 2010).

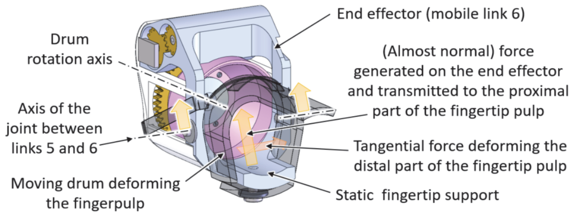


Figure 9: 2 DoF haptic feedback on the end-effector.

With this design, haptic feedback can be generated on the fingertip in two directions (1 DoF force feedback in flexion-extension plus 1 DoF pseudo force feedback in abduction-adduction, see Figure 9). Should haptic feedback be required in three directions, this local actuation system could easily be replaced with a 2 DoF solution as proposed for example in (Girard et al., 2016).

## 2.6 Hand Posture Measurement

At the time of the development of the glove presented in this paper, there was no joint sensor commercially available at a reasonable price that was small enough to be integrated in the device. As a consequence, we had to develop a custom solution. The association of a diode and photodiode, as proposed on the UBN Hand IV (Palli and Pirozzi, 2011), was judged very promising. It is cheap and relatively precise. However, its range of measurement is too limited to cover the movements of our glove.

To overcome this limitation, we propose to use a photodiode with a very large viewing angle yet a relatively constant response over this angle. It is illuminated with 2 IR diodes in order to increase the measurement range. The positioning of these components relative to the joint is optimized to get an as linear as possible response over a large range of motion. This arrangement is shown in Figure 7 for the proximal flexion axis: the photodiode represented in blue is positioned along the joint axis and the IR diodes shown in light blue are pointing at its centre.

It is worth noting that, while cheap, this sensor relies on mass produced components whose response can vary between samples. To cope with this issue, we measured the response of 27 emitter-receiver couples and identified a mean response (see Figure 10). Once calibrated in two points (typically the joints limits where the angles are precisely known), this solution gives a relatively linear response over about 60° with an error below 3° which is comparable to the repeatability of the sensors of the Cyberglove II (see http://www.cyberglovesystems.com/cyberglove-ii#specs). The precision is thus judged sufficient for the accurate capture of the fingers movements.

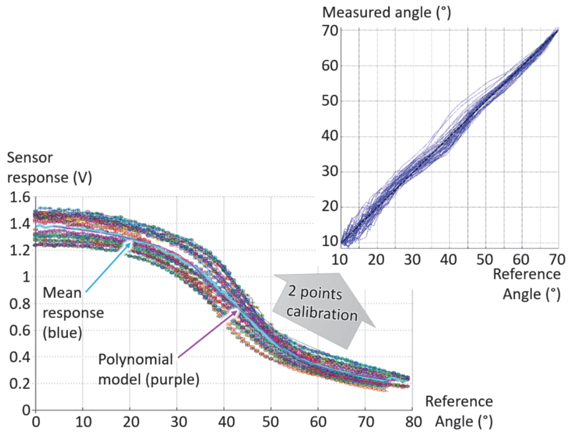


Figure 10: Optical sensors' response.

Thirteen such sensors are integrated in our glove, one on each of the abduction-adduction axes ($q_1$), one on each of the proximal and intermediate flexion axes ($q_2$ and $q_3$), plus one additional sensor for measuring the internal rotation of the thumb ($q_{xb0}$). Knowing that the angle $q_4$ can be computed from $q_3$ using the formula introduced in (Ngalé Haulin et al., 2001) and that the position of the fingertip does not depend on $q_5$, $q_6$ and $q_7$, it can be demonstrated that these sensors are sufficient to compute the position of the fingertips relative to the palm. The sensors measuring angle $q_2$ is even not mandatory as this angle is already measured by the motor's encoder. This redundant sensor is still useful to get an absolute measure and avoid the need to initialize the measurement at start-up on this axis.

### 2.7 Controller

To manage all sensors and actuators of the hybrid haptic feedback glove, a custom designed controller was developed. It is composed of three types of cards:

- Two cards in charge of the management of the ReMax21 actuators (each card being able to manage 2 motors and their incremental encoders). These motors are controlled using a current loop running at 25kHz and a speed loop running at 5kHz, managed by a Texas Instrument microcontroller (ref. TMS320F28035). The motor current is measured with a 14 bits AD converter, and the speed information comes from the 512ppt encoders. Each card integrates two microcontrollers, as well as a H bridge per motor (ref. Texas Instruments DRV8432).
- One card for the management of the four RE8 actuators. This card has also fourteen 12 bits analog inputs in charge of the acquisition of the 13 analog values of the joint sensors. Two microcontrollers (ref. TMS320F28035) are used therefore, each microcontroller being in charge of two actuators and seven analog inputs. Joints sensors' positions are acquired at a frequency of 5Khz, and the motors are controlled in speed mode using a U-RI control law running at a frequency of 25kHz (the RE8 actuators have no rotary sensors), with a 12-bits resolution for the current acquisition. A double H-bridge (ref. Texas Instrument DRV8848) allows the microcontroller to manage the power supply for each motor.
- Finally, a motherboard ensures the link between the UDP communication and the actuators' cards. This link is managed by a microcontroller (ref. Microchip PIC32MX695F512L) running at a frequency of 1Khz. This bi-directional communication allows sending position and current data to the simulation and receiving speed and force orders.

This controller is sufficiently compact to be integrated in a small backpack. It is powered by a 12V power supply, making it compatible with a battery.

## 3 VR APPLICATION

Figure 11 illustrates the architecture of the VR system used to test the hybrid haptic feedback glove. The PC running the VR simulation is coupled to the gloves' controllers using Ethernet cables. The user wears the left and right gloves and his hands' movements are measured by an ART motion capture system. An Oculus Rift DK2 Head Mounted Display (whose movements are measured by an Oculus tracker so as to adjust the viewing angle) is used for visual feedback. An additional TV screen is used to display the virtual environment to the audience.

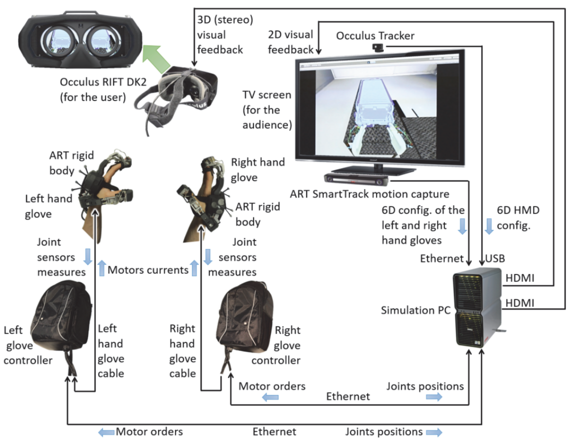


Figure 11: Architecture of the VR environment.

The dextrous hybrid haptic feedback interface is coupled to a VR application developed in Unity and running the XDE physics engine (Merlhiot et al., 2012). Given the nature of the tasks simulated, a particular attention was given to the simulation of the friction between the fingers and their environment, with an advanced Coulomb-Contensu model. As shown in Figure 12, an avatar of the haptic glove coupled at the joint level to the real glove is used to control the virtual hand that interacts with the environment. When the virtual hand is blocked, it constraints the movements of the glove's avatar thus of the real glove.

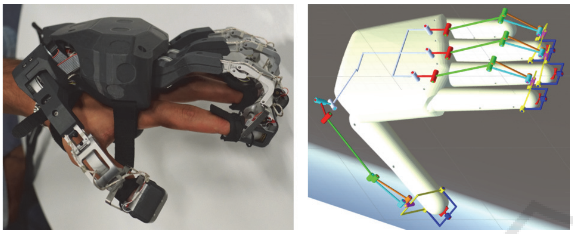

Figure 12: Coupling between the glove and its avatar at joint level.

Figure 13 illustrates an example simulation. The user can easily grasp and manipulate virtual objects.


Figure 13: Bimanual use of the gloves in VR.

The first tests performed with the virtual model of the battery demonstrated that simple operations are feasible (e.g. grasping and displacement of the on-board computing unit). Additional work is however still needed to allow for the simulation of finer tasks (e.g. unscrewing the bolts used to fix the computing unit, manipulation of internal cables and connectors).

## 4 CONCLUSION AND PERSPECTIVES

This paper presents a novel hybrid haptic glove, with details on its electro-mechanical design and its integration in a VR application. Contrary to most existing force feedback gloves, haptic feedback is generated in several directions, yet this multi-directional haptic feedback is attained in a more compact package than with devices equipped with large force feedback motors on several axes.

This design constitutes an interesting alternative to existing VR gloves which, despite large efforts, still suffer critical flaws that prevent their wide dissemination (weight, volume, complexity and cost of multi-fingers fully actuated exoskeletons and fingertip devices, limited number of force feedback degrees of freedom of under-actuated gloves, lack of rendering realism of fingertip wearables and thimbles). On the contrary, our design offers rich interaction capabilities and haptic feedback in a relatively compact and light system that could be produced at a reasonable cost in the future.

First tests show that this solution allows efficient dexterous interactions in VR. This observation tends to confirm the interest of hybrid haptic feedback, offering interesting perspectives for both VR applications and dexterous teleoperation. Potential VR applications cover training industrial tasks as exemplified in previous section, but also virtual surgery training, and, of course, immersive video games. Regarding teleoperation, it could be used for example for the control of a telepresence robot used for precise tele-manipulation of radioactive or dangerous material, for the control of dextrous human-like space or subsea robots like Robonaut 2 (Diftler et al., 2011) or Aquanaut (Manley et al., 2018), for remote bomb disposal or distant maintenance of an industrial setting.

Short term future work should be focused on a thorough evaluation of the device in order to confirm these first results. In the longer term, further work is planned on the VR application in order to allow the simulation of more complex scenarios.

## ACKNOWLEDGEMENTS

This research was partly supported by the "Agence Nationale de la Recherche" (Mandarin project - ANR-12-CORD-0011, labeled by "Cap Digital Paris Région", the French cluster for digital contents and services).

## REFERENCES


Arnaldi, B., Cotin, S., Couture, N., Dautin, J.L., Gouraton, V., Gruson, F., Lourdeaux, D., (2018), Nouvelles applications, *in Réalité virtuelle et réalité augmentée, mythes et réalités*, ISTE, 2018, pp. 27-93.

Conti, F., Khatib, O., (2005), Spanning large workspaces using small haptic devices, *Proc. IEEE Worldhaptics Conf.*, 6 pages.

Diftler, M.A., Mehling, J.S., Abdallah, M.E., Radford, N.A., Bridgwater, L.B., Sanders, A.M., Askew, R.S., Linn, D.M., Yamokoski, J.D., Permenter, F.A., Hargrave, B.K., Platt, R., Savely, R.T., Ambrose, R.O., (2011), Robonaut 2 - The First Humanoid Robot in Space, *Proc. IEEE Int. Conf. on Robotics and Automation*, pp. 2178-2183.

Feix, T., Pawlik, R., Schmiedmayer, H.B., Romero, J., Kragic, D., (2009), A Comprehensive Grasp Taxonomy, *Robotics, Science and Systems Conference: Workshop on Understanding the Human Hand for Advancing Robotic Manipulation.*

Girard, A., Marchal, M., Gosselin, F., Chabrier, A., Louveau, F., Lecuyer, A., (2016), HapTip: Displaying Haptic Shear Forces at the Fingertips for Multi-Finger Interaction in Virtual Environments, *Frontiers in ICT*, 3(6), 15 pages.

Gleeson, B., Horschel, S., Provancher, W., (2010), Design of a Fingertip-Mounted Tactile Display with Tangential Skin Displacement Feedback, *IEEE Trans. on Haptics*, 3(4), pp. 297-301.

Gonzalez, F., Gosselin, F., Bachta, W., (2014), Analysis of hand contact areas and interaction capabilities during manipulation and exploration, *IEEE Trans. on Haptics*, 7(4), pp. 415-429.

Gosselin, F., Jouan, T., Brisset, J., Andriot, C., (2005), Design of a wearable haptic interface for precise finger interactions in large virtual environments, *Proc. IEEE Worldhaptics Conf.*, pp. 202–207.

Hansen, C., Gosselin, F., Ben Mansour, K., Devos, P., Marin, F., (2018), Design-validation of a hand exoskeleton using musculoskeletal modeling, *Applied Ergonomics*, 68, pp. 283-288.

Hinchet, R., Vechev, V., Shea1, H., Hilliges, O., (2018), DextrES: Wearable Haptic Feedback for Grasping in VR via a Thin Form-Factor Electrostatic Brake, *Proc. ACM User Interface and Technology Symp.*, pp. 901-912.

Heo, P., Min Gu, G., Lee, S.J., Rhee, K., Kim, J., (2012), Current Hand Exoskeleton Technologies for Rehabilitation and Assistive Engineering, *Int. J. Precision Engineering and Manufacturing*, 13(5), pp. 807-824.

Manley, J.E., Halpin, S., Radford, N., Ondler, M., (2018), Aquanaut: A New Tool for Subsea Inspection and Intervention, *Proc. IEEE/MTS Oceans Conf. and Exposition*, 4 pages.

Massie, T., Salisbury, J.K., (1994), The PHANTOM haptic interface: A device for probing virtual objects, *Proc. ASME Symp. on Haptic Interfaces for Virtual Environment and Teleoperator Systems*, pp. 295–299.

Merlhiot, X., Le Garrec, J., Saupin, G., Andriot, C., (2012), The XDE mechanical kernel: Efficient and robust simulation of multibody dynamics with intermittent nonsmooth contacts, *Proc. Joint Int. Conf. on Multibody System Dynamics*.

Ngalé Haulin, E., Lakis, A.A., Vinet, R., (2001), Optimal synthesis of a planar four-link mechanism used in a hand prosthesis, *Mechanism and Machine Theory*, 36(11-12), pp. 1203-1214

Nilsson, M., Ingvast, J. , Wikander, J., von Holst, H., (2012), The Soft Extra Muscle System for Improving the Grasping Capability in Neurological Rehabilitation, *Proc. IEEE EMBS Int. Conf. on Biomedical Engineerig and Sciences*, pp. 412-417.

Perret, J., Kneschke, C., Vance, J., Dumont, G., (2013), Interactive Assembly Simulation with Haptic Feedback, *Assembly Automation*, 33 (3), pp. 214-220.

Perret, J., Vander Poorten, E., (2018), Touching Virtual Reality: A Review of Haptic Gloves, *Proc. Int. Conf. on New Actuators,* pp. 270-274.

Pacchierotti, C., Sinclair, S., Solazzi, M., Frisoli, A., Hayward, V., Prattichizzo, D., (2017), Wearable Haptic Systems for the Fingertip and the Hand: Taxonomy, Review, and Perspectives, I*EEE Trans. on Haptics*, pp. 580-600.

Palli, G., Pirozzi, S., (2011), Miniaturized Optical-based Force Sensors for Tendon-driven Robots, *Proc. IEEE Int. Conf. on Robotics and Automation*, pp. 5344-5349.