2014 IEEE International Conference on Robotics & Automation (ICRA)
Hong Kong Convention and Exhibition Center
May 31 - June 7, 2014. Hong Kong, China

HAIR: HAptic feedback with a mobile AIR jet

Mohamed Yassine Tsalamlal, Paul Issartel, Nizar Ouarti, and Mehdi Ammi

Abstract— **Haptic devices are dedicated to render virtual tactile stimulation. A limitation of these devices is the intrusiveness of their mechanical structures, i.e. the user need to hold or wear the device to interact with the environment. Here, we propose a concept of new tactile device named HAIR. The device is composed of a computer vision system, a mechatronic device and air jets that stimulate the skin. We designed a first prototype and conducted a preliminary experiment to validate our concept. The interface enables a tactile interaction without using physical contact with material devices, providing better freedom of movement and enhancing the interaction transparency.**

I. Introduction

Haptic rendering technologies are becoming a strategic component of the new Human-Computer Interfaces (HCI). Haptic interfaces stimulate users through tactile and kinesthetic channels to improve the interaction and immersion in teleoperated tasks or virtual environments [1]. Haptic technologies demonstrated their value in different application fields. The use of haptic feedback for robotic teleoperated minimally invasive surgery can significantly enhance a surgeon's accuracy, dexterity and visualization [2]. Haptic based Virtual Reality (VR) approaches have increased both speed and accuracy of human-computer interactions for the edition and the assembly of 3D Computer Aided Design (CAD) models [3]. In the field of rehabilitation, haptics plays an important role for the training of sensory motor skills and to alleviate the motor system impairments [4]. In education, games, and entertainment several studies have shown the role of haptics to improve the learning and the interactivity though the physical interaction with the content [5]. Despite the key role of haptic feedback in enhancing human computer interactions; the use of haptic devices in everyday and industrial applications is still limited. This is due to the intrusiveness and the limit of some performance factors of existing haptic devices. For example, haptic interfaces based on articulated robotic structures like exoskeletons [6], or cable systems [7] adopt devices that must be physically connected to the user through mechanical systems. These systems are often intrusive, limiting the comfort and the transparency of interaction.

Mohamed Yassine Tsalamlal, Paul Issartel, and Mehdi Ammi are with LIMSI/CNRS and the University of Paris-South, Bâtiments 508, 502bis & 512 Rue John von Neumann Université Paris-Sud 91403 Orsay, France (e-mail: first_name.last_name@ limsi.fr).

Nizar Ouarti is with ISIR/CNRS, University of Pierre and Marie Curie, Pyramide - Tour 55 4 Place Jussieu 75005 Paris - France (e-mail: first_name.last_name@isir.upmc.fr).

In this research, we introduce the concept and first design stages of a novel non-intrusive haptic interface based on direct air jet tactile stimulation. The interface named HAIR enables a tactile interaction without using physical contact with material devices, providing better freedom of movement and enhancing interaction transparency. This paper is structured as follow: In section II, we first highlight studies and new actuation technologies that address workspace and intrusiveness constraints. The section III presents the concept of the proposed tactile stimulation approach. In section IV, V, VI, and VII we detail the different parts of the prototype device. Finally in section VIII we present a preliminary user experimental study to evaluate some performances of the proposed haptic device.

II. Related work

Several works have address the intrusiveness contains of existing haptic devices [8]. The most promising approach does not require contacts with material devices. This approach can be classified into two different strategies.

The first strategy is based on acoustic radiations [9]. It consists in the control of the phase delays of acoustic waves to generate a focal point. This strategy provides a tactile feedback in 3D environments without physical contact with transductions. The main drawback of this strategy is the low intensity of generated force (Maximum force of 160mN). Moreover, the authors highlighted some potential medical risks for interactions with sensitive regions (e.g., head and face).

The second strategy consists in the use of air based stimulations. The first work proposed to use multiple air jets arranged in a matrix. These jets hit an air receiver, kept by the user, in order to apply a force on the user's hand [10]. This strategy generates a kinesthetic feedback with important force intensity. However, it provides poor force and position resolutions. Moreover, the user needs to handle an end-effector in order to interact with the air jets. Thereafter, Inoue et al. [11] proposed to use a flexible sheet driven by an air jet. This approach provides a virtual haptic sensation of lumps under the user's fingers. The main handicap of this method is that the flexible sheet is fixed and cannot move to enable a free exploration. For a free exploration and interaction, Romano and Kuchenbecker [12] proposed the AirWand device. The device is based on two air jets aligned along the longitudinal axis of the tool, comprising two air outlets. These two jets are used to create driving forces along the longitudinal axis in the positive and negative directions. The combination of three actuating axes enables the free interaction in a large working area but the resolution of the force is still limited. Finally, Bianchi et al. [13] proposed to use the air jet for the direct tactile stimulation. It consists to direct a thin stream of air on the finger pad. This work was limited to a distance of 2 cm. This system was designed for palpation using robot-assisted minimally invasive surgery (RMIS). This stimulation configuration (i.e., stimulation at 2 cm) greatly restricts the movement of the user and does not allow a free exploration of 3D environments. Recently, Disney research proposed the AIRAL device [14]. It consists to use toroid vortices that can travel large distances, to stimulate skin. Moreover, they proposed an efficient tilt pan system to control the orientation of the vortices generation. The main constraint of this approach concerns the discontinuity of stimulation. In fact, the device cannot provide continuous air tactile stimulation.

It is clear that air based stimulation strategy is a very promising approach to address intrusiveness contains of actual haptic devices. However, existing works exploit either intermediate object for interaction with air jets (i.e., air receiver), or exploit very short air jet stimulation distances, restricting the user's workspace, and devices that use air vortexes cannot provide continuous tactile stimulation witch is necessary for the continuous perception of data.

III. CONCEPT & PROTOTYPING DESIGN STAGES

In order to provide a continuous position and force tactile stimulation in the free space without handling or wearing any material device, we propose a new actuation technology based on the relevant features of the air jet tactile stimulation. The proposed concept consists on providing air jet tactile stimulation according to the movement of the user and the features of the interaction data. This approach uses long distance and continuous stimulation, addressing the limitations of actual air based interfaces.

The proposed device is based on combining an air jet, used on a suitable distance that provides the best compromises between flow features (i.e., level of turbulences, flow rate intensity), with a robotic structure for the positioning and the orientation of the stimulus according to the relative configuration of the displayed data (see figure 1).

The designed prototype includes three main components: 1) the air jet system to control the flow features; 2) the robotic structure to control the position and the orientation of the air jet; and 3) the computer vision system to track the region on the body to stimulate (e.g., hand, forearm).

The air jet tactile stimulation represents the central part of the proposed haptic device. The first step, it is to study and identify the different configurations of stimulation and the design of an air jet system.

The second step is the design and the implementation of the robotic platform to enable the positioning and orientation of the air jet in the 3D space. This task includes the study and development of the mechanical structure, the characterization and the integration of the actuators components, and the development of the control laws according to the required behaviors and involved constrains.

To simplify the implementation of the first prototype, the current version only supports 2D horizontal movements (X and Z axes) for the air jet. Moreover, the orientation of the air jet is fixed vertically (Y axes). We plan to include the additional Degree of Freedom (DoF) in next versions to support the 3D positioning and the orientation of the air jet.

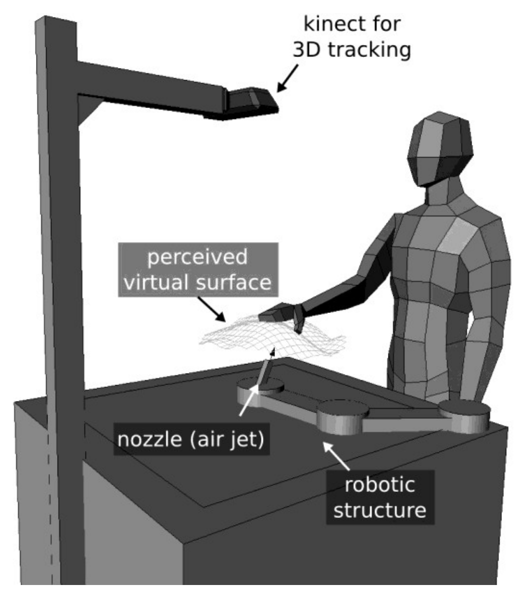


Figure 1. Interface design concept

To simplify the implementation of the first prototype, the current version only supports 2D horizontal movements (X and Z axes) for the air jet. Moreover, the orientation of the air jet is fixed vertically (Y axes). We plan to include the additional Degree of Freedom (DoF) in next versions to support the 3D positioning and the orientation of the air jet.

For this first prototype we decided to focus on tracking and stimulating the users hand palm, we developed a computer vision system that uses both color and depth information of the scene to detect the position the hand in 3D space. Although the robotic structure moves in 2D space, it is possible to modulate the tactile stimulation according to the distance from the air jet system to provide tactile feedback in 3D space. The color and depth information are computed by a kinect device placed above the user.

The last step was the implantation of a global software framework to provide a flexible access to the different levels of control and information of the haptic interface. We also designed some applications to study the usability of the proposed haptic device for the interaction with various types of environments (dataset exploration, perception of surface, etc.).

The design of the different parts of the device is detailed in the next flowing sections.

IV. AIR JET STIMULATION

A. *Dynamic modelling of air jet flow*

The design of the air jet tactile stimulation must respond to a number of constraints. In fact, it has to enable long distance tactile stimulation while providing the adequate applied force. A theoretical study was necessary to understand the air jet dynamics and characteristics. This should lead to an efficient design of air jet stimulation and address the mentioned constraints. The free air jet has been widely studied with different configurations. This is mainly due to the high number of parameters that affect the aerodynamic of the air jet. In fact, the system is affected by many factors [15], including the shape of the nozzle, the initial rate of turbulence of the jet (i.e., Reynolds number)…

Gauntner et al. [16] highlighted that the free round air jet is characterized by two different flow regions. The potential core region and the free jet region (see figure 2). These regions are related to centerline velocity of the jet.

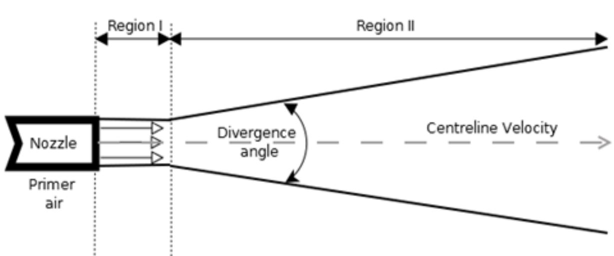


Figure 2. Free air jet flow regions

Region 1: Corresponds to a short zone (potential core) where centerline velocity U_x at a distance x from the outlet is equal to outlet velocity U_0.

$$U_x \simeq U_0 \tag{1}$$

The region 1 presents the best air jet features, but it provides a very short stimulation distance which could constraint the user movements. Moreover, it covers a small area limiting the surface of stimulation. This may not be suitable for some applications requiring greater stimulation area (e.g., hand palm).

Region 2: Corresponds to the full air jet development zone. The centerline velocity of the jet in region 2 can be calculated from an equation based on the principle of momentum conservation along the jet (2).

$$\frac{U_0}{U_x} = K \frac{D}{x - x_p} \tag{2}$$

Where x_p corresponds to the end of the potential core zone (region 1), D corresponds to the outlet diameter, and K is the decay constant coefficient. The K value is an important factor for describing jet performance. x_p and K value is usually calculated by measuring mean velocities in different centerline positions of the air jet.

Obviously, to measure theses velocities it is necessary to perform tedious experimental studies.

Velocity distribution in the cross-section of a jet in the region of fully developed jet follows a general trend of the Gaussian distribution

$$\frac{U_y}{U_x} = exp(-\frac{y^2}{2\sigma}). \tag{3}$$

Where y is the trasverse distance from the centerline or axis and σ the root-mean-square-deviation.

Region 2 presents intermediate features. In fact, it corresponds to a longer distance region 1, which provides greater workspace allowing free users' movements. Besides, with an average flow rate, the velocity intensity is sufficient to provide high range of force stimulation intensity. Additionally, the contact zone is greater than region 1, because of the spreading effect, providing greater stimulation area. Yet, the end of region 2 corresponds to a highly turbulent flow, where the centerline velocity decreases rapidly.

This state of the art of air jet flow permits to understand its dynamics and features. To provide a relevant haptic rendering, we propose to exploit region 2 for tactile stimulation. However, it is necessary to perform empirical studies to the physical features of the air jet. In fact, it is not possible evaluate the jet characteristics (like the regions length) from theoretical models due to the large number of influencing factors. These empirical studies should be addressed in our future works.

The next step of our design is to develop the air jet system for the haptic device and identify its features.

A. *Air jet system & Physical features*

An air jet system is required for the generation of the air flow. In our implementation, this is based on three components. The air compressor, to generate the require working pressure; a mass flow controller which enables continuous control of the intensity and frequency of the air jet; the nozzle, which allows control of some flow features such air jet diffusion envelope.

The nozzle is supplied by air through a flexible tube with a 6 mm diameter. An air compressor provides sufficient air pressure (4 bars) and continuous air flow. The flow rate is accurately controlled (up to 50L/min ±0.02) using an industrial mass flow controller (MFC Burkert 8711). In this device the flow rate value measured by a sensor is compared by the integrated electronic controller with the digital set value. If a difference is detected, the control applied to the proportional valve is changed by using a PI control algorithm. The flow rate can be maintained at a fixed value or be assigned to a profile, regardless of variations in pressure or changes in the system.

To provide an accurate resolution of air jet tactile stimulation, we need to generate a concentrated air jet. The choice of the nozzle shape is a key parameter. In fact there is a direct relationship between this parameter and the diffusion angle of the jet [17]. Several types of nozzles were examined and tested. The adopted nozzle (SILVENT MJ4) is made of stainless steel with a central hole surrounded by slots to generate a concentrated air stream while limiting the sound level. Its small dimensions make this nozzle suitable for incorporation into the device.

Ideally, the impinging force and the diameter of the jet envelope would be determined using models of fluid mechanics. Although, an accurate model is difficult to obtain since the system is affected by many factors [15], including the outlet geometry (e.g., shape, size), the type of air flow (e.g., laminar, turbulent), pressure losses due to friction along the length of the tubing, air temperature etc. In this study we propose to use empirical models determined using the datasheet of the nozzle.

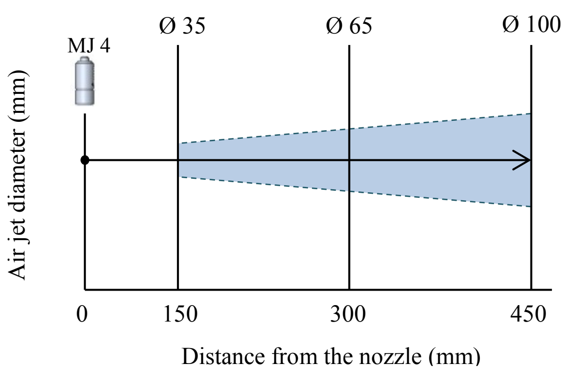
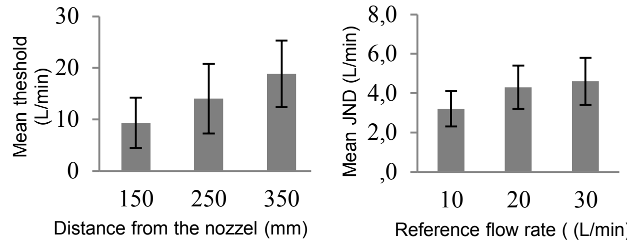


Figure 3. Air jet envolope

The technical specifications provide information about the jet flow including the blowing force (F) in Newton according to the flow rate (Q) in L/min, and the jet diameter (Ø) in millimeter as a function of distance (x) in millimeter (Figure 3). According to the datasheet, these two relationships, present a linear profile in a distance range [150;450] mm and flow rate range [23.3;135] L/min:

$$F = 0.012Q + 0.082 \tag{4}$$



$$\phi = 0.215x + 1.561 \tag{5}$$

B. *Air jet perception features*

Beyond the physical features of the air jet, it is necessary to characterize the perception of users of the air jet tactile stimulation. We performed a quantitative study of human tactile perception, examining the relationship between the observed quantifiable physical stimuli and users responses [18]. The study of tactile perception involved two types of measurements: determining the absolute threshold and the differential threshold. Absolute threshold measurement is performed by detecting the presence of a stimulus. This value corresponds to the minimum intensity at which the stimulus is just detectable. Moreover, it is important to determine the differential threshold. This threshold refers to the smallest change incremented or decremented in stimulus intensity that is detectable by the subjects. It is also known as the just noticeable difference (JND). The differential threshold is measured according to a reference stimulus; it must be presented in relation to this reference value. Both of the absolute and differential thresholds can be measured by similar experimental procedures. The details of experimental method used in the experiments can be found in [18].

Results (see figure 4) revealed that there is a linear relationship between the perceived absolute threshold and the distance from the hand palm to the nozzle.

Figure 4. Psychophysical featrues

The second psychophysical experiment was made to determinate the just noticeable difference of the air flow rate according to three referential stimuli. Then we estimated the Weber fraction. These two results are important for the display control of the air jet tactile stimulation. Indeed, these features allowed to identify the optimal stimulation configuration (distance, applied tactile stimulus, etc.).

V. TRACKING SYSTEM

The tracking system allows the monitoring of the user's hand position. The system is based on a kinect sensor placed above the workspace. The Kinect provides a depth map of the scene. With this information, it is possible to determine the position and orientation of the hand in three axes. The main reason for choosing the Kinect sensor for this project is it's relatively low cost. Despite of some limitations, in particular the quality of depth image, the sensor is cheap and efficient for the design of a prototype. Today many computer vision projects are based on the Kinect sensor. However, Most of these works deal with 3D reconstruction [19], obstacle avoidance [20] and monitoring of entire silhouettes [21]. Some studies deal with the hand tracking only in the image. It is often the position of the fingers is sought [22]. However, none of these projects meet the needs and requirements of our system. Therefore, it was necessary to design a tracking algorithm suitable for the application.

To simplify the tracking algorithm, a certain number of constraints have been adopted. The workspace is placed in the working range of the kinect. Only the arm and hand may enter a defined workspace. The palm of the hand is facing downwards. The fingers have to be tight (only the thumb can be removed); the inclination of the hand relative to the working plane must be less than 45°. The tracking system uses the OpenCV library specializing in the analysis of real-time images.

VI. ROBOTIC STRUCTURE

A. Mechanical Structure

The robotic structure moves the end-effector (i.e., nozzle) according the user's actions and the features of perceived data. The design of the robotic structure must consider different constraints. The available working space must be suitable and sufficient. For some applications the end-effector must follow the movement of the user's hand. To limit the risks of contact between the mechanical structure and the user, we propose to separate the space reachable by the robotic structure and the working space of the user. The main movement of the end-effector corresponds to a horizontal translation (2 DoF) to follow the movement of the hand. For the first prototype, we adopted a serial mechanical structure with three rotoid joints. This configuration addresses the constraints mentioned above, and is relatively simple to implement (see figure 6). Considering that our first approach is consisting on designing a prototype to validate the proposed stimulation strategy. Simplicity feasibility and material cost constitute important criteria. To design the prototype we used a robotic kit [23]. This solution was chosen for the simplicity of the assembly of mechanical components and the control of actuators.

B. Robot control method

The robot end-effector (i.e., nozzle) has to move according to the user's actions. For example, the nozzle tracks and stimulates the users hand palm. We propose to implement a position control. The control loop of the end-effector is represented in the figure 5. The robot is positioned using individual movement of the joints which are described by the vector of joint variables (θ). Since we know the length of the different axes of the manipulator and the operational variables that we want to target (X), we can calculate the values of the corresponding joint variables(θ) [24] [25] [26].

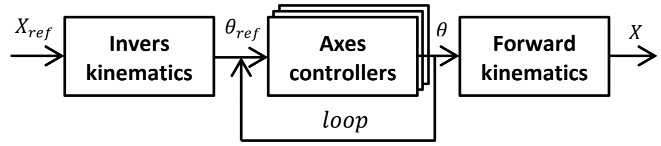


Figure 5. Robot control loop

We used the Jacobian Pseudoinverse matrix to J^* calculate the θ vector [27]. This algorithm provides a relationship between a small ΔX movement $\Delta\theta$ of the end effector and a small change in posture, as in

$$\Delta\theta = J^* \, \Delta X. \tag{6}$$

The different positions of the articulations are computed on a host PC and sent to the servomotors through a control board based on the Atmel386 microcontroller.

VII. GLOBAL PLATFORM

The global platform consists on assembling the three systems and the design of the software framework. First the nozzle of the air jet system is coupled to the robotic arm. The structure is fixed on a table that represents surface the work space. The Kinect sensor must be above the hand of the user, so it is attached to metallic support at 1m height (see figure 6).

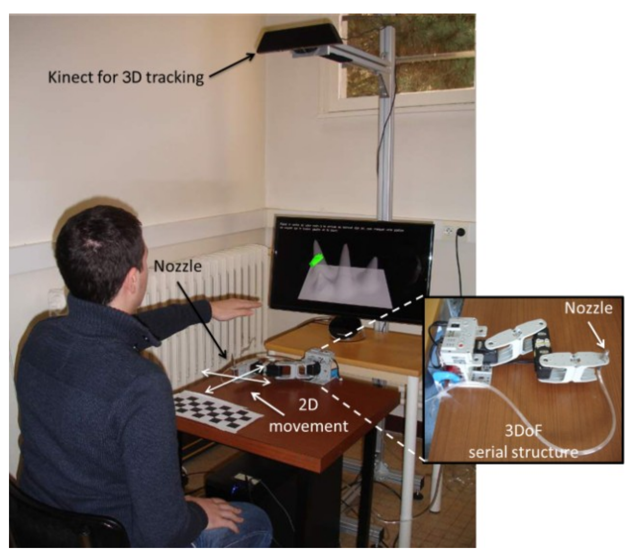


Figure 6. Haptic drvice prototype

We have developed a software Framework in C++ to control the device. The software interface provides access to two levels of control: the first concerns the high input / output level functions. This mode allows the implementation of high-level haptic features, such as generating haptic surfaces with a simple description of plane coordinates. The second level provides functions of input / output low-level, such as controlling the position of the end effector or rate of the jet according the user movements.

VIII. EVALUATION EXPERIMENT

We performed a preliminary user experiment to compare the some performances of the air jet tactile device with two other haptic devices. The first device is the CyberGlove, a wearable vibrotactile device [28]. The second device is the Phantom Omni, a desktop force feedback interface [29].

We designed a target detection task and measured mean duration and path length. Seven participants took part to the experiment. The task was to detect five invisible spheres of 5 cm diameter on a virtual surface using. The spheres were placed in random position on a surface of (20 × 20) cm. Each participant used the three devices. The devices have the same physical metric scale. When the hand of the user touches a virtual sphere, he receives a haptic stimulation. The HAIR stimulates the users hand palm with an air jet. The CyberGlove stimulate the user with the vibrotactile actuator on his hand palm. Finally the participants held the tool of the Phantom and receive vibration when they touch a sphere.

A training stage was performed by the subject with a visible sphere and the representation of the user's hand in 3D (see figure 7). Then, the proper experiment can begin with the random invisible sphere but with a representation of the user's hand still visible. The three conditions (Air jet, CyberGlove, Phantom) were presented randomly.

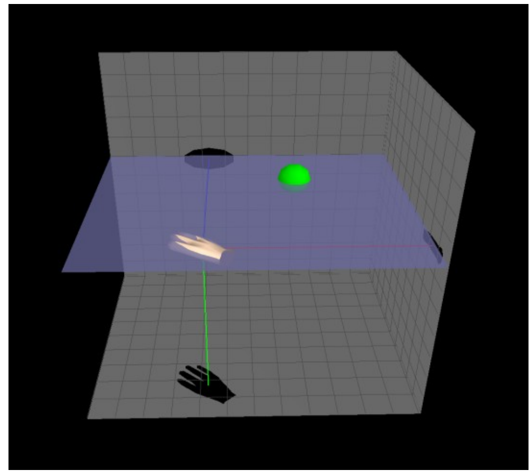


Figure 7. Graphic interface of the experiment. The green ball represents the target to reach and the 3D hand represents the hand of the user. These two objects are in the same 2D plane (in blue). The shadows of the objects are represented to help the user to move properly. In the training stage, the sphere is represented in green but in the experiment it is invisible.

For the three configurations, we measured the duration to reach each target, the path length covered by the hand of the participant to find a target. Mean results of the experiment are reported in figure 8.

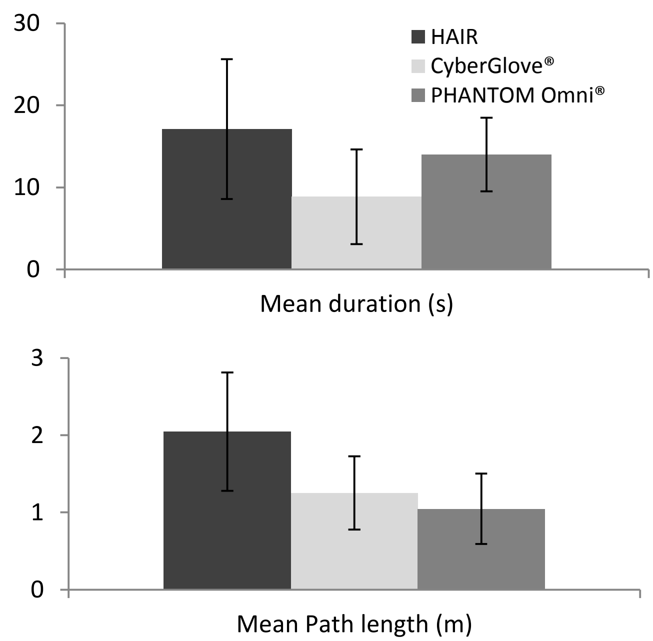


Figure 8. Performences results

We performed a repeated measure ANOVA analyses to highlight if there is any significant differences. The analyses showed significant (p=0.012) differences in duration between the three devices. Post-Hoc pairwise analyses showed that participants take more time to find the target using the air jet device then using the CyberGlove (p=0.02). But, there is no significant difference between the HAIR device and the Phantom. The analyses also reveal that there were significant differences (p=0.02) between the three devices in the path length covered by the hand of the participants. Post-Hoc pairwise analyses showed that participants needed a longer path length to reach the targets using the HAIR device then the CyberGlove and the Phantom (respectively: p=0.004; p=0.013). The difference of performances of the HAIR interface can be related to the dynamics of the robotic arm of the device. In fact, as explained in section VI, the device is designed with a low quality robotic kit. Also, the CyberGlove and the Phantom are attached to the hand of the user witch permits higher max acceleration and velocity amplitudes. These results seem to be promising. We can say that air jet device have comparable performances with the two different other haptic devices, even it still remains at a prototyping stage.

IX. Conclusion and Outlook

This paper proposes a new non-intrusive haptic interface based on air jet tactile stimulation. The proposed concept consists on stimulating the user with an air jet according to his actions and the rendering data. The device is based on combining three main parts: a computer vision system, an air jet system, and a robotic system.

In this paper we presented a first prototype that allows a user to interact with virtual objects projected on a 3D scene. The proposed haptic interface provides an alternative to the use of intrusive mechanical systems. The device offers continuous haptic stimulation, and provides greater transparency of haptic rendering, while providing the user with a secure operating environment.

The next step consists on the design of a more efficient robotic system. We plan to study another robot configuration like planer systems. This should enhance the tracking characteristics (i.e. acceleration, max speed, position accuracy). We also we manage to add three other DoF. This to allow control of the orientation of the nozzle (2 DoF) and distance (1 DoF) of the user's hand (to maintain a constant distance between the nozzle and the stimulated region).

We will also use tactile sensors to collect physical data like the pressure impact distribution according to the dynamics of the air jet. Stimulation time delay…etc. This will provide performance specifications for the air jet haptic display.

We started to investigate some application for the designed interface. The first application consists on the exploration of a 3D volumetric data. This type of application should support the needs of scientists who are exploring a volumetric dataset. We propose to uses the air jet tactile stimulation to explore a dataset in the field of fluid mechanics (i.e. Finite Time Lyapunov Exponent data). We evaluated the device with fluid mechanics experts and report on their qualitative feedback. They reported that this exploration technic seems to be promising. In fact, it provides a natural interaction with datasets and permits to rapidly identify targeted data. Another application is the use of the mobile air jet stimulation to communicate affective states [30]. The air jet stimulation permits to generate low amplitude forces, which might be more suitable than high amplitude forces for the stimulation of the mechanoreceptors involved in tactile affective perception.

References

[1] V. Hayward, O.R. Astley, M. Cruz-Hernandez, D. Grant, and G. Robles-De-La-Torre, “Haptic interfaces and devices,” *Sensor Review*, 2004.24:16–29.

[2] A.M. Okamura., “Methods for haptic feedback in teleoperated robot-assisted surgery,” In Rob, 2004, 31(6): 499–508.

[3] M. Bordegoni, U. Cugini, P. Belluco, and M. Aliverti, “Evolution of a haptic-based interaction system for virtual manual assembly,” *In Proceedings of the 3rd International Conference on Virtual and Mixed Reality*, Berlin, Heidelberg, (2009), pp. 303–312.

[4] J. Broeren, M. Georgsson, M. Rydmark, and K. Sunnerhagen, “Virtual reality in stroke rehabilitation with the assistance of haptics and telemedicine,” *Proc. 7th ICDVRAT with ArtAbilitation*, 2008, Portugal.

[5] O. Sourina, Q. Wang, and M. K., Nguyen “EEG-based Serious Games and Monitoring Tools for Pain Management,” In Proc. MMVR18, (2011), California, 8(12), pp. 606-610.

[6] A. Nakai, T. Ohashi, and H. Hashimoto, “7 dof arm type haptic interface for teleoperation and virtual reality systems,” *In Proceedings of IEEE/RSJ International Conference on Intelligent Robots and Systems,1998*, pp. 1266–1271.

[7] M. Ishii, Z. Tang, S. Hasegawa, and M. Sato. “Flat pointers for pick and place in virtual environments using spider,” *In Proceedings of Virtual Environments* 2009.

[8] M.Y. Tsalamlal, N. Ouarti, M. Ammi, “Non-intrusive Haptic Interfaces: State-of-the Art Survey,” *In Proceedings of Haptic and Audio Interaction Design, 2013*. pp. 1-9.

[9] T. Wamoto, M. Tatezono, H. Shinoda, “Non-Contact Method for Producing Tactile Sensation Using Airborne Ultrasound,” *In Ferre, M. (ed.) EuroHaptics 2008*. LNCS, vol. 5024, pp. 504–513.

[10] Y. Suzuki, M. Kobayashi, “Air jet driven force feedback in virtual reality,” *IEEE Computer Graphics and Applications*, 2005, 44–47.

[11] K. Inoue, F. Kato, S. Lee, “Haptic device using flexible sheet and air jet for presenting virtual lumps under skin,” *In: Proc. IEEE/RSJ Intl. Conference on Intelligent Robots and Systems*, (2009), pp. 1749–1754.

[12] J.M. Romano, K.J. Kuchenbecker, “The AirWand: Design and Characterization of a Large-Workspace Haptic Device,” *In Proceedings, IEEE International Conference on Robotics and Automation*, 2009, pp. 1461–1466.

[13] J.C. Gwilliam, M. Bianchi, L.K. Su, A.M. Okamura, “Characterization and Psychophysical Studies of an Air-Jet Lump Display,” *In IEEE Transactions on Haptics, 2011,* pp. 156 – 166.

[14] R. Sodhi, I. Poupyrev, M. Glisson, and A. Israr, AIREAL: Interactive Tactile Experiences in Free Air. In Proc. ACM SIGGRAPH (2013). Article No. 134.

[15] R. Stephane. “Aerothermal experimental contribution for an acoustically forced impinging air jet,” *PhD thesis*, university of Poitiers, Jun 2011.

[16] J.W. Gauntner, J.N.B. Livingwood, P. Hrycak, Survey of literature on flow characteristics of a single turbulent jet impinging on a flat plate, NASA TN D-5652, 1970.
[17] “Statistical Properties of Turbulent Free Jets Issuing from Nine Differently-Shaped Nozzles,” *In Flow, Turbulence and Combustion Volume 84, Issue 4* , 2010, pp. 583-606
[18] M.Y. Tsalamlal, N. Ouarti, and M. Ammi “Psychophysical study of air jet based tactile stimulation, *“In IEEE World Haptics Conference*, 2013, pp. 639-644.
[19] S. Izadi, D. Kim, O. Hilliges, D. Molyneaux, R. Newcombe, P. Kohli, J. Shotton, S. Hodges, D. Freeman, A. Davison et A. Fitzgibbon, “KinectFusion : real-time 3D reconstruction and interaction using a moving depth camera”, *Proceedings of the 24th annual ACM symposium on User interface software and technology,* 2011, pp59-568.
[20] V. Baltzinger, J. Derepper et Samuel Gosselin, “Integration of a Kinect on a Drone Platform,” Master dissertation Compiegne university of technology, 2011
[21] L. Xia, C. Chen, and J. K. Aggarwal, “Human Detection Using Depth Information by Kinect,” *International Workshop on Human Activity Understanding from 3D Data in conjunction with CVPR (HAU3D)*, 2011,pp.15 – 22.
[22] V. Frati, and D. Prattichizzo, *“Using Kinect for hand tracking and rendering in wearable haptics,”* Proc.World Haptics Conference (WHC), 2011, pp.317 – 321.
[23] Robotis bioloid Kit. http://www.robotis.com/xe/bioloid_en
[24] J. Korein and N. Balder, "Techniques for generating the goal-directed motion of articulated structures", IEEE Computer Graphics and Application, 1982, vol. 2, no. 9, pp. 71-81.
[25] A. Goldenberg, B. Benhabib, and R. G. Fenton “A Complete Generalized Solution to the Inverse Kinematics of Robots”, *IEEE Journal of Robotic and Automation*, RA-1, n°. 1, March 1985.
[26] L.-C.T Wang, C.C. Chen, “A Combined Optimization Method for Solving the Inverse Kinematics Problem of Mechanical Manipulators,”*IEEE Transactions on Robotics & Applications,* Vol. 7, No. 4, p.489-499, 1991.
[27] R. Penrose, “A Generalized Inverse for Matrix,” *Proc. Cambridge Phil,* 1955, 406-413.
[28] CyberGlove http://www.cyberglovesystems.com/
[29] Phantom Omni http://www.dentsable.com/haptic-phantom-omni.htm
[30] Tsalamlal, M. Y. and Ouarti, N. and Martin, J.C. and Ammi, M. “Perception of Emotions from Air Jet Based Tactile Stimulation, International,” *International Conference on Affective Computing and Intelligent Interaction (ACII 2013),* pp. 215-220.