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AIRVIS: AN AIR-BASED PHYSICAL VISUAL AND TACTILE DISPLAY

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Abstract. *Although air-properties have been used to provide tactile stimulation or air-based display, there is no existing air-based device that can provide physical visualization and tactile stimulation at the same time. AirVis is an air-based prototype which can levitate objects and generate non-contact tactile sensations simultaneously. It consists of an array of fan-motors to push objects into mid-air inside a transparent box and to generate air-tactile sensations simultaneously using air flow pressure. AirVis is able to levitate multiple adjacent objects to form simple geometric patterns and surfaces. Concurrently, AirVis allows users to recognize patterns constructed from air flow exiting from the top.*
Keywords: Air, Tactile display, Perception, Physical visualization

1. **Introduction.** Physical visualization can provide more engaging user experience; however, the main challenge for visualizing data using physical objects is representing changes in data dynamically. Although some works [1, 2, 3] tackled this limitation by using a matrix of actuated columns or acoustic levitation, touching a levitated object directly can disturb and occlude visual perception of the physical visualization. Thus, there is a need for tactile awareness without directly touching and disturbing the feedback with the user's hand. Some previous works provided non-contact tactile sensation by using air [4, 5, 6] and ultrasound [7, 8]. However, these devices are dedicated to generating non-contact tactile sensations only and they do not support this with direct visual feedback (i.e., physical visualization). In this paper, we present the suitability of air-properties to concurrently generate non-contact tactile sensations with dynamic physical visualization which together comprise our *AirVis*: an air-based physical visual and tactile display (Figure 1). Furthermore, we conducted a user study to evaluate the effectiveness of *AirVis*.

2. **Related Work.** Our work focused on developing a device that can concurrently provide (1) physical visualization, and (2) non-contact tactile sensation, where the non-contact tactile sensation delivers a multi-point representation of the pattern of the physical visualization.

One challenge of using air to provide multipoint sensation is that air tends to spread around, and thus we need to find ways to focus the air on providing a consistent tactile sensation. A single air source like that in Air Jet [6] or Aireal [5] would not apply to this case. Our solution is to represent each air source as one pixel, similar to the concept used in inForm [1] where a matrix of individually manipulable columns are used to represent different 3D information dynamically.

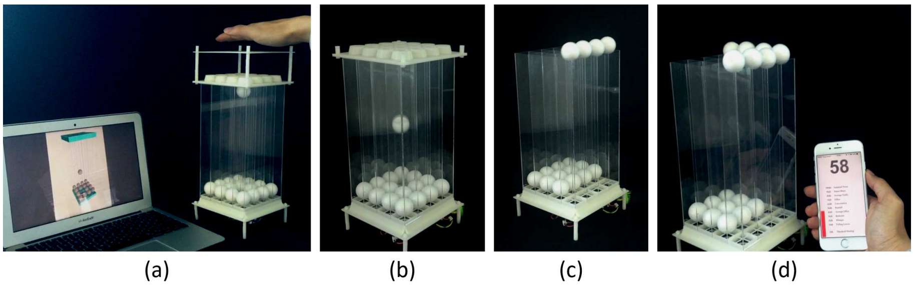

FIGURE 1. The *AirVis* prototype: (a) user's hand feeling air-tactile sensation from the top of the device, (b,c) balls levitated as visual display, (d) fan-motor noise around 58 decibels (dB)

Ultrasound is able to provide either physical visualization [2, 3] or non-contact tactile feedback [7, 8]. However, the core limitation of ultrasound is that the same array of ultrasound cannot concurrently provide both physical visualization and non-contact tactile feedback.

For concurrent visual feedback and tactile sensation, air is a promising method. To allow tactile sensation without occluding the physical visualization, a common approach is to provide the sensation in mid-air, separated from the visualization. For example, aerial tunes [9] levitate a light-weight ball in mid-air using a stream of air flow enabling users to interact with the levitated ball. However, these devices are limited to only one object with a single point of tactile sensation, and thus, it cannot represent 3D data. Our work will fill this gap.

3. **AirVis.** AirVis is designed to levitate objects and generate air-tactile sensations concurrently using air flow. Figure 2 shows that *AirVis* consists of arrays of transparent boxes/bodies with a light-weight ball inside each of the boxes. Array of fan-motors positioned at the bottom of the transparent bodies generates air flow upward to push and levitate the balls. At the same time, the air flow that levitates the balls can be felt as a soft tactile sensation from top of the transparent bodies.

3.1. **Hardware specification.** Figure 2(a) shows a diagram of circuitry for the *AirVis*. *AirVis* consists of sixteen 25×25 mm^2 fan-motors in a 4×4 array with a specification of 5v, 0.21A, and 2000 rpm each. All of the circuits and fan-motors are driven by a 5v, 10A switching power supply. The complete prototype of *AirVis* is shown in Figure 2(b). Figure 2(c) shows the working scheme of *AirVis*, where *AirVis* consists of a fan-motor array at the bottom of the transparent box (body) which generates air flow to levitate balls and provides touch sensation from the top of the box.

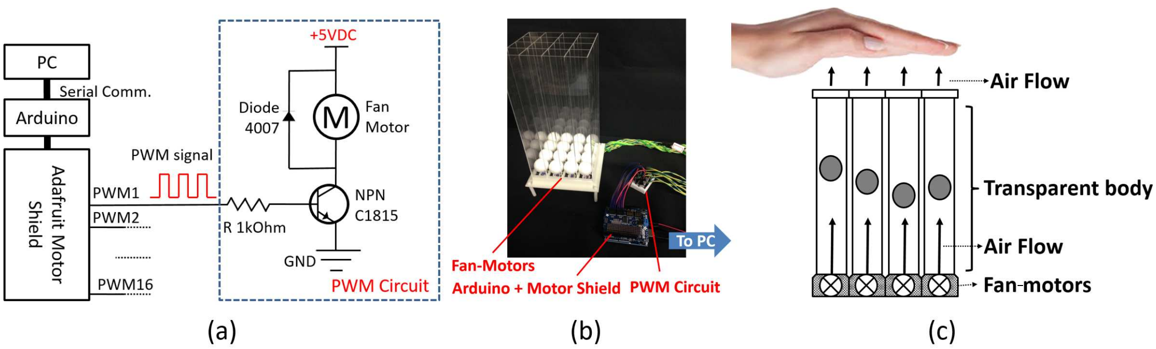

FIGURE 2. (a) Electronic circuitry of *AirVis*, (b) *AirVis* prototype and controller, (c) *AirVis* work scheme

The Arduino Uno microcontroller receives patterns and location information for each fan-motor from a PC via serial communication. Adafruit Motor shield translates the information into pulse-width modulation (PWM) signals and sends the signal to all the fan-motors through the PWM circuits. The prototype allows the control of an individual ball or a group of balls forming a pattern using a keyboard or mouse. Each PWM circuit consists of an NPN transistor (C1815), a $1k\Omega$, and a diode (N4007). This circuit enables the control of motor speed by PWM (duty cycle of a square wave). An N4007 flyback diode is added to protect the circuit from inductive current that may occur when the motor is stopped.

The *AirVis* prototype uses light-weight balls to construct the physical visualization. In pilot studies, different sized balls (diameter of 13, 15, 18, and 20 mm) and different sized transparent body tubes (18×18 and 25×25 mm^2) were tested. The balls weighed 1.04, 1.60, 2.76, and 3.79 g respectively. Identical fan-motors were used for all tests. Pilot studies showed that increasing the ball size required an increase in the power needed to levitate the ball. It is recommended to use a ball that has a diameter similar to the size of the transparent body inner diameter, with less than 6 mm and more than 2-3 mm in difference. The larger diameter of the tube permits air to flow around the ball causing it to spin quickly and create turbulence inside the tube, making it difficult to levitate the ball. Conversely, if the difference in diameter is very small (less than 2 mm) or the ball fits too tightly inside the transparent tube, the ball will touch the inner wall of the tube adding resistance to the air flow that levitates the ball. Based on pilot studies, *AirVis* is constructed using arrays of balls with 20 mm diameter and transparent tubular bodies which are 200 mm in height with a 25 mm inner diameter following the diameter of the fan-motors to minimize air flow leakage.

3.2. **Air flow force.** The air-tactile sensation is closely related to air flow force that exits from the top of *AirVis* (Figure 2(c)). To understand how strong the emitted air flow force is, measurements of air flow force were conducted using a digital weight scale with 10^{-3} gram precision. *AirVis* was set upside down and perpendicular to the weight scale. A smaller version of *AirVis* (2×2 pixels) was used, as it was easier to hold it upside down. The distance between weight scale and *AirVis* can be adjusted to measure the effect of different distance to the air flow force.

Without properly focusing the air, air will be increasingly dispersed from the top of *AirVis* and the air flow force will decline. Therefore, several nozzles with different heights and angles (Figure 3(a) and Figure 3(b)) were developed to focus the air flow force and

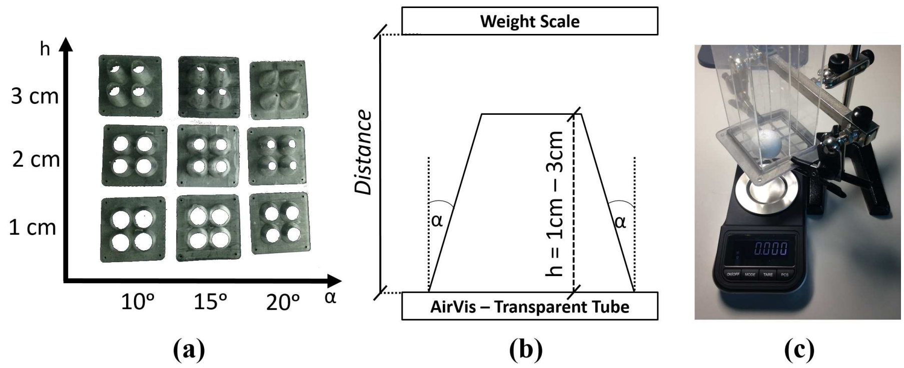

FIGURE 3. Nozzle effect test: (a) various nozzle with different heights and angles, (b) illustration of nozzle dimension with h = nozzle height and α = nozzle angle, and (c) air flow force measurement setup (*AirVis* is put upside down and perpendicular to digital scale, with changeable distance)

TABLE 1. Effect of nozzles to air flow force from multiple distances (Dis)

$Dis(cm)$	NT	T	T, 3, 20	T, 3, 15	T, 3, 10	T, 2, 20	T, 2, 15	T, 2, 10	T, 1, 20	T, 1, 15	T, 1, 10
3	67.375	229	N.A.	N.A.	N.A.	113.75	133	87	159	155.5	151.5
5	20.25	197.125	7	73	126.25	124.375	146	120	162.375	162.5	164.25
7	12.875	187.875	7.5	77	134	128.5	133.25	121.5	158.875	163.625	167.25
9	4.75	130.25	8.75	75.75	136	115.25	129.5	109.625	134.75	140.75	146.75
11	0	109.875	2	67.375	131.5	88	114.125	105.125	104.25	113.25	120.75
13	0	96.5	0	61.375	118	79.625	118.75	72.75	91.875	102.75	113
15	0	81.25	0	55	101.625	46.75	88.875	68.75	81.25	88.875	97.125

Measured using digital scale in 10^{-3} gram precision. (NT = No transparent tube, T = with transparent tube attached. T, h, α = with transparent tube, nozzle height(h), nozzle angle(α))

enhance the tactile sensation. The measurement was done on one pixel only as can be seen in Figure 3(c).

Table 1 shows the measurement results of air flow force in multiple conditions. No tube (NT) and with tube (T) conditions were conducted to investigate the effect of transparent tube to air flow force. Subjectively, tactile sensations for both NT and T conditions were similar. However, measurements show that the transparent body/tube of *AirVis* is important not only as the container for the levitated ball, but also to enhance the air flow force. As for the air flow force with the nozzle, the nozzle with a 1 cm height and 10° angle has the best overall air flow force for distances from 3 to 15 cm. Although air flow force with the nozzle is slightly lower for short distances compared to the non-nozzle condition, air-tactile sensations with nozzle are better compared to the non-nozzle condition. Therefore, we used this nozzle for the user study in the following section.

3.3. **Ball movement.** The individual ball position is controlled by the amount of force and the duration the ball is pushed by the air flow from the fan-motor. In this prototype, a fixed force of air is used to lift the ball, i.e., the maximum force of the fan. Thus, the ball position can be controlled by simply varying the duration. Levitating balls to form various patterns by varying the force duration is limited because the balls need to be reset before each pattern is formed (i.e., balls need to return to the bottom, and the fans are turned off) before forming each different pattern.

Figure 4 shows the average ball position over time, with two regression lines (linear and quadratic). The relation between ball position and the applied time of air flow was investigated through the measurement of the ball position every 10 ms using an ultrasound ranging module HC-SR04 which was placed 10 cm from the top of the *AirVis* while the

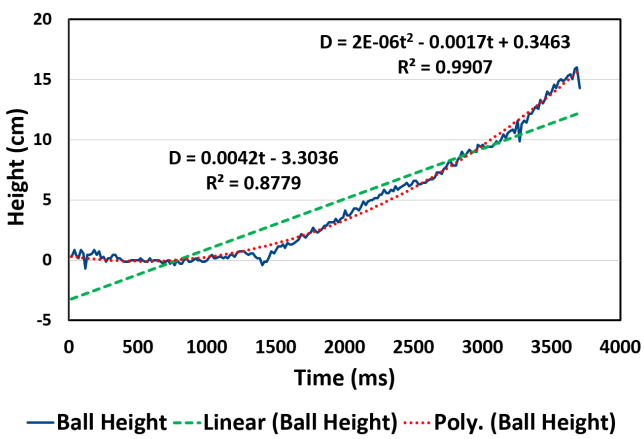

FIGURE 4. Measured average height of the ball (cm) over time (ms) with two regression lines (linear and quadratic)

maximum air flow force was applied to the ball from the fan-motor. This procedure was repeated six times to better validate the measurement data. Based on the regression equation shown in Figure 4, around 3 seconds is required to levitate the ball at 10 cm high which is half the height of *AirVis*. Theoretically, in ideal conditions with unlimited body height and unlimited time, the ball could travel high indefinitely; however, this is not the case for *AirVis*. The equation for ball height over time is strictly limited to our prototype with a 20 cm tall transparent body. Thus, the ball will stop at a maximum height of 20 cm.

4. **User Study on Effect of Visual Condition on Users' Air-Haptic Perception.** The user study was conducted to investigate: 1) user perception of a single-point air-tactile sensation and also of multi-point air-tactile sensation and 2) the effect of different visual condition modes on user air-tactile perception.

4.1. **Design.** We tested the users perceived air-tactile perception in association with three different visual conditions. Figure 5 shows the illustration of the experimental conditions: (5a) The user wears a Headphone for noise canceling and the hand is supported by a structure in the no-visual cue condition (no ball and no monitor), (5b) a list of shapes was used in the user studies (12 different patterns consisting of 8 simple lines, 2 composite lines, and 2 diagonal lines), (5c) the tactile-only condition, no-visual cue (NV), (5d) tactile with computer graphic (CG) on monitor as the visual cue (VM), and (5e) tactile with levitated balls as the visual cue (VB). The three conditions were conducted in a counter-balanced manner using a Latin square method. Air-tactile sensations were produced from 16 fan-motors that were positioned in an equally spaced 4×4 grid at the bottom of the box. Two kinds of air-tactile sensations were presented: single-point (16 different points) and multi-point tactile sensation (12 patterns). The prototype was positioned perpendicular to the participants' palm at a given distance. This configuration was chosen to ensure that the palm was kept at a static distance relative to the device. The distance between the top of the prototype and the participants' hand could be modified according to the experimental conditions. Three distances of 3, 5, and 7 cm were tested in all the conditions. Each of 12 patterns was presented in random order and repeated twice. The total number of trials that each participant performed was 3 *Conditions* $\times 3$ *Distances* $\times$ (16 positions + 12 patterns) $\times 2$ repetitions totaling 504 trials. The independent variables for the study were: distance (3, 5, 7 cm), fan position (16 positions) for the single-point mode and pattern (12 patterns) for the multiple-point mode. The dependent variables were: detection (if the air-tactile sensation was detected), accuracy (whether the users can tell correctly the position or pattern given), and perception level (how well the tactile sensation was perceived).

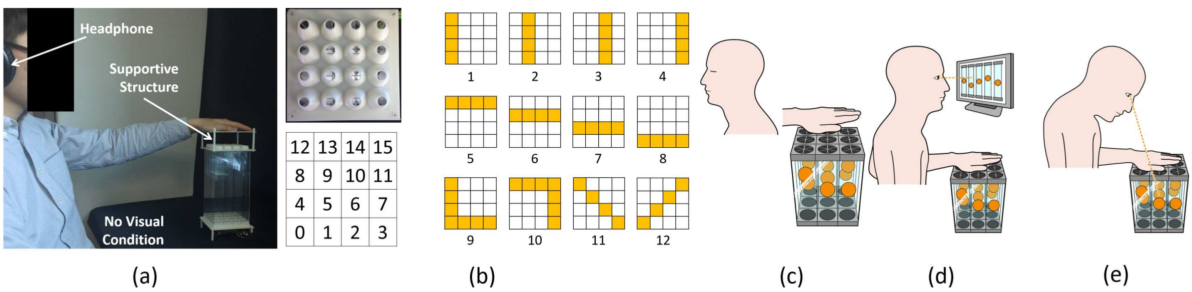

Figure 5. Illustration of experimental conditions

4.2. **Participant.** Twelve university students were recruited as participants, eight males, aged 21 to 28 ($M = 24.4$, $SD = 2.4$). One participant was left-handed and the others were right-handed. Each was paid US$10. All participants knew and had experience with normal tactile feedback (e.g., smartphone touch vibration) but none had previous experience with non-contact tactile devices.

4.3. **Procedure.** Participants were first told how the device works, the purpose of the experiment, and the experimental procedure. They were then required to fill in their demographic information and their experience with tactile devices. To become familiar with the prototype, participants were allowed to feel several different air-tactile sensation intensities and patterns with all three conditions freely. For each of the three conditions, the participants were asked to place themselves in front of the desk and to place one of their dominant hands on the supporting structure and wear noise canceling headphones. For all three conditions, the participants were required to give their subjective perception level on a 7-point Likert scale. This was repeated until all 16 single tubes and all 12 patterns had been presented. Participants could take a rest whenever they felt tired. After completing the trials, participants were interviewed and required to complete a questionnaire about their tactile sensation and general impression of *AirVis*. The entire experiment took approximately 2 hours in total (around 35 minutes for each condition, a 10-minute interview and questionnaire, 5 minutes' rest).

4.4. **Results.** The data of interest were *stimulus detection*, *accuracy*, *perception quality*, and *subjective evaluation*. Stimulus detection was measured by the percentage of air flow that participants claim to recognize as the tactile sensation. Accuracy was the percentage of correct answers given by the participants regarding which tactile pattern was given to them. Perception quality was measured by the participants' subjective evaluation of how clear the tactile sensation was. User evaluation was measured by the participants' subjective evaluation as a tactile device and subjective opinions about their performance during the experiment.

4.4.1. *Stimulus detection.* Results show that participants can detect all the air tactile stimulus given for all experimental conditions with different modes of visual conditions and hand position distances, i.e., the air tactile stimulus was strong enough to be detected and recognized clearly by all participants.

4.4.2. *Accuracy.* Participants identified the tactile stimuli with 89.02% accuracy on average. The data were analyzed using repeated measures ANOVA. The detection accuracy was significantly high when the hand distance was 3 cm with the mean of 93.49% for single point detection and 94.14% for pattern detection. Post-hoc comparisons with Bonferroni correction confirmed that increasing the hand distance from 3 cm to 5 cm significantly reduced detection accuracy to 89.61% and 87.31% for both conditions. Further increments in hand distance to 7 cm reduced the accuracy from 84.81% to 84.78% for single and pattern perception respectively. There was no significant difference in detection accuracy between single point and multi-point perception.

4.4.3. *Perception quality.* Perception quality for all conditions was measured. The data were measured in a 7-point Likert scale, then analyzed using repeated measures ANOVA tests. Figure 6(a) shows the summary of perception for all conditions in percentage values. The perception quality of VB condition showed a mean value of 6.659, while perception values for VM and NV conditions were 6.100 and 5.349, respectively. Post hoc comparisons with Bonferroni corrections confirmed a significant difference between NV and VM ($p < 0.001$), NV and VB ($p < 0.001$), and VM and VB ($p < 0.001$). However, there were no significant differences in perception between a single point and multi-point (pattern) air-tactile stimuli with mean perception values of 6.036 and 6.161 for single point

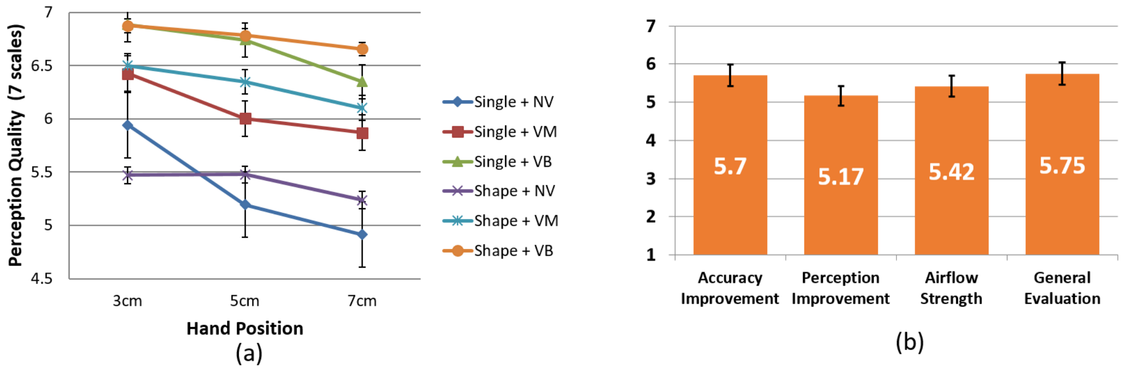

Figure 6. (a) Summary of the effect of distance to the user's tactile perception, (b) summary of user evaluation

and multi-point respectively. There were no significant differences when the hand distance was increased from 3 cm to 5 cm ($M = 6.349$ and 6.092), however there was a significant difference when we increased the hand distance to 7 cm ($M = 5.855$, $p < 0.001$).

4.4.4. *Subjective evaluation.* In general, participants gave positive evaluations for *AirVis*. Nine out of twelve of the participants answered that direct visual perception improved their perception better than representation on a monitor (computer graphic). Figure 6(b) shows subjective user evaluation of *AirVis* for all participants. One participant suggested that, if *AirVis* can accommodate different air temperatures, it would improve the devices value and tactile perception. Another participant commented that it may be interesting to add fragrance/smell feedback together with the air flow feedback.

4.5. **Discussion.** Overall, the high perception quality of direct vision of ball movement suggests that users prefer to see the actual physical object because it gives the sense of volume and proper proportions. The results suggest that direct visual perception of the balls is better than computer graphic representation on a monitor. This might be because, in the direct visual condition, the users' hand, the air tactile device, and the balls are aligned in one straight line. The device is closer to the users' reach, thus increasing the perception and sense of reality. It is difficult to adjust the viewing angle of the computer graphic representation on the monitor with air-tactile sensation and the user's hand. While physical visualization of the current prototype is limited, expanding the prototype with more pixels such as 10×10 or 50×50 pixels could allow more variety in the visualization such as for a terrain surface. Combined with a map application this could provide an interesting and useful interaction of the concept of dynamic physical visualization.

5. **Conclusion and Future Work.** We have evaluated the capability of the device to provide physical visual feedback and tactile sensation simultaneously through air flow force and ball movement control. We confirmed that *AirVis* is well-accepted by the participants and has potential as both a visual and tactile display device. We also confirmed that participants can perceive different patterns of tactile sensations with high confidence. These patterns can be further exploited in two primary ways. First, these patterns can serve a *utilitarian* purpose where users use the perception of patterns for tactile code (a.k.a braille) or to engage in a learning experience. Second, these patterns can serve *hedonic* purposes where they can be used as artistic or cultural expressions, for example, to provide an integrated expression of different colors, smells, and temperatures (e.g., dancing fountain).

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