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Floating Charts: Data Plotting using Free-Floating Acoustically Levitated Representations

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ABSTRACT

Charts are graphical representations of numbers that help us to extract trends, relations and in general to have a better understanding of data. For this reason, multiple systems have been developed to display charts in a digital or physical manner. Here, we introduce Floating Charts, a modular display that utilizes acoustic levitation for positioning free-floating objects. Multiple objects are individually levitated to compose a dynamic floating chart with the ability to move in real time to reflect changes in data. Floating objects can have different sizes and colours to represent extra information. Additionally, they can be levitated across other physical structures to improve depth perception. We present the system design, a technical evaluation and a catalogue of chart variations.

Keywords: Acoustic Levitation, Charts, Physical visualizations

Index Terms: User interface Evaluation/ methodology

1 INTRODUCTION

Charts are a way of visualizing data that facilitates extracting trends, relations and in general allow us to have a better visual insight of raw numbers. By representing numerical values as visual information (i.e. position, size or colour), we take advantage of our inherent skill set to analyse the spatial world [3]. Consequently, there has been a significant interest in evolving the way that visual information is presented to the users. This information can be displayed in various ways, either with physical objects or digitally on a computer screen.

Several types of physical visualizations (physicalizations) related to charts have been created. For instance, 3D-printed static objects can be used to represent charts [4] but they lack the ability to change dynamically without the need of rebuilding the objects or user intervention. Another possibility is to utilize actuators to move columns or other physical entities [2][8] but the scalability, power consumption and occlusions are still to be improved; something as simple as a scatterplot is yet to be presented [3].

Here, we use for the first time acoustic levitation to create displays capable of rendering free-floating dynamic physical representations of data. The displays are called Floating Charts and are constructed by joining together building blocks. Each building block has a different configuration of ultrasonic speakers that can levitate and control one or a group of particles inside it. This enables the creation of displays of various sizes and characteristics, in which the levitated particles represent different values of data.

Acoustic levitation suspends objects in mid-air and can translate them around 3D paths. This is a new opportunity for creating dynamic physical visualizations without the restrains of gravity or mechanical actuation.

We believe that there are several advantages in building a display capable of representing acoustically levitated charts. Firstly, the levitated objects can be moved accurately and at a considerable speed, enabling information that gets updated in real time. Secondly, the floating particles do not require any physical support and thus do not occlude each other, allowing the user to have better viewing angles. Thirdly, the values are represented by physical objects that do not need to emit light to be visualized with the benefit of reducing eye fatigue; also, this enables a more natural perception of depth. Finally, acoustically transparent embellishments can be intertwined with the system, which can have a significant effect on our perception of the presented data.

In this paper, we create a modular system that represents charts using mid-air floating objects actuated individually with acoustic levitation. Additionally, we present a list of modifications that can be applied to the levitated objects to enhance the displayed information (e.g. using coloured beads of different sizes or fabrics and threads connecting them).

2 PRINCIPLES OF ACOUSTIC LEVITATION

Sound waves can exert forces and completely suspended them in air [1]. The most basic arrangement to produce this effect is a transducer (sound emitter) and a reflector on top [9], this creates a standing wave and particles levitate in its nodes (i.e. areas of low amplitude). By changing the phase of the transducers, movement of the particle can be achieved [5][6][7].

Ochiai et al. [6] presented a system composed of 4 opposing arrays of ultrasonic speakers that could suspend and move objects in 3D space. Later, Omirou et al. [7] created a modular system composed of 2 opposing arrays of speakers; the system was used for the physical representations of 3D paths. Recently, acoustic levitation has been achieved with all sort of geometries and even single-sided arrangements using a holographic method [5].

Here, we present a modular display that uses the holographic method to create dynamic physical representations of data composed of dozens of free-floating particles that are levitated and moved independently.

In this paper, we use levitators composed of two arrays of transducers. The arrays are in a flower pattern with 7 transducers arranged in a hexagon. The distance between the transducers was approximately equal to the wavelength and therefore the flower array makes a better use of the constructive interferences at the target point. Also, the hexagonal pattern permits to pack more transducers in less space. The geometries we tested are the two opposed arrays, a reflector and an array, L-shaped, and V-shapes.

To apply the holographic method in our levitators, first all the transducers get focused in the target point by adjusting their phases; then, a π-phase difference is added to one of the arrays. For the reflector, it is enough to generate a focal point at the target point since the reflected wave will create the standing wave pattern. More details about this method can be found in [5].

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3 FLOATING CHARTS DISPLAYS

In this section we present the composition of Floating Charts displays. An instance of the display is made by assembling different building blocks together. The levitating objects inside the building blocks are denominated as floating values, a collection of them form a Floating chart.

3.1 Building Blocks

In this section we explore the possibilities of the most promising arrangements. We tested these geometries of building blocks to minimize the amount of transducers required, their size and the interferences created when joined together.

3.1.1 Two-opposed

In this block, two flower arrays face each other and are separated by a distance of 6cm. Smaller distances are possible, with the maximum separation for stable levitation being 10 cm. Also, larger separations imply that the building blocks have to be assembled together leaving bigger gaps between them for avoiding interferences. Although the levitating particle is occluded from the top, the system presents a very good visualization angle from any direction, and can be visualized laterally from any angle.

A display composed of 4 columns and 3 rows of two-opposed blocks is presented in Figure 1. Each building block is separated by 2cm, this distance was selected to allow individual movement along the vertical axis with minimal interference between neighbouring building blocks.

3.1.2 Reflector

The second type of building block utilizes only a single array with an opposing reflector made of transparent acrylic. The acoustic wave is reflected off the acrylic and a standing wave is formed between the acrylic and the array. This block requires half the amount of transducers but its manoeuvrability and range is reduced. An interesting feature of this block is that it can be viewed from the top through the transparent acrylic. However, this block is more suitable for static representations since the levitated particles can only be moved laterally. In Figure 2.a we show a display composed of 4 of these blocks in a row that share the same transparent reflector. The particles were preplaced at the appropriate heights.

3.1.3 L-shape

L-shape blocks are created by placing two flower arrays at a 90º angle as shown in Figure 2.c. The particles have good manoeuvrability in this block and can be observed from any angle but not from the back. The main disadvantage of these block is that it can only accommodate one particle given the tilted pattern of the standing wave.

3.1.4 V-shape

V-shape blocks are composed of two flower arrays placed at a 35º angle as shown in Figure 2.b. There are no obstructions from any viewing angle since the objects levitate above the block. However, it is limited in terms of range, strength and speed.

3.2 Floating Values

Inside each of the building blocks an object can be levitated and moved to the target position to represent different numbers. We denominate these particles as floating values. Different characteristics of the particles can be modified to reflect the value that they represent. The default floating values used in our system are white expanded polystrerine beads of approximately 2 mm.
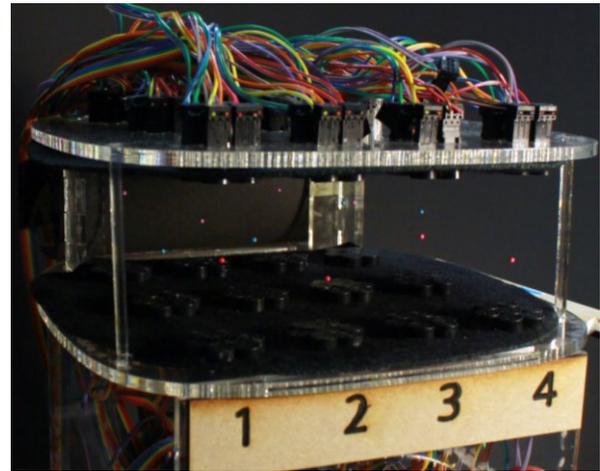

Figure 1: A Floating Chart display composed of 4x3 two-opposed blocks. Floating values of various colors are levitated at different heights to represent numerical values of tabular data. The dimensions of the display are 14x17x8cm and the particles are 2mm in diameter.
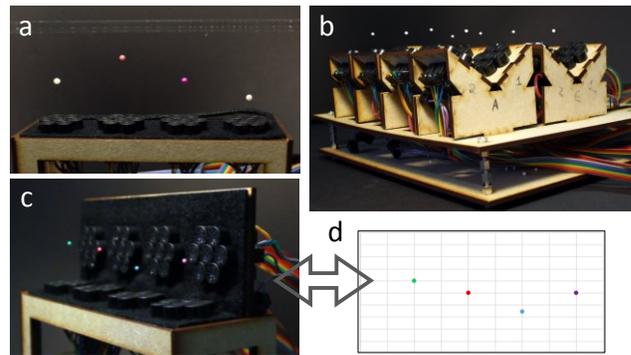

Figure 2: a) A Floating Chart made of 4x1 reflector blocks. The dimensions of the display are 14x17x8cm and the particles are 4mm in diameter. b) A Floating Chart composed of 4x2 V-shape blocks, the particles are 2mm in diameter. c) A Floating Chart composed of 4 L-shape blocks, the particles are 2mm in diameter; (d) the digital counterpart of the floating chart

3.2.1 Height and Movement

The main property of the floating value is its height which is directly proportional to the value it represents. The height can be changed dynamically to reflect real-time modifications of the value.

Additionally, the objects can be moved along other axis and therefore different repetitive movements (e.g. vertical, horizontal or circular) can be used for each floating value. These movements can change in speed or length to represent complex values such as imaginary numbers or the standard deviation. Moreover these movements can be used to create time-based visualizations.

3.2.2 Size and shape

Floating charts support levitation of beads of different size, ranging from a diameter of 0.6mm to 5mm (Figure 3.a). The size of the bead can be used not only to enhance visual perception but also to convey extra information of the number. For instance, the size can represent the importance or reliability of the value. Additionally, the shape of the bead can change from spherical, to disks or other planar shapes.
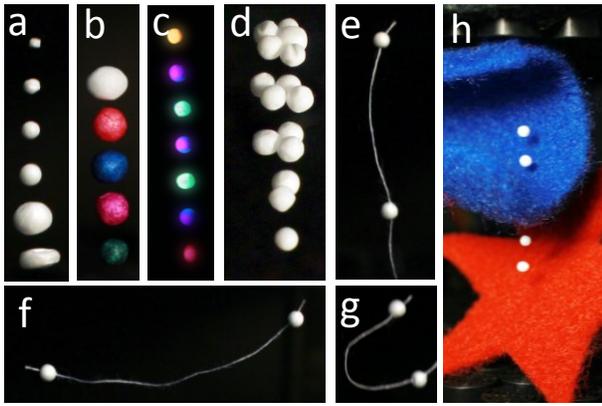
Figure 3: a) Beads ranging from 0.6mm to 5mm in diameter, flat bead on the bottom. b) Different colors applied to the beads. c) Fluorescent paint. d) the nodes can allocate up to 5 beads of 2mm. e,f,g) a thread joining the beads. h) Acoustically transparent fabrics are intertwined with the Floating Chart.

3.2.3 Colour

The particles can be painted or coated with different colors to show similarities in the dataset or attract attention towards specific areas. Varied substances can be used for coloring the bead ranging from traditional colors (Figure 3.b) to fluorescent pigments (Figure 3.c) that would allow to visualize the charts in dark environments.

3.2.4 Number of particles

Particles can be stacked in the same column to create columns instead of single dots (Figure 3.b). Columns are useful to create bar charts whereas individual points can be used for scatterplots. Also, each node can allocate up to five 2mm polystyrene beads at the same time (Figure 3.d). The amount of particles per node reflects an extra discrete number that ranges from 1 to 5 and it can be used to indicate the stars of a hotel when the height is used to convey the price.

3.2.5 Lines

Threads can be attached to a single levitated object or passed through multiple of them. A horizontal thread can join beads to enhance the perception of the different values, (Figure 3.f), while a vertical thread can be used to represent columns of different heights either in a straight (Figure 3.e) or bent line (Figure 3.g). These threads do not directly affect the sound field, but they make the levitated objects heavier and more unstable when they move.

3.2.6 Physical Integrations

Acoustically transparent materials with micro-holes, such as cloth or metallic meshes can be placed inside the levitators without reducing the strength of the levitation. These physical structures can be intertwined with the floating charts (Figure 3.h) to embellish the charts to motivate user approach.

3.3 Implementation

3.3.1 Hardware

The ultrasound transducers (MA40S4S, Murata Electronics, Japan) used in Floating Charts have 1cm of diameter with a central frequency of 40kHz, a beam spread angle of ±40° (measured at -6dB points) and sound pressure levels of 120±3 dB (measured on the axis at z = 30cm).

These transducers are driven with a custom-made electronic circuit. The circuit boards use XMOS L1-128 processors (XMOS, Bristol, UK) to generate a control signal of 3.3V and 40KHz for each channel. A MOSFET circuit per channel amplifies the square wave signal to 15V. The driver boards can generate the signals for the transducers with a phase resolution of π/10. Our electronics allowed us to drive up to 192 transducers with a power consumption of 26 Watts (15V x 1.7A).

A computer running our custom software calculates the phase delays for the target levitation points and sends the phases to the driver boards through a UART serial port. The phases could be updated at up to 67 frames per second. The levitated particles are expanded polystyrene spheres ranging from 0.6 to 5 mm of diameter (Custompac Ltd., Castleford, UK).

3.3.2 Software

The software that controls the phase of each transducer was implemented in Java, using the holographic method [5] which does not require any optimization to run in real-time. The software is able to read datasets from an Excel spreadsheet and map the numbers to the target heights of each floating value, taking into account the limitations of each building block in terms of levitation volume.

4 TECHNICAL EVALUATION

In this section we analyse the technical capabilities of each of the building blocks. These values can guide the design of the display depending on the required update speed, size of the floating values or capacity for holding threads.

The working volume represents the area in which a particle can be controllably moved. The limits in this area are due to the attenuation of sound with distance and the directive nature of the transducers. The working volume for different building blocks is presented in Figure 4. For the Two Opposed design, this area expands laterally, slightly further than the transducers end, and transversally up to half a centimetre from the transducers. In the L-shape design, the area gets slightly reduced frontally since the pushing force from the vertical flower needs to be counteracted by the horizontal flower. The Reflector block design features working slices instead of volumes meaning that the particles have to be preplaced at the desired height and can be moved laterally within that height; the lateral span increases as the wave gets closer to the reflector and so do the slices. In the V-shape design, the working volume is reduced in height and can only go 1cm above the transducers because none of the flowers emit directly contrary to gravity. To obtain the working volume, a particle was placed in the centre of the levitator and moved along one axis until it fell.

The repositioning error of the particles was approximately 0.3 mm. and was measured by taking a front picture of a particle, moving 1cm away, returning it to the same position and taking another picture. A ruler was used to transform between pixels and cm. The absolute error is relative to the wavelength and phase resolution, that is 0.42 mm in our systems (wavelength = 8.57mm, phase resolution = 20).

The linear speed for positioning the particles was up to 17cm/s laterally and 2cm/s vertically with the two-opposed block. L-shapes offered slightly slower movements and both reflectors and V-shapes were around three times slower. This occurs because the trapping forces were not enough to supress the oscillatory behaviour that the particles exhibit when they are translated in mid-air. To measure the linear speeds, the particles were moved along one axis in oscillatory movements of 2cm amplitude, and the speed was increased until the particle was ejected.

Forces of the order of μN were generated on the levitated particles since they were made of expanded polystyrene (29Kg per m^3) and had diameters ranging from 0.6mm to 5mm.

The two-opposed block design generated the strongest forces transversally, since the arrays were placed perpendicular to the gravity direction, and a standing wave was generated with arrays that are directly facing each other. Two-opposed design was capable of levitating the biggest particles even when they had threads attached. For the same reason, Reflector blocks design had good strength since the reflected wave was perpendicular to the incident one. L-shape blocks design had less strength because only one array was perpendicular to gravity and in the V-shape blocks design, the strength was the weakest since the force component to counteract gravity was obtained as an addition of the two flowers.

A summary of the values is shown in Figure 4. When several blocks are combined to create displays of multiple floating particles, the presented values decrease since even small interferences from one block slightly affects the others.

5 DISCUSSION

Floating Charts offer some advantages compared with other dynamic physical displays. They can be handheld without affecting the levitation, allowing the users to explore them. The power consumption per actuated unit is low. Also, the used beads are inexpensive and available in big quantities, thus they can be easily replaced, shaped or painted to provide richer information.

5.1.1 Use Cases

A simple plug-in for Excel can be used to synchronize the digital charts with the Floating charts. That is, any change in the data values is reflected in physical space allowing users to even use both the physical and digital representations to make decisions and identify trends. Another possibility would be a public display, to which users can upload pictures of charts with their phones; the public display analyses the chart for extracting the numerical values and represents them as a Floating Chart.

5.1.2 Limitations

Floating Charts enable scatterplots, bar charts and some additions like lines between data points. However, other types of charts like pie charts are still not realizable. Similarly, the points in the scatterplots cannot be in any random positions since there should be a minimum distance between them.

The amount of beads used was limited and consequently the complexity of the data that could be represented, yet a 4x3 scatterplot was a good first step. As Floating Charts are modular, bigger systems can be created to promote collaborative graph inspection without the need of mounting devices on the users. By using more directional transducers or by reducing the frequency, distance between the levitated objects can be reduced thus increasing the resolution of the system.

Future research should focus on the interaction with Floating Charts. A limitation of the presented systems is the fact that the users were unable to directly touch the levitated objects without reducing the robustness of the system in terms of maintaining levitation. A certain amount of user interaction is still possible but if a non-acoustically transparent object is placed between the levitated object and the transducers, then the wave will be reflected and the object will fall. The same will happen if air is blown onto the array either by the user or from another source.

While the frequency used in our system is not audible to humans, several animals such as dogs will be able to hear the ultrasonic noise.
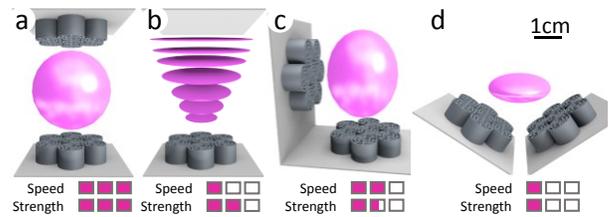

Figure 4: Working volume (pink area), speed and strength for: (a) two-opposed, (b) reflector, (c) L-shaped and (d) V-shape blocks.

6 CONCLUSION

An acoustic levitation display for representing dynamical free-floating charts has been presented. The displays are modular and are created by assembling different building blocks. Building blocks are structures with different transducer configurations that can levitate particles inside them. Each levitating particle represents a data value and thus a collection of them form a chart. Several modifications can be applied to the levitating particles to enhance the presented information.

This paper is the first showing a display capable of controlling independently a significant amount of levitated particles.

7 ACKNOWLEDGMENTS

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