Electrolysis Bubble Display based Art Installations

Ayaka Ishii
ishii.ayaka@is.ocha.ac.jp
Ochanomizu University
Tokyo, Japan

Manaka Fukushima
g1620533@is.ocha.ac.jp
Ochanomizu University
Tokyo, Japan

Namiki Tanaka
g1620523@is.ocha.ac.jp
Ochanomizu University
Tokyo, Japan

Yasushi Matoba
y.matoba2011@gmail.com
Ochanomizu University
Tokyo, Japan

Kaori Ikematsu
g0920502@gmail.com
Yahoo Japan Corporation
Tokyo, Japan

Itiro Siio
siio@acm.org
Ochanomizu University
Tokyo, Japan

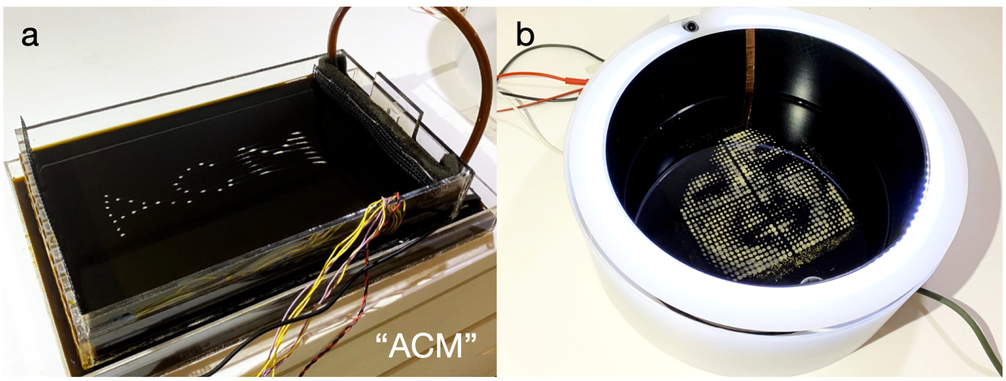

Figure 1: (a) Overview of UTAKATA: "ACM" is displayed using flowing electrolysis bubbles. (b) Overview of Bubble Mirror: the facial image is displayed using grayscale electrolysis bubbles.

ABSTRACT

Research was conducted on a digital information display using electrolysis bubbles. Although the research mainly focused on information displays in daily life, the ephemerality of bubbles is also a promising method for dynamic art installations. In this paper, we present two novel artworks using this electrolysis bubble display mechanism. First, we present "UTAKATA," a ticker-like bubble display, using a running-water channel. Seven electrodes are placed linearly on the channel bed, and they generate text messages using bubble dots that drift toward the lower end of the channel. Second, we present the "Bubble Mirror," which is a water pan with a camera that captures a visitor's face and displays it using electrolysis bubbles as pixels. Facial images with six levels of grayscales are displayed on the water surface using 32 × 32 electrodes. We evaluated the output properties of these configurations and discuss the results obtained.

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CCS CONCEPTS

• **Human-centered computing → Human computer interaction (HCI)**; *Displays and imagers.*

KEYWORDS

Bubble Display; Electrolysis; Water; Art; Ephemeral User Interface

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1 INTRODUCTION

Water is indispensable to human life and enriches our daily environment. From ancient times, people have enjoyed watching water flowing in rivers, bubbles floating on the water, and scenery reflected on the surface of ponds or water basins. As Kamo no Chomei mentioned in Hojoki[1], since time immemorial, flowing water and floating bubbles have been metaphors for impermanence in literature and other art. Recently, focusing on the ephemerality of

[1] Historical short work of the early Kamakura period (1185–1333) in Japan. The opening sentence of Hōjōki is "The current of the flowing river does not cease, and yet the water is not the same water as before. The foam (UTAKATA) that floats on stagnant pools, now vanishing, now forming, never stays the same for long. So, too, it is with the people and dwellings of the world."

bubbles, several devices that use bubbles to print or display text and images on a liquid surface have been proposed. BubBowl [10] is a liquid surface display using bubble clusters generated by electrolysis as pixels. It dynamically displays information, such as low-resolution text, on the surfaces of beverages. Although BubBowl was intended to be used as a device that ordinarily displays information, we intuitively assume that the ephemerality of the bubbles holds potential as a method for dynamic art installations.

In this paper, we present two novel artworks using the electrolysis bubble display mechanism presented in the previous study [10]. The first artwork is "UTAKATA," a ticker-like bubble display using a running-water channel (see Figure 1 (a)). In the previous study [10], the pixels of electrolysis bubble clusters required a much longer time to disappear (more than 1 min), whereas they were generated in seconds. This resulted in a slow refresh rate of the display; consequently, the display contents were difficult to animate or scroll. UTAKATA overcomes this drawback using a water channel. Seven electrodes are installed at the water bed, and they generate text messages using bubble dots that drift toward the lower end of the channel. The second artwork is a "Bubble Mirror," which is a water pan with a camera that captures a visitor's face and displays it using grayscale pixels of bubble clusters generated from the electrolysis of water (see Figure 1 (b)). The facial image is displayed on the water surface when a visitor looks inside the water pan. Although it has been reported that a grayscale display is possible by adjusting the time for which the electrodes are energized, a detailed investigation has never been conducted [10]. The Bubble Mirror is the first attempt to realize a high-resolution (1024 pixels) grayscale (6 levels) display using electrolysis bubbles.

As mentioned above, although the electrolysis bubble display is not a new mechanism, both artworks that we implemented posed technical challenges that could not be solved by simply applying the mechanism. Hence, we addressed these challenges and evaluated their technical properties. In summary, our contributions are as follows:

(1) We present and implement the novel artworks, i.e., "UTAKATA" and "Bubble Mirror," that use the electrolysis bubble display mechanism.
(2) We address two major technical issues remaining from the previous electrolysis bubble display (i.e., we improve the refresh rate and increase the expressive tone range of bubbles).
(3) We evaluate and investigate the output properties of the proposed systems.
(4) We discuss further possible expressive implementations based on the findings and user feedback.

2 RELATED WORK

2.1 Bubble Display

Several studies have been conducted on digital information displays using bubbles as pixels. Information Percolator [6] is a display that uses bubbles rising in water. The system contains a group of transparent pipes that are filled with water and supplies air from the outside to these pipes to realize a bubble display. Shaboned Display [8] is a 10×10 pixel 2D display that uses soap bubbles as pixels. It comprises 100 sponge nozzles dipped in soapy water. Each nozzle has a shape-changing mechanism to create a soap film and is connected to an air pump that generates soap bubbles. These systems require moving parts, such as air compressors and electromagnetic valves for each pixel or column, to supply air from the outside in order to control the bubbles. Therefore, it is difficult to increase the number of pixels at a low cost. Additionally, as the number of pixels increases, the number of required mechanical parts increases, and the bubble display apparatus becomes large. To avoid such issues, a bubble display using electrolysis to supply gas has been proposed [10]. The device can generate fine bubble clusters quickly; however, it takes a approximately 1 min for the bubbles to disappear. In the UTAKATA introduced herein, the refresh rate has been improved by introducing a ticker-like display mechanism using flowing water. Moreover, although Ishii et al. [10] reported that a grayscale display could be achieved by adjusting the period during which the electrodes are energized, no detailed investigation has been conducted yet. Hence, we propose the Bubble Mirror, which is a six-grayscale level bubble display with a high-resolution of 1,024 pixels to display human faces captured by a camera.

In terms of high-resolution bubble displays, Volumetric Bubble Display [11] has been proposed. This is a high-resolution 3D display unit that uses micro bubbles generated in a high-viscosity liquid (e.g., glycerin) using focused femtosecond laser pulses. Although the 3D pixels are optically generated without mechanical or electrical components, the refresh rate is extremely low because the bubbles remain in the high-viscosity liquid once they are generated. In our system, a low-viscosity liquid can be used as the electrolytic solution, thereby avoiding a low refresh rate due to the solution's high-viscosity.

Similar to our systems, H_2 Bubble Display [1] uses electrolysis to produce bubbles to create artwork. This generates rising bubbles in a transparent water tank equipped with 8×8 pairs of electrodes at the bottom. Although each electrode in the tank generates gas from electrolysis, the gas is not used to generate pixels, but a rising mist of bubbles synchronized to music. In our system (as well as that discussed in the previous study [10]), we used clusters of bubbles formed on the surface of a tinted electrolytic solution (e.g., coffee) as pixels to display a character or images.

Several studies have presented information using physical materials by utilizing the energization of electrodes located in aqueous solutions. In several studies [13, 19, 24], liquid metal drops were moved by controlling their surface tension by varying the energy levels. Voltage was applied to electrodes placed in an aqueous solution of sodium hydroxide. Consequently, electrolysis occurred, and hydrogen and oxygen gases were generated. The main purpose of these studies was to implement a visual and tactile display by controlling liquid metal drops; therefore, the generated gas was not used as pixels for presenting the information. An actuator powered by hydrogen and oxygen gases generated by electrolysis was proposed [7, 22]. As this method does not require an external gas supply, it realizes compact, low-noise, and highly efficient actuators. In this study, we applied a low-noise and high-efficiency electrolysis mechanism for display devices and created novel artworks that afforded new experiences with the bubbles on the water surface.

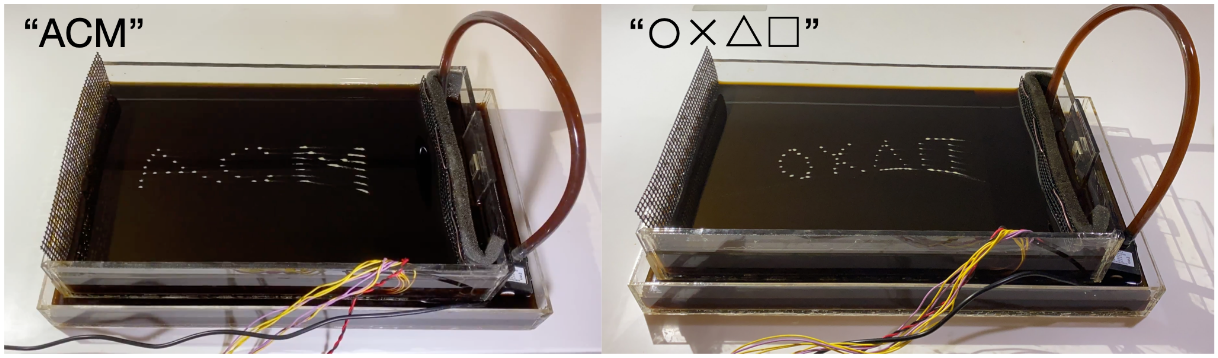

Figure 2: Display examples by UTAKATA. "ACM" (left) and symbols (right).

2.2 User Interfaces and Artworks with Ephemerality

The information displayed using bubbles is fragile and makes users focus on it. Interfaces that remain for only a limited time are referred to as ephemeral user interfaces (EUIs) [4]. Several examples of using transient materials to implement EUIs are as follows. Initially, water and bubbles were often used to develop EUIs. Bit.Fall [17] is an example of an EUI implemented using water. It is an art installation that displays words as a water curtain, in which words are visible for only ~1 s, while water drops fall to the ground. In another similar implementation, Bit.Flow [16] is a display that uses water drops moving in a tube as pixels. Several tubes are arranged horizontally, and characters can be displayed by controlling the position of colored water drops poured into each tube. In association with Bit.Flow, another technology called Tuve, has been proposed to establish a dynamic shape-changing display using a single tube and wrapping it around various objects [9]. In these display systems, the characters are gradually formed from bits that flow chaotically and then disappear. The temporary impression of a message attracts attention and provides interesting experiences.

User interactions using the fragility of bubbles have been proposed. Bubble Cosmos is a soap bubble display wherein an image is projected onto real soap bubbles with white smoke encapsulated inside them [15]. It provides sound and image output by employing user interactions, such as the bursting of soap bubbles. Mid-air displays that provide visual and olfactory outputs by injecting scented white smoke into soap bubbles were proposed [12, 20]. Additionally, a method using soap bubbles as fragile tangible input was proposed [3, 23]. When a user causes the soap bubbles to move, the room lighting can be changed according to the position of the bubbles. Choi et al. introduced an art project representing the ephemeral and intangible aspects of human communication using soap bubbles [2].

As in the aforementioned examples, water and bubbles are the popular medium of expression used in EUIs because it embodies ephemerality by flowing easily or by bursting and disappearing. We focused on the ephemerality of water and bubbles, and utilized them in artworks to create unique experiences.

The works most similar to ours are Bit.Flow [16] and Wooden Mirror [18]. Similar to UTAKATA, Bit.Flow has a ticker-like structure to present information by the flow of water. Wooden Mirror is a display that uses pieces of wood as pixels. Similar to the Bubble Mirror, it displays a facial image of a person who views the system with approximately 30 × 30 pixels. Wooden Mirror controls the angle of each wooden piece, whereas we control the energization for each electrode.

3 UTAKATA

In this section, we present UTAKATA[2], a ticker-like bubble display using a running-water channel. The display examples are shown in Figure 2. Figure 3 shows an overview of the device completely emptied of water. The device is composed of acrylic inner and outer containers, and a shallow water channel for the display was placed in the inner container. A linear array of seven electrodes (cathodes) was fixed into the display bed of the water channel, which generated up to seven circular clusters of fine hydrogen bubbles on the water surface using electrolysis. By activating only the appropriate electrodes among the seven, an N × 7 dot-matrix display with a short refresh time can be implemented as the bubble clusters float downstream. We assume that UTAKATA can be used as an ephemeral display to offer temporal information via fragile and floating bubble characters. The main technical challenge we addressed in implementing this artwork was to display bubble pixels on the flowing water with a small amount of distortion such that characters comprised of the pixels were readable while the entire water channel was in flow.

3.1 Water Circuit

As shown in Figure 3, an inner container was placed in a larger outer container that held water darkened with coffee. The inner container was made of acrylic plates 5 mm thick and approximately 35 cm × 21 cm × 6 cm in size. We placed this inner container proud of the outer container using 2 cm legs.

To generate a water flow in the inner container, water must be supplied and drained in and out of the inner container. To supply water, a water pump was placed in the outer container, and the end of the output tube from the pump was placed at the upstream

[2] UTAKATA is an old-fashioned word that means foam in Japanese.

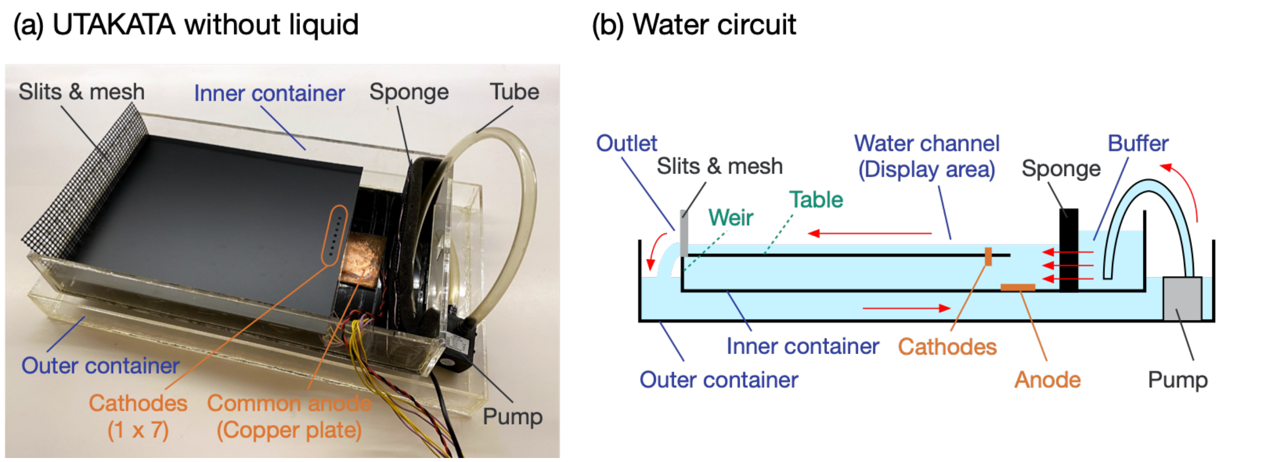

Figure 3: (a) Overview of UTAKATA when empty. The water circuit is constructed for outer and inner containers. (b) Cross section of water circuit. Water flows downstream (right to left) and upstream (left to right) in the inner and outer containers, respectively. Red arrows represent water flow.

end of the inner container. The water was stored in the buffer reservoir of the inner container. Between the buffer and the water channel, we placed a sponge to mitigate possible turbulence caused by the pumping mechanism. A 1-cm-thick sponge was placed 6 cm upstream from the cathodes to facilitate laminar flow in the display area.

At the outlet of the inner container, we placed a weir made of an acrylic wall, slits, and a mesh. It is important to ensure that the surface flow of the water is uniform to avoid the distortion of bubble clusters. For a simple weir structure, only the flow near the water surface spills over the weir at the outlet, whereas the flow involves a deeper part of the water at the upstream part. This causes the surface water to flow faster and slower at the outlet and upstream, respectively. Consequently, the displayed content created by floating bubble clusters will be distorted. To isolate the surface flow so that it does not affect the deeper water, the bed of the channel was raised to the same height as the weir by placing a table with 2.5 cm high legs. This enabled a uniform surface flow along the stream over the display area. Furthermore, we placed slits (10 mm width with 4 mm separation) and a rough mesh (approximately 4 mm) over the weir to create a uniform surface flow along the weir. Without those, the flow tended to concentrate on a particular part of the weir according to the micro-disturbances caused by unevenness or roughness at the top of the weir, thereby distorting the clusters of floating bubbles.

3.2 Bubble Generation

In the inner container, electrolysis is performed and a floating bubble display is realized by the system. To generate bubbles by electrolysis, we set common anode and pixel cathodes. The common anode of copper plate measuring 15 cm × 6.2 cm was placed on the floor of the inner container. Seven cathodes were arranged in a row at the bottom of the water channel's entrance. Off-the-shelf gold-plated pin header parts were used for the cathodes, as we assumed that the pillar shape of the pin header parts would facilitate rising of bubbles toward the water surface. The spaces between the cathodes were 7.6 mm. Similar to the previous study [10], coffee was used as the electrolytic solution; we used instant coffee (prepared using 1.5 % w/v coffee powder) with sodium bicarbonate (0.4 % w/v) to promote electrical flow and cornstarch (0.25 % w/v) to provide sufficient viscosity and avoid the diffusion of bubble clusters. The amount of cornstarch was greater than that used in the previous study— to hold pixels with bubbles in the presence of flow. The viscosity of coffee solution was 15 mPa·s.

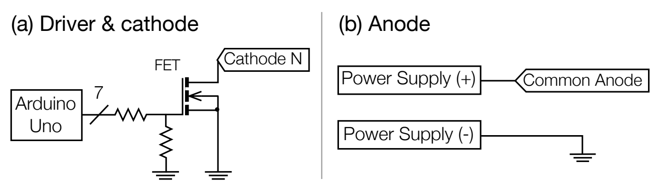

Figure 4: Circuit diagram representing wiring of Line N. (N = 1 to 7)

Figure 4 shows the circuit diagram employed in UTAKATA. As shown, seven pixel electrodes were connected to an Arduino UNO microcontroller board via a metal-oxide-semiconductor field-effect transistor (MOSFET)[3]. The gate of the MOSFET was connected to the Arduino board, the source was connected to the ground, and the drain was attached to the pixel electrode. When the Arduino activated several MOSFETs, the corresponding pixel electrodes were connected to the ground. Subsequently, the electrodes functioned as cathodes for electrolysis, and hydrogen was generated from the electrodes. As shown in Figure 4 (b), the positive output of the DC power supply was connected to the common anode, and the negative output was connected to the common ground.

[3]Toshiba, 2SK2232

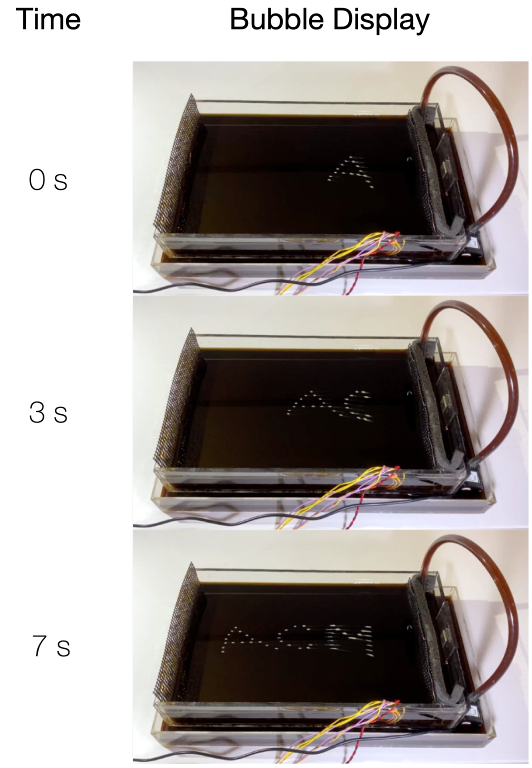

Figure 5: Transition of the "ACM" bubble display (Top) Character "A" is displayed; (middle) subsequently, "AC" is displayed; (bottom) finally, "ACM" is displayed on the water surface.

3.3 Technical Evaluation

Figure 2 shows the UTAKATA that displays the letters "ACM" and several symbols. The current applied to each electrode was approximately 23 mA, and the voltage was 20 V at the time. Since one to seven electrodes are energized for the display of one character, a total current of 23 mA–161 mA flows, that is, the system consumed 0.5–3 W of electric power in a normal operation. The depth of the water in the display area was approximately 5 mm. As the interval between electrodes was 7.6 mm, the vertical pixel resolution was approximately 3 dpi. The pixel size was approximately 4.5 mm in diameter, and the length of the display area (from the cathodes to the outlet) was 25 cm.

Figure 5 shows the bubble character's transformation due to the flow. When the character "A" is displayed, the electrode is energized for 300 ms to display a single dot. For the dot to display clearly, the electrodes were de-energized for 300 ms to create a space between the adjacent dots. Therefore, the time required to produce a five-dot-wide character is approximately 3 s. Although it depends on the font width, up to five characters were visible simultaneously in the present implementation. We believe that a larger number of characters can be observed simultaneously by extending the length of the water channel. The velocity of the central bubble was approximately 2 cm/s near above the cathode. As mentioned above, each electrode is energized for 300 ms to display a single pixel. This generated bubble pixels that have approximately the same intervals as the interval of the cathode pins and the horizontal resolution was approximately 3 dpi. This allows a 1:1 aspect ratio display with UTAKATA.

3.4 Limitations

External influences, such as the installation angle or wind would distort the display contents of the systems. The systems are recommended to be installed indoors horizontally to reduce display distortions.

The outlet structure, which may further reduce the distortions, can be further improved. In our current implementation, we placed the slits and mesh at the outlet. Although the slits were necessary to hold the mesh evenly, the shape should be optimized to create a more uniform flow. The walls between the slits and rough notches at the bottom of the slits may contribute negatively to water flow. The exit design should be improved while experimenting with or without the use of slits and with different mesh shapes and sizes.

4 BUBBLE MIRROR

In this section, we present the Bubble Mirror. It utilizes the features of electrolysis bubble display, that is, it can easily increase the number of pixels and realize a grayscale display. The Bubble Mirror is a water pan equipped with 32×32 pixel electrodes and a camera (Figure 6(a)). The camera captures a visitor's face (Figure 6(b)), and the image of the face is displayed using pixels of bubble clusters in grayscale generated by water electrolysis (Figure 6(c)). Analogous to a water surface that reflects the face of the person looking into it, the Bubble Mirror displays the image of the face on the water surface when the person looks into the system. In this study, we addressed several technical challenges, such as the fabrication of a display with over 1,000 pixel bubbles and the appropriate electrode control for grayscale imaging.

4.1 Overview and User Experience

Figure 7 shows an overview of the Bubble Mirror. The system is comprised of a water pan with an Arduino UNO controller, a foot switch[4], a USB camera, and a PC running Processing program on macOS. The water pan is filled with water darkened with instant coffee powder. The foot switch is connected to the Arduino, which is connected to the PC through a USB. The PC receives the foot switch status and sends the display image data from/to the Arduino.

When a visitor stands in front of the system, the foot switch detects it. Next, when a visitor looks into the pan, the camera captures the visitor's face and displays it as a pixel of a cluster of bubbles on the water surface. An LED tape was attached to the outer edge of the pan to prevent the face of the person looking into it from darkening. To diffuse the LED light, a 3-mm-thick donut-shaped white translucent acrylic plate was attached on the LED tape.

[4]Tapeswitch Corporation, Sensing Mat CVP1723

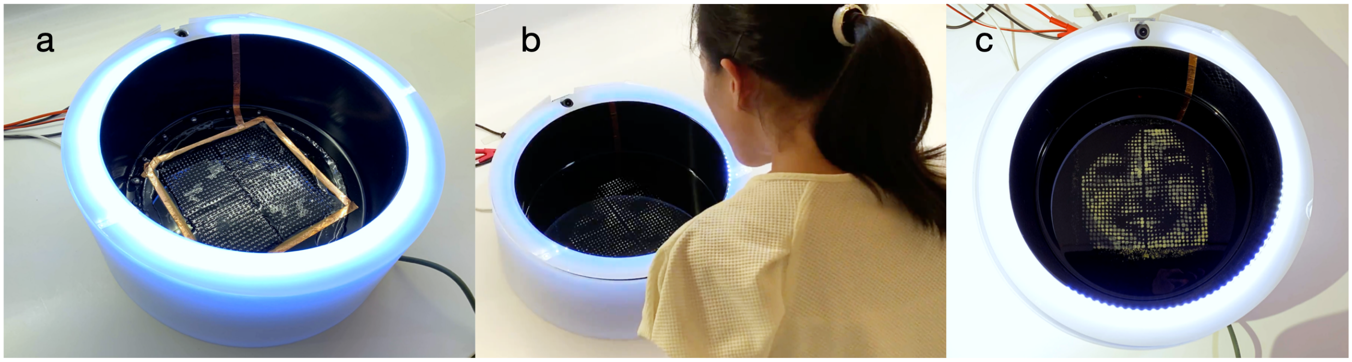

Figure 6: Overview of the Bubble Mirror. (a) Matrix cathode pins and common anode are placed at the bottom of the water pan. (b) A visitor looks into the Bubble Mirror, and the facial image is displayed on the water surface. (c) Facial image using grayscale bubble pixels.

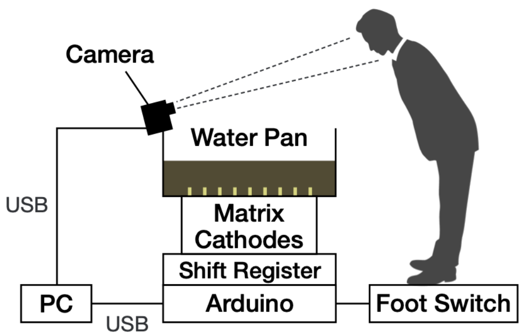

Figure 7: System configuration of Bubble Mirror.

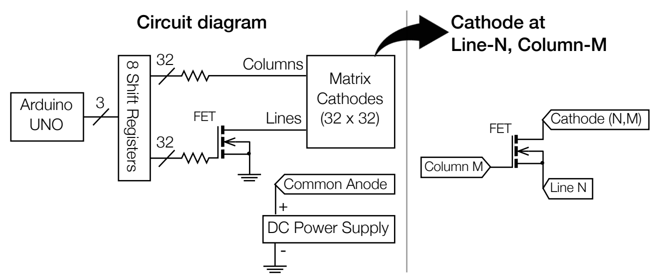

Figure 8: Circuit diagram. Right side shows the wiring of line N and column M. (N = 1 to 32; and M = 1 to 32)

4.2 Bubble Generation

We designed a display with 32 × 32 pixels, which is approximately the same number of pixels as the Wooden Mirror mentioned in the Related Work section. Figure 6(b) shows the bottom of the empty water pan. A 32 × 32 matrix of electrodes (cathode pins) with intervals of 5.1 mm was installed at the bottom of the pan, whereas a common anode was placed around the cathodes. The overall area of the cathode pins was 16 cm × 16 cm. We used off-the-shelf gold-plated pin header parts for the cathodes and copper tape as the common anode. Similarly to UTAKATA, a coffee solution was used as the electrolytic solution. We used instant coffee (prepared with 1.5% w/v coffee powder) with sodium bicarbonate (0.4% w/v) to promote electrical flow and cornstarch (0.2% w/v) to provide sufficient viscosity to avoid the diffusion of bubble clusters. The viscosity of the coffee solution was 10 mPa·s.

Figure 8 shows the circuit diagram of the electrodes of the Bubble Mirror. Although a similar active-matrix circuit was used in the previous study [10], the display specification of 100 binary pixels was insufficient to provide a recognizable human facial image in grayscale. In this device, 1,024 pixel electrodes were connected to an active-matrix circuit, and they underwent pulse-density modulation (PDM) by the Arduino to provide a grayscale display.

Each electrode functioned as a cathode when the pixel was turned on. As shown on the left side of Figure 8, we used eight shift registers[5] for 32 columns and 32 line wires to reduce the number of necessary output pins to the Arduino board. Each of the 32 line wires was switched to ground when the Arduino activated one of the MOSFETs[6]. The right side of Figure 8 shows the intersection of the matrix circuit, where the M-th column and N-th line wires crossed. Each intersection of the matrix comprised a MOSFET[6] and a pixel electrode. With the control from the Arduino, a high or low voltage was applied to several arbitrary column wires, and one among the 32 line wires was grounded. Consequently, the MOSFET connected to the column wire with high voltage is turned on, and the pixel electrodes on the grounded line wire connected to this MOSFET are grounded. By repeating this process for each of the 32 line wires, all arbitrary combinations of electrodes can be grounded temporarily. The positive output of the DC power supply was connected to the common anode and the negative output was connected to the common ground. Subsequently, the grounded pixel electrode functioned as a cathode for electrolysis, and the pixel electrode generated hydrogen.

The current implementation of the Bubble Mirror provides a display with a 0.6 Hz refresh rate, that is, it repeats the electrolysis process for a picture at 1.6 s intervals. We set the refresh cycle to 1.6 s because we observed that the bubbles emerged in approximately

[5]Texas Instruments, SN74HC595N
[6]ROHM Semiconductor, RK7002BMT116

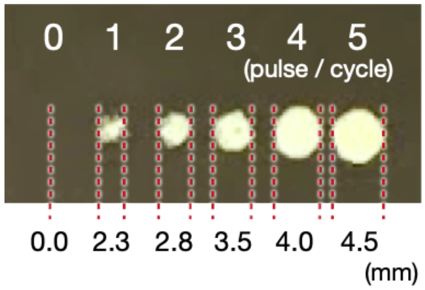

Figure 9: Bubble clusters generated by PDM current. Numbers 0 - 5 indicates number of pulses (10 ms width) per refresh cycle (1.6 s). Numbers below are the actual diameters of the clusters of bubbles.

1 to 2 s in the current electrolysis configuration. The Arduino program applied an electric current to arbitrary pixel electrodes on a line wire among 32 line wires for 10 ms. It requied 320 ms to scan all the 1024 electrodes on the 32 line wires. We performed programming to repeat the above-mentioned 320 ms scan five times to provide six levels of grayscale for the display by using pulse-density modulation (PDM) of the electrolysis current. For a pixel assigned to level N (0–5) of the grayscale, the program activates the corresponding electrode N times (in total N × 10 ms) during the five scans. Therefore, the electrolysis process for a picture requires 1.6 s (320 ms × 5) and the refresh rate of the display is 0.6 Hz. Figure 9 shows the experimental results of applying the PDM current to the pixel cathodes. The number indicates the number of current pulses applied to each electrode during a refresh cycle.

4.3 Facial Image Processing

The PC captures the visitor's face via the camera and converts it to the 32 × 32 pixels with six grayscale levels. To determine the optimal grayscale levels, we created simulation software that converts a 32 × 32 facial image to 1,024 halftone dots. As shown in Figure 10, halftone dots were used to simulate the bubble image because the size of the bubble cluster varied with the applied current. The results show that six grayscale levels were sufficient to display recognizable human faces.

In our system, when a visitor stands on the foot switch in front of the water pan, the PC starts detecting a face via the camera. We used OpenCV for Processing as the face detection library. Subsequently, the system saves five facial images at 100 ms intervals only when the visitor's face is detected around the center of the camera frame. The saved images are then resized to 32 × 32 pixels in 256 grayscale, and the image with the maximum contrast (i.e., the sum of the absolute value of the difference between adjacent pixels is the greatest) is selected from among them. Subsequently, the pixels are assigned to six equally distributed grayscales, and 32 × 32 pixels of six grayscale (0–5) images are generated. Once the face data for the bubble display is ready, the PC sends it to the Arduino to energize each pixel electrode according to the grayscale data obtained using the PDM current (see Figure 11). When the visitor leaves, the foot switch is turned off, and the PC sends an image of 32 × 32 black pixels to the Arduino to stop energizing the electrodes.

4.4 Technical Evaluation and Demonstration

Based on the arrangement of cathode pins at the bottom, the size of the display area was approximately 16 cm × 16 cm, and the interval between the pixels was 5.08 mm (5 dpi). The required liquid depth to obtain a clear display was approximately 1 cm. By applying 30 V to the electrodes, this system smoothly displayed a human face and approximately 300 - 400 mA of electric current was used, that is, the system consumed approximately 12 W of electric power in a normal operation.

Although human faces displayed on the Bubble Mirror were recognizable, they were slightly noisy and had black cross lines at the center, as shown in Figure 11 (right). To reduce the fabrication cost, we divided the printed circuit board (PCB) for the matrix cathodes into four pieces, that is, four PCBs comprising 16 × 16 electrodes were placed at the bottom of the water pan. Then, blank black crossing lines appeared on the gap among the four PCBs. They can be removed by fabricating a larger single PCB comprising a 32 × 32 pixel circuit. Pixels at the edge of the PCB tend to be slightly brighter than the other pixels, and this emphasizes the blank lines. We assume that this is caused by the difference in electric resistance between the common anode, that is, the cathodes at the edge have a larger electric contact with the anode than the others because they are facing open water, where they do not have to share current with the other cathodes. This problem can be solved using a single PCB or by display calibration, that is, adjusting the software to reduce the assigned grayscale for the pixels at the edge. Furthermore, we observed that some pixels tended to be brighter or darker than the assigned grayscale. We reduced this type of noise by evenly sealing all sides of the cathode pins using a UV curing resin; however, the reduction was insufficient. In our opinion, the noise can be removed more effectively by modifying the software to adjust the grayscale assigned to the noisy pixels.

We measured the black-to-light-gray (BTG) and white-to-dark-gray (WTG) response times of the Bubble Mirror. Based on the previous study [10], the BTG response time used in this measurement was the time lapse between 0% gray (black) and 80% gray of the maximum (100%) bright color generated by the device, and the WTG response time was between 100% and 40% gray. We prepared a single dot of white (maximum grayscale level 5) image data and measured the BTG and WTG response times by displaying a bubble dot on the Bubble Mirror. The device required a voltage of 30 V and an average current of 1.2 mA. The bubble pixel was video recorded, and the BTG and WTG response times were measured by analyzing the video. The results show that the BTG and WTG response times were approximately 3 s and more than 60 s, respectively. In the Bubble Mirror installation, a BTG response time of 3 s will contribute to a fast response time that effectively attracts visitors to the art installation. Meanwhile, the long WTG response time may affect the user experience because the face of the previous visitor remains on display. To avoid such issues, we have considered using an electric fan or asking visitors to eliminate the bubbles by blowing them.

We demonstrated the operation of the display for three students from a local university. The participants were asked to look into the Bubble Mirror one by one, and observe the bubble display of their faces. Afterward, we interviewed them about their subjective perceptions of the Bubble Mirror. Each the participants easily

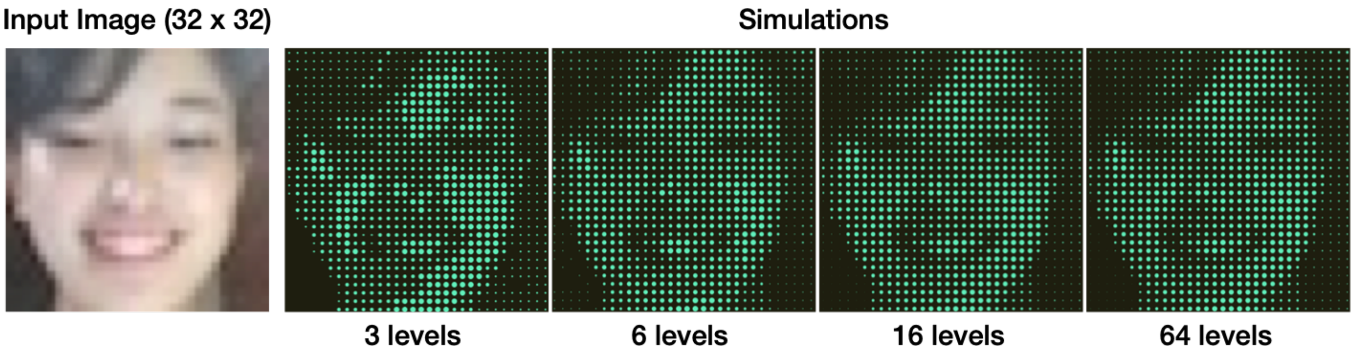

Figure 10: Software simulation to evaluate image quality over grayscale levels.

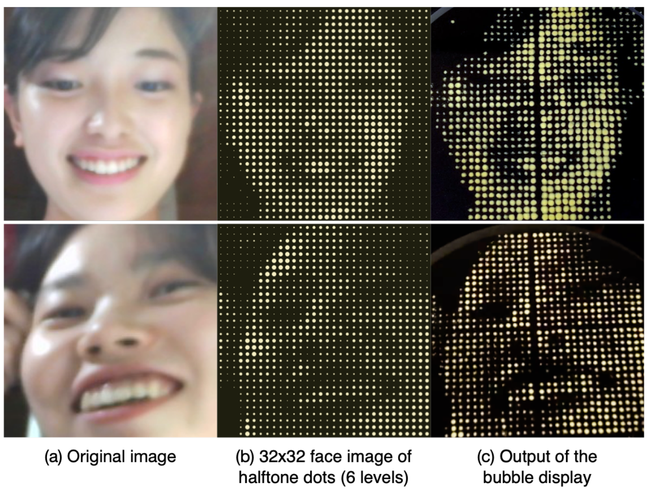

Figure 11: (a) Facial image acquired by face recognition. (b) 32×32 pixel of halftone dots image (6 levels). (c) The actual bubble displays.

recognized the displayed bubble facial image as theirs (see Figure 11). Some participants commented that the display speed of the bubbles was faster than expected, which supports our expectation of the BTG response time. Furthermore, we discovered that the participants enjoyed distorting the facial image by blowing on it. Additionally, a participant commented that she wished to trace the bubbles with a stick and deform the face more freely, as in latte art. The facial image displayed by the Bubble Mirror distorted spontaneously when the power was stopped. Another participant mentioned that she enjoyed watching this process.

4.5 Limitations

The Bubble Mirror is a six-grayscale bubble display. However, we should consider implementing a display with more shades of gray. The greater the grayscale level, the smaller is the difference in size among the bubbles, and the better the facial image quality. Calibrating the current for particular noisy pixels is another simple approach.

Another issue is that the Bubble Mirror's WTG response time (as discussed in the previous section) was extremely long, that is, the bubbles required approximately 60 s to disappear spontaneously. We plan to use an electric fan to eliminate bubbles quickly. In this context, it is better to employ wind-related representational techniques to avoid degrading the artistic experience. Hence, we plan to further improve the quality of the Bubble Mirror as an interactive artwork.

5 FUTURE VISION

In the design of UTAKATA, we focused on avoiding the distortion of the display in the water flow; however, we assume that some expressions such as the shape change or animation of the contents are possible by intentionally distorting the displayed contents. The displayed content can be easily distorted by simply tilting the device or placing a bump at the bottom of the water channel. We assume that the shape or movement of the bubble characters can be controlled by electrically raising part of the bottom of the water channel. Exploring the design space for distortion-based displays is a future challenge. Referring to several previous studies [5, 14], we believe that besides output, UTAKATA can allow for further input modalities. For example, UTAKATA could detect a user's touch action on the water surface and change the floating bubbles according to the contact.

Furthermore, we plan to apply UTAKATA's technique to small natural rivers. An artwork exists that projects words onto a water flow [21]. In this study, words projected on a water surface were supposed to float like leaves in a stream. The authors of this study attempted to introduce computer technologies into a real garden in harmony with stone, water, and plant materials. We believe that the UTAKATA mechanism can be enlarged to display digital information on natural structures such as small natural rivers. This features floating bubbles on a river described by Kamo no Chomei in his essay.

As for the Bubble Mirror, we consider improving it from an artistic perspective. Our current system displays the captured faces as they are; however, we are considering intentionally distorting or modifying the facial images (e.g., applying an image processing filter) to display them.

A previous study proposed a mirror-like display system that captures a facial image with a camera and feeds back its deformed image [25, 26]. In this study, it is suggested that this technique can manipulate an emotional state via visual feedback from artificial facial expressions. In our future work, we plan to investigate whether this effect is applicable to the Bubble Mirror as well as the LCD. Additionally, we are considering extending the expression range by testing different types of electrolytic solutions and electrodes. We will also investigate the expressive capability of the proposed system by having more people experience it.

6 CONCLUSION

In this paper, we proposed two novel artworks using the electrolysis bubble display mechanism. The first artwork was UTAKATA, a ticker-like electrolysis bubble display using channel of running water. The second artwork was the Bubble Mirror, which is a water pan with a camera that captures a visitor's face and displays it using electrolysis bubble pixels. Through implementation, we addressed two technical issues encountered in the previous electrolysis bubble display system, that is, we (1) improved the refresh rate and (2) increased the expressive tones of bubbles. Furthermore, we investigated the possibilities for the further expression of the proposed artworks through a series of evaluations of the output properties as well as discussions based on the implementation findings and user feedback. We believe that our methods will enrich the field of human–computer interaction and media art as a new technology for computationally controlling physical objects.

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