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Phenomenological Augmented Reality with the Sequential Wave Imprinting Machine (SWIM)

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***Abstract*—SWIM (Sequential Wave Imprinting Machine) is an invention that makes for visual art as well as scientific discovery of otherwise invisible physical phenomenology around us, such as sound waves, radio waves, etc.. It uses *multimediated reality* (sensing, computation, and display) to turn phenomena such as interference patterns between multiple sound sources, into pictures "painted" by nature itself (rather than from computer graphics). This gives us a glimpse into the nature of the real world arouond us, i.e. phenomena arising from physics (natural philosophy).**

SWIM also reveals the otherwise invisible capacity of a microphone or microphone array to "hear", by "painting" a picture of its metasensory (sensing of sensors) wave functions.

SWIM can also be a robotic mechanism for the precise scientific sensing of sensors and the sensing of their capacity to sense.

I. Introduction

The Latin phrase "Quis custodiet ipsos custodes?", by Roman satirist Juvenal [1], translates to English as "Who watches the watchers?". Juvenal's belief is that ethical surveillance is impossible when the surveillers (custodes) are corruptible.

In this paper we focus more on the appartaus (i.e. sensor technology) of "watching", rather than on the people/politics. Thus we don't care whether "watching" is sur**veillance** (oversight) [2], [3], or sous**veillance** (undersight) [4], [5], [6], [7], [8], [9], [10], [11], [12], [13], [14], [15]. We treat both veillances equally.

We also examine metaveillance (the sight of sight itself) [16]. Meta is a Greek prefix that means "beyond". For example, a meta conversation is a conversation about conversations, and meta data is data about data. Metaveillance is the veillance of veillance, and more generally, metaveillance is the sensing of sensors and the sensing of their capacity to sense.

Thus we might ask:

"Quis sensum ipsos sensorem?"

i.e. "Who senses the sensors?", or more generally, "How can we sense sensors, and sense their capacity to sense?", and how and why might this ability be useful?

"Bug-sweeping", i.e. the finding of (sur)veillance devices is a well-developed field of study, also known as Technical surveillance counter-measures (TSCM) [17], [18], [19]. However, to the best of our knowledge, none of this prior work reveals a spatial pattern of a bug's ability to sense.

A. Metaveillance and metaveillography

Metaveillance (e.g. the photography of cameras and microphones to reveal their capacity to sense) was first proposed

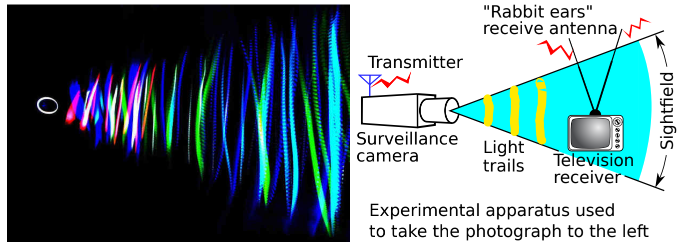

Fig. 1. Early example of metaveillography (metaveillance photographs) using the feedbackographic techinque [23], [20]. Phenomenological augmented reality from the 1970s using video feedback with a black and white television screen. Mann observed that when a television was tuned to the frequency of a surveillance camera's transmitter, it would glow more brightly when visible to the camera. Thus waving the TV back and forth in front of the camera in a dark room would trace out the camera's metaveillograph, visible to the human eye or photographic film (by way of a second camera loaded with film). Modifying the video amplifier for various gain levels and photographing the moving TV through color filters showed spatial variation in the quantity of metaveillance: blackness indicates zero metaveillance; dark blue indicates moderate metaveillance, and red indicates strong metaveillance. Green indicates a quantity between that of red and blue.

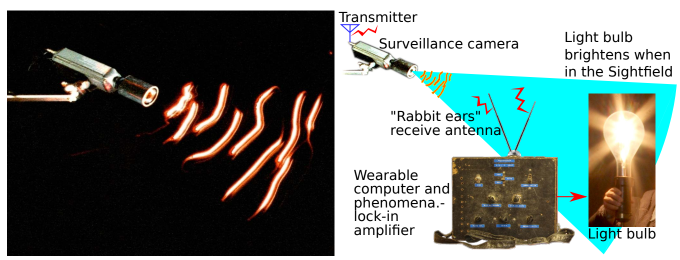

Fig. 2. Improved version of the apparatus of Fig. 1, using a light bulb instead of an entire television display [23], [20]. A wearable computer and videographic lock-in amplifier was designed specifically to lock in on extremely weak television signals. The light bulb goes from a dim red glow to a brilliant white whenever it enters the camera's field-of-view, and then the bulb brightness drops off again when it exits the camera's field of view. Waving it back and forth in a dark room reveals to the human eye, as well as to photographic film (picture at left) the camera's metaveillance field. The glow from the light bulb lags behind the actual physical phenomenon. Thus as we sweep back-and-forth, odd numbered sweeps (1st, 3rd, 5th, and 7th, and 9th) appear near the top of the sightfield, whereas even sweeps (2, 4, 6, 8) appear near the bottom.

by Mann in the 1970s [20], [21], [22] (see Fig. 1 and 2). Metaveillance was envisioned as a form of visual art [24] and scientific discourse [20], and further developed by Mann, Janzen, and others [25], [26] as a form of scientific measurement and analysis.

SWIM for phenomenological augmented reality using a linear array of light sources, sequentialized through a wearable computer system with a lock-in amplifier, was a childhood

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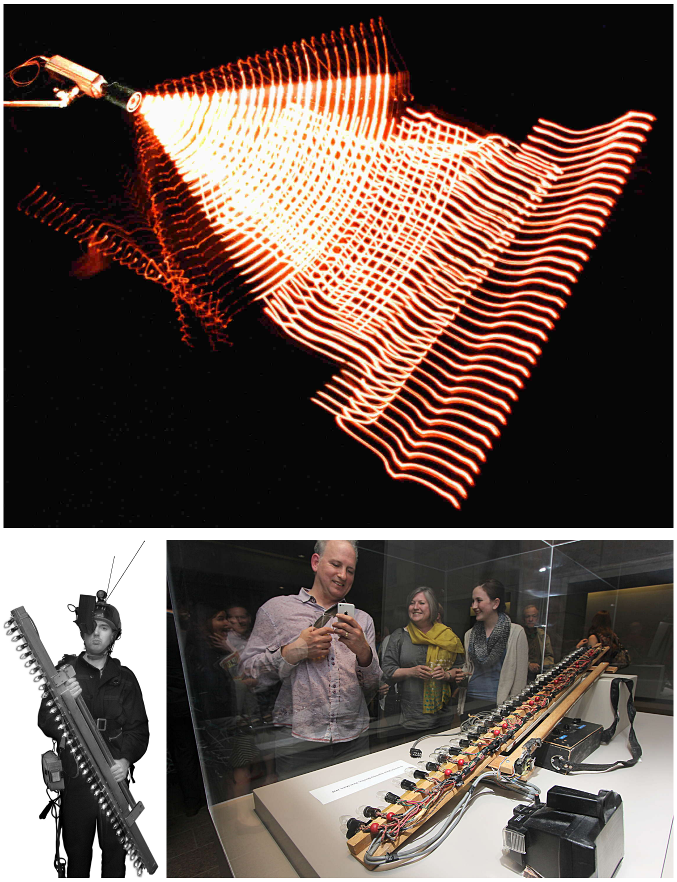

Fig. 3. Sequential Wave Imprinting Machine (SWIM) consisting of a linear array of electric light bulbs connected to a wearable computer and wearable lock-in amplifier. This functioned like a giant "paintbrush" to create an augmented reality world from the physical phenomenology of metaveillance [16], [21], "painting" with the light to expose the human eye or photographic film to the camera's metaveillance field. Rightmost: World's first wearable augmented reality computer (built by S. Mann in 1974) on exhibit at National Gallery in 2015.

invention of S. Mann [21], [22]. See Fig. 3.

A more modern version of this apparatus appears in Fig. 4

B. Veillance games

A number of games have been built around the concept of metaveillance and metaveillogrammetry, as illustrated in Fig. 5 Veillance games are based on sensing of sensors, such as cameras or microphones. Game themes such as "spy versus spy" are played out in the realm of veillance, counterveillance, and metaveillance. Some games play directly to human vision whereas others use an eyeglass-based device to capture and freeze the exposures into a 3D virtual world or the like. Some games use photographic media, which also creates a new visual art form in and of itself.

Note that the pictures in Fig. 1 to 5 are photographs, not computer graphics. The word "photography" is a Greek word that means "drawing or painting" ("graphy") with "light" ("photos" or "phos"). Thus the Greek word "photography" means "lightpainting" if we translate the word directly into

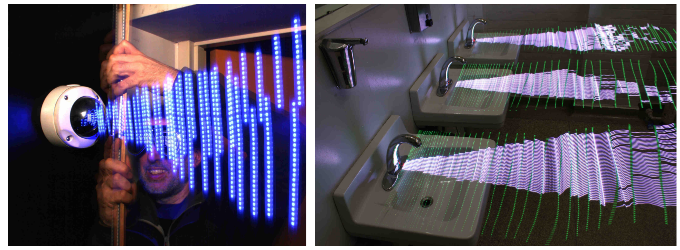

Fig. 4. Modern LED-based version of SWIM. Waving the wand back and forth makes the sightfield (metaveillance) of the surveillance camera or other vision sensor visible, using the methodology of [27]. This allows us to see and better understand the otherwise invisible Internet of Things (IoT) around us. The Internet of Things has grown tremendously in recent years. For a good summary of this development, see [28] and the earlier version of the paper on arXiv [29]. In this figure, we see the metaveillograph of a surveillance camera (left) as well as three sensor-operated handwash faucets (right) that each contain a 1024 pixel camera and vision system. Many washroom fixtures contain low-resolution cameras [30], [31], [32] that can be better understood by way of metaveillography.

English. In this way, photography has been regarded as "nature's pencil", as evident in the following quote:

> "The plates of the present work are impressed by the agency of Light alone, without any aid whatever from the artist's pencil." [33], [34]

In a similar way, we aim to create new computational media that arise directly from nature itself, using computers to reveal natural philosophy (the physics of waves, sensing, etc.) and thus make visible otherwise hidden phenomenology.

C. Seeing and photographing radio waves and sound waves

In addition to seeing sight itself (i.e. metaveillance), SWIM has also been used to see and photograph radio waves and sound waves in near-perfect alignment with their actual situated existence (unlike an oscilloscope, for example, which does not display waveforms situated at their natural physical scale and position). See Fig. 6.

D. Grasping radio waves and sound waves

In addition to merely seeing radio waves and sound waves, we can also reach out and touch and feel and grasp these otherwise intangible waves. This is done using a mechanical form of the SWIM, as shown in Fig. 7.

See Fig. 8.

E. Representing complex-valued electric waves using color

A method of representing spatially varying complex-valued electric waves was proposed by Mann [21], in which the color at each point encodes the phase in a perceptually uniform Munsell colorspace, and the amplitude as the overall quantity of light. An example of Mann's method also appeared as cover art for the book, depicting the Fourier operator (i.e. the integral operator of the Fourier transform as a two-dimensional function in which one dimension is time and the other dimension is frequency). See Fig. 9, and the following Matlab fragment:

```
% fourieroperator2dat.m                          Steve Mann 1992 Jan 20
%
% creates the fourieroperator W = exp(j2pi|f><t|)
f = (-(M-1)/2:(M-1)/2)*frac;        % time span 1 second:  (-.5,.5) second
...
  t = (n - (N+1)/2)/N;  % freq range for the given block
  W  = exp(j*2*pi*f(:)*t(:).');  % faster as a one-liner
```

Fig. 5. Veillance games played with a camera mounted onto a toy gun. There are at least two players: the shooter and the defender. The shooter tries to shoot a recognizable picture of the defender and wins points for doing so. The defender enforces a "no photography" policy. The defender wins the game by catching the shooter taking pictures, which is done by waving the SWIM (Sequential Wave Imprinting Machine) back and forth in front of the camera, to make its picture-taking activity visible. The SWIM is visible in the middle picture. It is 48 cm long, runs on three AA batteries.

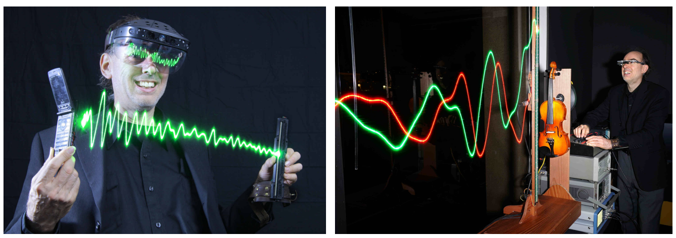

Fig. 6. Photographs of radio waves and sound waves taken with SWIM. (left) Custom-modifications to a smartphone were made, and it was desired to see and understand the radio waves from the phone, and how they propagate through space. Waving the wand back and forth allows the waves to be seen by the naked eye, as well as be photographed. (right) In the design of musical instruments it is helpful to be able to see the sound waves from an instrument and see how they propagate through space. Here a robotic mechanism was built to excite the violin at various frequencies and their harmonics, using a Pasco Fourier Synthesizer driving a robotic actuator that keeps the strings vibrating continuously. A robotic SWIM moves back-and-forth on a 10 foot long (approx. 3m long) optical rail. The SWIM includes 1200 LEDs (Light Emitting Diodes), that make visible the complex-valued waveform (real, i.e. in-phase component in red, and imaginary, i.e. quadrature component in green).

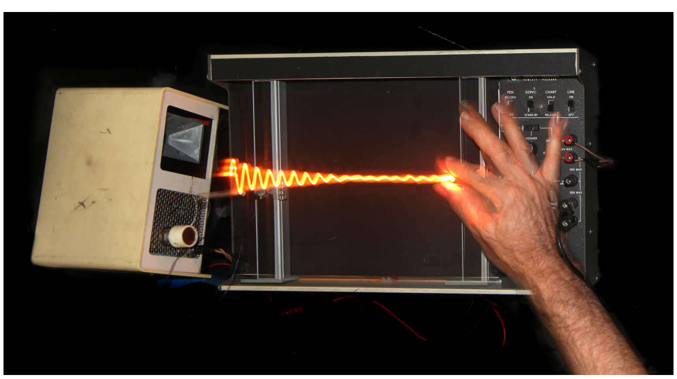

Fig. 7. Mann's early 1970s apparatus for seeing, touching, grasping, and feeling electromagnetic radio waves. An XY plotter was arranged to freely move from left-to-right ("X"), while the up-down movement ("Y") was driven by the output of a lock-in amplifier tuned to a desired radio frequency of interest. A light bulb was placed where the pen of the XY plotter would mormally go. An antenna was placed on the moving part of the XY plotter. In this way the antenna moves together with the light bulb to trace out and make visible the otherwise invisible electromagnetic wave, while also allowing the user to grasp and hold the pen holder that also houses the light bulb.

```
  mag = abs(W);  %  change rowvec to colvec
  o = pi/180;   % the degree symbol
  p   = 180 - angle(W)/o;  % angles per degree shifted to all positive
...
  g_to_r_indices = find (p < 144 &  p >= 0);  % red to green crossfade
  r(g_to_r_indices) = p(g_to_r_indices)/144;         % RED
  g(g_to_r_indices) = (144-p(g_to_r_indices))/144;  % GREEN
  b(g_to_r_indices) = zeros(size(g_to_r_indices));  % BLUE

  r2b_ind = find (p >= 144 & p < 288);        % r to b crossfade
  r(r2b_ind) = (288-p(r2b_ind))/144;
  g(r2b_ind) = zeros(size(r2b_ind));
  b(r2b_ind) = (p(r2b_ind) - 144)/144;

  b2g_ind = find ( p >= 288 & p < 360 );      % b to g crossfade
  r(b2g_ind) = zeros(size(b2g_ind));
  g(b2g_ind) = (p(b2g_ind) - 288)/72;
  b(b2g_ind) = (360-p(b2g_ind))/72;

  R = floor(r.*mag*255.99);   % scale by magnitudes; from black to red
  G = floor(g.*mag*255.99);   % scale by magnitudes; from black to green
  B = floor(b.*mag*255.99);   % scale by magnitudes; from black to blue
...
```

In what follows, we will be using this method to show the spatially varying complex-valued electric waves from a transducer moved through space to sample a complex-valued wave function or meta wave function.

II. Veillogrammetry versus Metaveillogrammetry

It is useful to define the following basic concepts. Thus we proffer the following *veillance taxonomy*:

- **Surveillance** is the purposeful sensing by an entity in a position of authority (typically a government or a an organization within their own space, such as a convenience store monitoring their own premises);
- **Sousveillance** is the purposeful sensing of an entity not in a position of authority (typically an individual or small group);
- **Veillance** is purposeful sensing. It may be sur-veillance or sous-veillance. For the purposes of this paper, we focus on the mathematics, physics, and visual art of veillance, and thus make no distinction between surveillance and sousveillance. Thus we use the term "veillance" rather than "surveillance" when we wish to ignore the political elements of sensing, and concentrate exclusively on the mathematics and physics of sensing.
- **Veillography** is the photography (i.e. capture) by way of purposeful sensing, such as the use of surveillance or sousveillance cameras to capture images, or such as the photography of radio waves and sound waves and similar

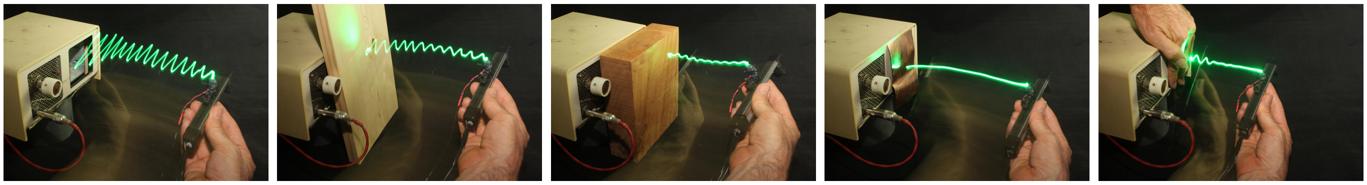

Fig. 8. Tactile Sequential Wave Imprinting Machine (TSWIM) uses a mechanical actuator to move a single light source up-and-down while the device is waves side-to-side. The user can feel the mechanical movement and thus feel the wave. Here we can see and touch and grasp and hold electromagnetic radio waves as they pass through various media. Leftmost: wave propagation in air. Second from left: radio wave propagation through thin wood. Third: radio wave propagation through thick wood. Fourth: through copper foil. Fifth: through flesh. Note the differences in amplitude which can also be felt as well as seen.

phenomena as illustrated in Fig. 6. Our experimental setup for this is shown in Fig. 10.

- **Veillogrammetry** is quantified sensing (e.g. measurement) performed by purposeful sensing. For example, video from a bank robbery may be used to determine the exact height of a bank robber, through the use of photogrammetry performed on the surveillance video. Likewise, veillogrammetry with a microphone moved through space can be used to quantify the sound field distribution around a musical instrument in order to study the instrument's sound wave propagation.
- **Metaveillance** is the veillance of veillance (sensing of sensors). For example, police often use radar devices for surveillance of roadways to measure speed of vehicles so that they can apprehend motorists exceeding a speed limit. Some motorists use radar detectors. Police then sometimes use radar detector detectors to find out if people are using radar detectors. Radar detectors and radar detector detectors are examples of metaveillance, i.e. the sensing (or metasensing) of surveillance by radar.
- **Metaveillography** is the photography *of* purposeful sensing, e.g. photography of a sensor's capacity to sense, as illustrated in Figures 1 to 5. Our experimental setup for metaveillography is shown in Fig. 11.
- **Metaveillogrammetry** is the mathematical and quantimetric analysis of the data present in metaveillography.

Comparing the setup of Fig. 10 with that of Fig. 11, the difference is that in Fig. 10, a signal sensor (receiver) moves with the SWIM, and the reference to the lock-in amplifier remains fixed at a stationary location, whereas with Fig. 11 the reverse is true: a transmitter that feeds the lock-in amplifier reference moves with the SWIM, and the signal input comes from a stationary sensor fixed in the environment.

We make the argument that veillography and metaveillography are inverses of each other, and that veillogrammetry and metaveillogrammetry are also inverses of each other.

A. *Experimental comparison of veillography and metaveillography*

Here we produce two photographs of acoustic intereference patterns due to two transducers. The first photograph is a picture (veillograph) of sound waves coming from two identical fixed (non-moving) ultrasonic tranducers transmitting at 40,000 cycles per second, captured by a third identical moving transducer (used here as a microphone) in a plane defined by the central axis of the speakers. A diagram showing the experimental apparatus is shown in Fig. 12.

The second photograph is a picture (this time a metaveillograph) in which the roles of the transmitters (speakers) and receiver (microphone) are reversed.

These two photographs are shown in Fig 13, directly above one-another for easy comparison (since the sound waves travel left-to-right or right-to-left).

We chose to use ultrasonic transducers (the exact transducers used in most burglar alarms and ultrasonic rangefinders) because they work equally well as microphones or speakers.

What we discovered is that the two pictures are visually indistinguishable from one-another. We see the same interference fringes (interference patterns) from the pair of transducers whether they function as speakers or microphones. As an array of speakers we see the sound waves coming from them. As an array of microphones, we see the metaveillance wavefunctions [16], and both appear identical.

Moreover, storing the data from the lock-in amplifier into an array, using a 24-bit analog to digital converter, allowed us to compare precise numerical quantities, and to conclude experimentally that veillogrammetry and metaveillogrammetry are inverses of one-another, i.e. that the two image arrays give precisely the same quantities.

Fig. 14 shows a comparison between these two experimental setups:

1) a transmitter array sending out sound waves that are sensed with a single receiver (veillogrammetry), and;
2) a receiver array (microphone array) metasensed [16] with a single transmitter (metaveillogrammetry).

Here the coefficients of correlation between sensing and metasensing were found to be 0.9969 for the real parts, and 0.9973 for the imaginary parts.

We also tested the situation of just one transmitter and one receiver (i.e. array size of 1 element). With single transmit and single receive, the correlation coefficients were found to be 0.9988 for the real part and 0.9964 for the imaginary part.

III. Using SWIM for engineering design

In one of our "spy versus spy" game scenarios we wished to design a microphone array. Being able to see the metaveillance of the microphone array helped us design it better. Fig. 15 shows a metaveillograph of an example microphone array of six microphones.

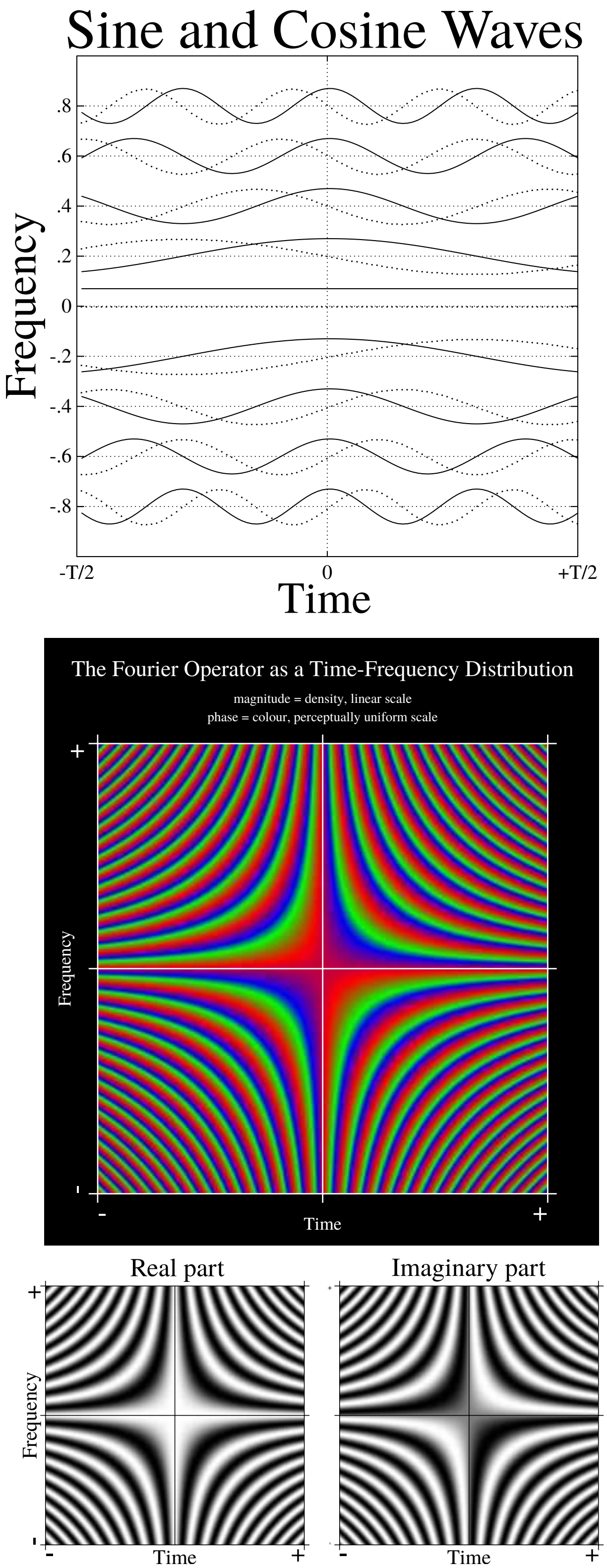

Fig. 9. Fourier operator (integral operator of the Fourier transform) as a spatially and temporally varying complex-valued wave function. Here color is used to represent the complex-valued electric waves, allowing us to see both the real and imaginary parts superimposed together. In the corresponding plots, solid lines indicate the real parts, and dotted lines indicate the imaginary parts. Reproduced from [21].

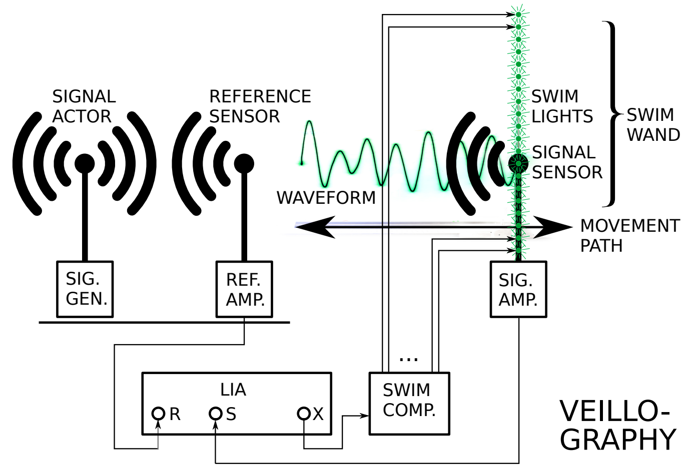

Fig. 10. Here is the experimental setup that was used to generate the photographs of radio waves and sound waves in Fig. 6. A moving sensor (receive antenna for radio waves, or a microphone for sound waves) is attached to the linear array of lights (SWIM LIGHTS) and moves with it. This sensor feeds the signal input of a lock-in amplifier. The reference input to the lock-in amplifier comes from a reference sensor fixed in the environment (not moving), near the radio signal source or sound source.

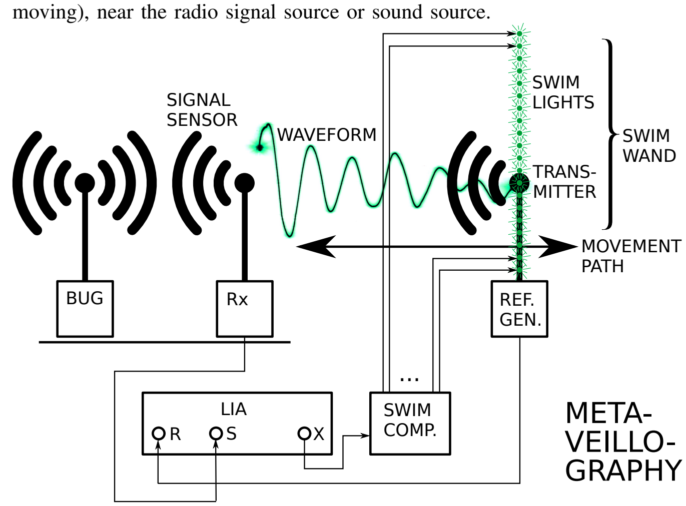

Fig. 11. Here is the experimental setup that was used to generate the photographs of Figures 1 to 5. It functions much like a "bug sweeper" but in a much more precise way, driving the linear array of light sources (SWIM LIGHTS) that is waved back-and-forth. For Figures 1 and 2, the array is a single element (just one light source). For Figures 3 to 5, the transmitter is the light source itself. Alternatively, as we shall see, the TRANSMITTER can be the light source itself, or a loudspeaker (for audio "bug sweeping"), or a transmit antenna (to detect and map out receive antennae).

IV. The Art of Phenomenological Reality

We have, in some sense, proposed a new medium of human creative expression that is built upon nature itself, i.e. natural philosophy (physics). In this new medium, nature itself "paints" a picture of an otherwise invisible reality.

For example, consider a microphone like we often use when we sing or speak at a public event. There is an inherent beauty in its capacity to "hear", and in that beauty there is a truth in the physical reality inherent in it.

Its capacity to "listen" is something that we can photograph, as its veillance wave function [16], which is a complex-valued

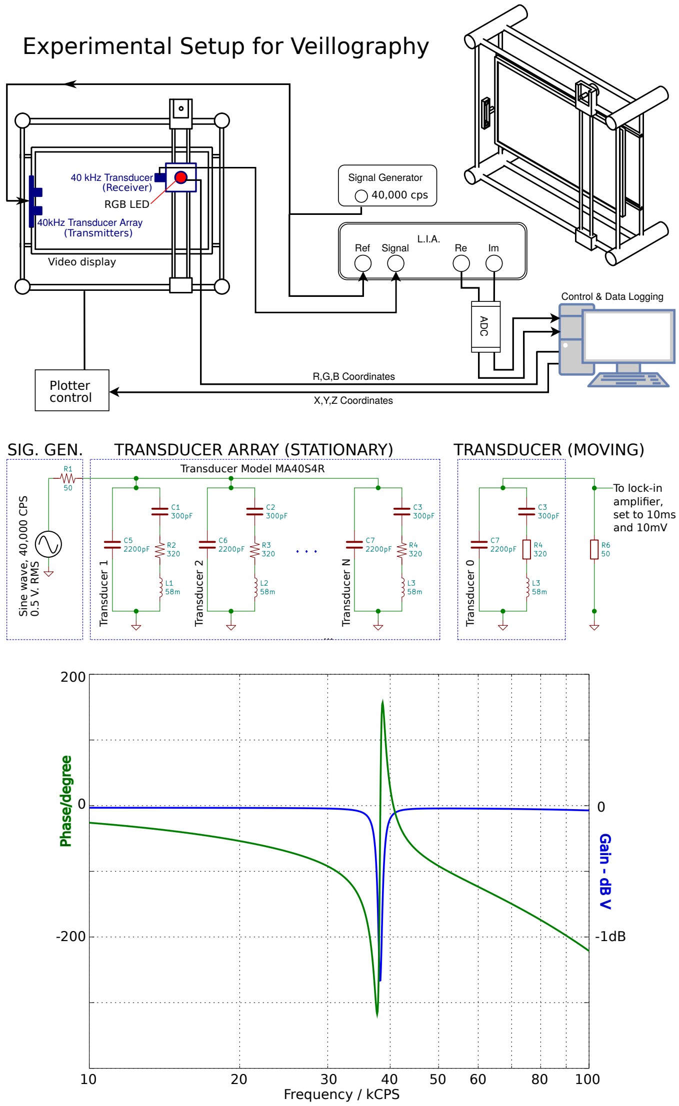

Fig. 12. Apparatus (with equivalent circuit schematic and frequency response) for the experimental comparison between veillography and metaveillography. Here is shown the apparatus connected for veillography, with a stationary array of transmitters (speakers) and a moving receiver (microphone). This corresponds to the top picture in Fig. 12. For metaveillography (bottom picture of Fig. 12), the connections between the stationary transducer array and the moving transducer are simply swapped.

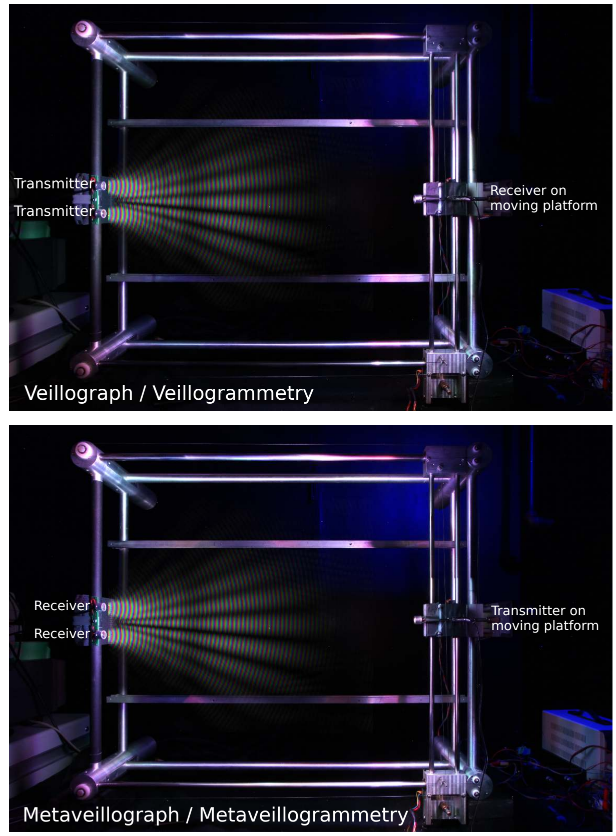

Fig. 13. Top: photograph of a sound wave emanating from two speakers. Bottom: photograph of a veillance wave function "emanating" from two microphones (i.e. a photograph of the capability of two microphones to "hear").

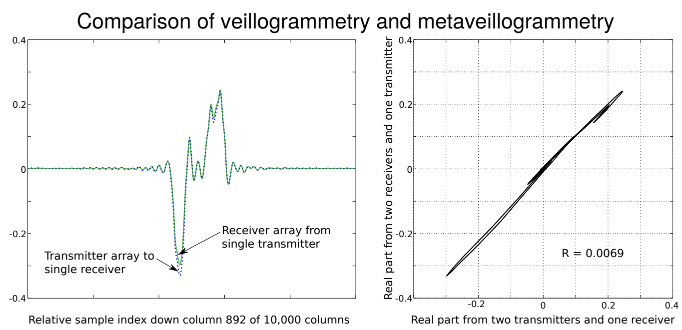

Fig. 14. Comparison between double transmit and single receive (veillogrammetry) and double receive and single transmit (metaveillogrammetry).

function. See Fig. 16 and 17.

As this function evolves over time, the veillance waves move outwards from the microphone as the sound waves move inwards towards it. The two move in opposite directions, i.e. in the same way that holes and electrons move in opposite directions in semiconductors.

This movement is merely a phase change, and therefore when we capture a number of photographs over time, we can animate the phase change, to produce a new kind of visual art that also forms the basis for scientific exploration, as well as practical engineering. For example, we discovered that there was a defect in the microphone, as can be seen in Fig. 16. There is visible a dark band in the colored rings. The dark band emanates outwards, pointing up and to the right, at about a 2-o-clock angle, i.e. about 30 degrees up from the central axis. Thus we can see the immediate usefulness of this new form of visual art and scientific sensing. Consider, for example, use in quality control, testing, sound engineering, and diagnostics, to name but a few of the many possible uses of SWIM. Visualization of sound is commonly used in virtual environments [35], [36], [37], and with SWIM, we can directly visualize actual measurements of sound waves.

In our case, we were able to find defects in the microphones we were using, and replace them with new microphones that did not have the defect. Fig. 18 is a metaveillograph of two

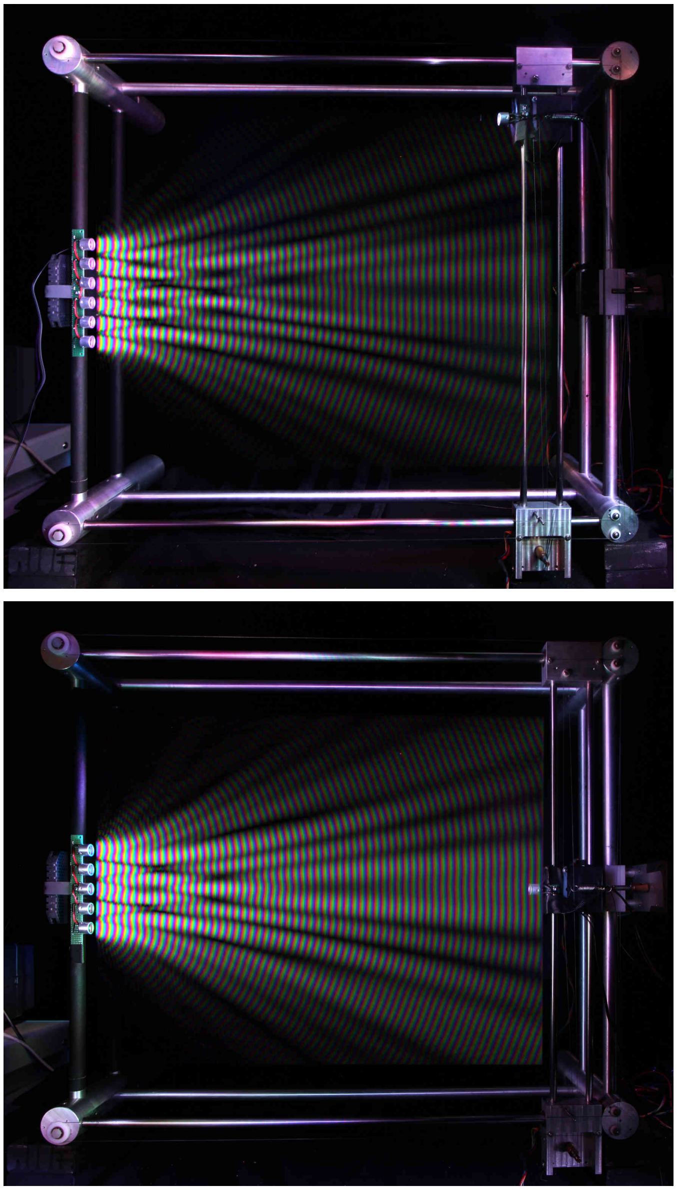

Fig. 15. Using SWIM to assist in sound engineering design. For a game we wished to design an ultrasonic listening device that was very directional. By being able to visualize the metaveillance function (capacity of the microphone array to listen) spatially, we were able to come up with an optimum number of array elements and optimum spacing between them. Here we see a preference for an odd number of elements, i.e. that 5 elements perform better than six, especially in the near-field where the central beam emerges stronger and sooner (sometimes "less is more").

new Shure SM58 microphones we purchased and tested. The SM58 microphone is free of defects that were visible in some of the other brands we tested.

V. Conclusion

We have presented the SWIM (Sequential Wave Imprinting Machine) as a form of visual art and scientific discourse.

As a form of visual art, it can be used for Games, Entertainment, and Media. As a scientific tool, it can be used for engineering, design, testing, and understanding the world around us.

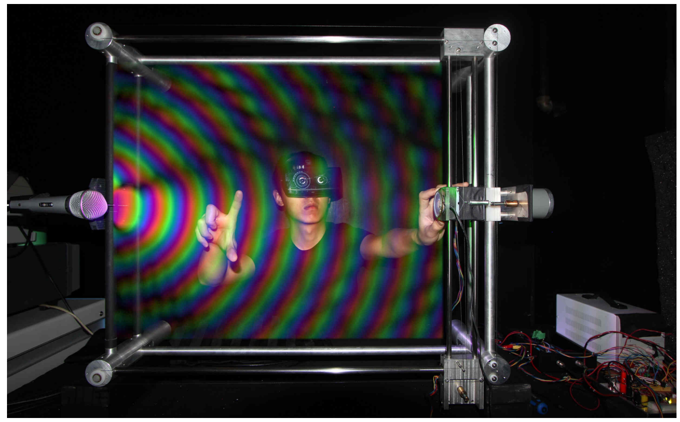

Fig. 16. Metaveillograph of a microphone's capacity to listen to a 7040 cycles per second tone from the speaker at the right: Visualizing hidden defects in sensors. This microphone has a defect in its phase response, as well as a weakness in a particular specific direction. Here the MR (Multimediated Reality) eyeglass is worn by a participant able to see in three dimensions the relationship between cause and effect in real time, even though the photograph only shows a 2D slice through the 3D space.

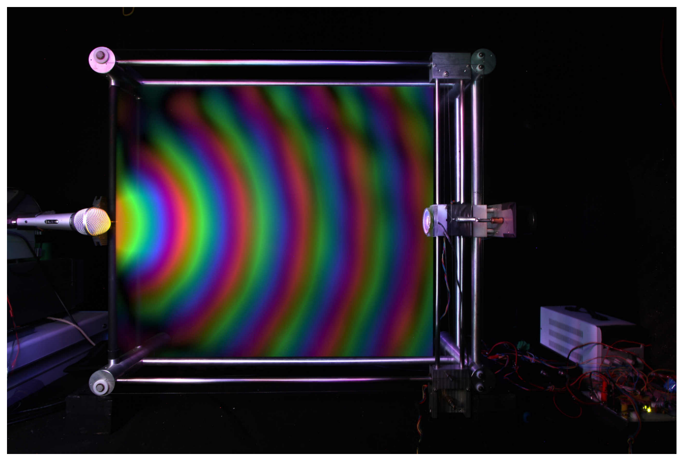

Fig. 17. Metaveillograph of a microphone, where we can see its capacity to hear a speaker (at the right) emitting a 3520 cycles per second tone.

We have shown examples of veillance and metaveillance, as well as also shown that they are, in some sense, inverses of each other (i.e. when we swap roles of transmitter and receiver), and we determined experimentally that this reciprocity holds true to a correlation of better than .995 for the specific cases of a transducer array of length 1, 2, 5, and 6.

Thus SWIM, and phenomenological augmented reality, can be used for engineering, design, testing, art, science, games, entertainment, and media.

Acknowledgments

Thank you to many past and present students, including Ryan, Max, Alex, Arkin, Sen, and Jackson, and others in MannLab, including Kyle and Daniel. Thanks also to Stephanie (age 12) for the observation that the phase of ultrasonic transducers is random, and for help in devising a method of sorting them by phase into two piles: "Stephative" (Stephanie positive) and "Stegative" (Stephanie negative).

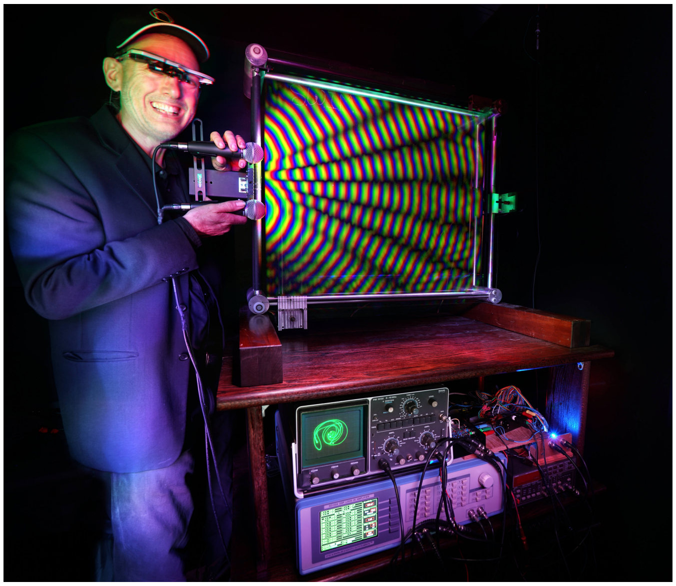

Fig. 18. Metaveillograph of two Shure SM58 microphones. Here we can clearly see their metainterference pattern. Note also the X-Y trace on the CRO (Cathode Ray Oscillograph) that is stacked on to of the lock-in amplifier. The CRO trace shows the real (in-phase) versus imaginary (quadrature) components of the lock-in amplifier output during a portion of the speaker print head's movement.

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