Augmenting Reality with High Dynamic Range Imaging and Sequential Wave Imprinting Machines

by

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Abstract

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A method to automatically adjust multiple exposure-value settings for HDR video compositing has been proposed.

The method uses imagespace-to-lightspace post-conversion and tonal extrapolation to iteratively select optimal exposure settings, as opposed to present systems, which use manually set settings. The limiting factor becomes the image sensor as opposed to the implementation of the algorithm, as in present systems. By choosing the exposure settings with the described algorithm, the high dynamic range sampling process can be adapted to various lighting environments. This algorithm is especially useful for ultra low power capture of optimally selected exposures which can be processed later using well-known HDR compositing methods.

A new Sequential Wave Imprinting Machine (SWIM) based on Steve Mann's invention, has been designed, developed, built and used to teach concepts such as wavelength and wave measurement and wave detection in an immersive and convincing way, by means of phenomenological augmented reality.

The SWIM is like an augmediated reality oscilloscope which uses a linear array of LEDs to paint out detected waves in real-space and real-time. The SWIM allows the user to experience waves in a new way, by painting the wave out, via the tangible interaction of sweeping the SWIM device itself through space.

Improvements in SWIM which are made possible by a simple circuit (with only 2 transistors per element) have been outlined. The result makes possible greater resolution and denser packing, making it more wearable, and thus more accessible in general. Photos and scientific results of the new SWIM are presented.

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Thanks to the amazing group of people at the Humanistic Intelligence Lab who welcomed to their group and helped me throughout this journey. Special thanks to my great colleagues and friends Max Hao Lu and Pete Scourboutakos, who taught me all about sequential wave imprinting machines, for all their great help and guidance. Thanks to Ryan Janzen and Mir Adnan Ali for teaching me the concepts of high dynamic range imaging and providing me with the inspiration for my work on high dynamic range imaging.

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This thesis has been a very informative, inspiring and stimulating journey and has opened my gates to academic research and I hope to continue on the path of academia in the future.

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Chapter 1

Introduction

This thesis highlights a portion of the work carried out over the course of the last 4 months by the author while working with Professor Steve Mann, while being enrolled as a student in the Engineering Science Thesis. Two different projects were contributed to, developing a method for optimal exposure selection for high dynamic range imaging and designing a new sequential wave imprinting machine without the use of LM3914 chips to eliminate the size limitation.

A large portion of this thesis centers around the topic of high dynamic range imaging, which was invented by Steve Mann during his time at the Massachusetts Institute of Technology.

High dynamic range imaging is a technique used in imaging and photography to reproduce a greater dynamic range of luminosity than is possible with standard digital imaging or photographic techniques. The aim is to present a similar range of luminance to that experienced through the human visual system. The human eye, through adaptation of the iris and other methods, adjusts constantly to adapt to a broad range of luminance present in the environment. The brain continuously interprets this information so that a viewer can see in a wide range of light conditions.

A large portion of this thesis also centers around the topic of augmented and augmediated reality, which is a major area of work for the Humanistic Intelligence Lab. The Sequential Wave Imprinting Machine is a wearable computer for shared augmented reality experiences that don't require the additional participants to wear any special apparatus. With the Sequential Wave Imprinting Machine, you can see otherwise invisible sound waves and radio waves, imprinted onto your retina, onto photographic media, or eyeglass/camera. This is due to something Steve Mann calls Phenomenological or Phenomenal Augmented Reality, i.e. the AR (Augmented Reality) of physical phenomena.

A unique feature of Phenomenal Augmented Reality is that the alignment (registration) between the direct view and the overlaid information is near-perfect, because the alignment happens naturally, in the feedback loop of the process. In this sense SWIM is a Natural User Interface.

Steve Mann built the first SWIM 42 years ago, back when he was 12 years old, out of a bunch of old Christmas tree lights that were thrown in the garbage, which he mounted to some scrap wood, driven by a home-made wearable computer he built from surplus parts.

Chapter 2

Background Information

2.1 High Dynamic Range Imaging

Steve Mann invented high dynamic range imaging. When everybody was busy talking about the ways of increasing the number of pixels in an image he wondered about improving the quality of the pixels rather than the mere quantity of the pixels.

High Dynamic Range (HDR) imaging is a process where a number of bracketed exposures are combined and using a process known as tone mapping, an image with more detail in both the highlights and shadows is produced.

This thesis refers to terms such as photoquantity and lightspace. This section attempts to explain the meaning of these terms.

Photoquantity is neither radiometric (e.g. neither radiance nor irradiance) nor photometric (e.g. neither luminance nor illuminance). Photoquantity is the actual light falling on the image sensor.

To determine a set of photoquantities (up to a scalar multiple), the most logical method is to determine the camera response function. The camera response function is a monotonically increasing function which takes a photoquantity and returns a pixel value. The collection of returned pixel values is commonly referred to as imagespace. Consequently, the domain of the camera response function (f) is referred to as lightspace. The camera response function (f) takes as input photoquantimetric values and returns pixel values.

2.2 Sequential Wave Imprinting Machine

In his childhood Steve Mann noticed a transition from transparent easy-to-understand vacuum tube technologies, where manufacturers printed schematic diagrams inviting end users to understand their technologies, to a more secretive closed-source mentality where manufactures started using ICs (Integrated Circuits), and no longer including schematic diagrams. Not only were the schematics absent but many manufacturers took the extra time to grind numbers of the chips to make things harder to understand. So he witnessed the change from manufacturers providing "maps" (schematics = deliberate openness), to manufacturers providing gouges and scratches (deliberate obfuscation).

This was in the early 1970s, and he wanted to be able to see the otherwise invisible radio waves coming from all these new incomprehensible gadgets.

He had an oscilloscope, but it lacked the bandwidth to view radio waves directly. Moreover, its sweep generator was broken: the dot on the screen would only go up-and-down, not across. So he had only a one-dimensional vertically-oriented display. He discovered that if he connected it to a radio receiver, and placed the receive antenna on top of the oscilloscope, while moving the oscilloscope along, that the radio wave from a stationary transmitter would be "painted" out in space. In this sense, he discovered a concept he calls "spacebase" rather than "timebase". The result was a display device that:

1. makes otherwise invisible sound waves or radio waves visible;
2. makes them appear in exactly the same place as they actually are -- perfectly aligned with their actual location in space.

Instead of the oscilloscope, he discovered that he could use a linear array of light sources, electrically controlled, to make a giant augmented reality oscilloscope that, when waved through space, made the radio waves visible in perfect alignment with their actual physicality. He built a wearable computer system to control the lights and display a variety of physical quantities such as sound, video, and radio signals.

He completed this project in 1974 and named it the Sequential Wave Imprinting Machine because it made waves visible by "imprinting" them on the retina of the human eye, or upon photographic film, through PoE (Persistence of Exposure), i.e. the time-integrating property of photographic exposure to light.

Chapter 3

HDR Paper

A research paper was written about the work done on high dynamic range imaging during this thesis. This paper will be published at the IEEE International Symposium on Multimedia 2016.

3.1 Title

Extrapolative Lightspace Method for HDR Video Exposure Selection

3.2 Authors

Sarang Nerkar, Ryan Janzen, Pete Scourboutakos, and Steve Mann

3.3 Abstract

We propose a method to automatically adjust multiple exposure-value settings for HDR video compositing.

The method uses imagespace-to-lightspace post-conversion and tonal extrapolation to iteratively select optimal exposure settings, as opposed to present systems, which use manually set settings.The limiting factor becomes the image sensor as opposed to the implementation of the algorithm, as in present systems. By choosing the exposure settings with the described algorithm, the high dynamic range sampling process can be adapted to

various lighting environments. This algorithm is especially useful for ultra low power capture of optimally selected exposures which can be processed later using well-known HDR compositing methods.

3.4 Introduction

In high dynamic range (HDR) compositing, multiple image exposures of a scene are taken while adjusting the exposure setting to different values, thereby covering a wider dynamic range then that of a single image exposure. In this way, it is possible to overcome the limited dynamic range of a camera.

One aspect of this research is to intelligently combine the data from multiple exposures, while accounting for the nonlinear response of cameras [3] [4] [5] [6] [7] [8] [9]. One method is to reverse the nonlinearity for each exposure, and then weight each pixel in each exposure according to the response function's derivative at that pixel brightness, thus giving a measure of degree of certainty each exposure's pixel gives to the combined measurement [3][5].

A critical step is the choice of exposure settings.

HDR exposure optimization was developed for time-varying signals [1]. This work found a set of constraints used to control exposure settings, based on the properties of a time-varying signal such as light or sound. This method used an "exposure packing" dynamic range to compute the values of exposure gains. Specifically, for imaging, we could apply this to cameras by adding a compensation factor for the camera's nonlinear response.

3.5 Method

To overcome these previous limitations, we convert the tonal range of the image into an equivalent tonal range of physical light levels, for each pixel. The available tonal range given from an image is referred to as imagespace [10], and typically ranges in value from 0 to 255 for an 8-bit image, across red, green and blue channels.

Instead we calibrate a nonlinear model of the camera's response function, which converts a pixel value into an estimated true quantity of light. This true, physical range of values are referred to as lightspace [10].

The M exposure settings, {E1,E2,E3,…,EM}, were chosen as follows:

1) Lowest (darkest) exposure value E1 is set at 1/3 of the difference between the minimum possible exposure setting Emin and maximum possible exposure setting Emax.

2) Highest (brightest) exposure value EM is set at 2/3 of the difference between the minimum possible exposure setting Emin and maximum possible exposure setting Emax.

3) Camera set to E1, and image I1 captured.

4) Camera set to EM, and image IM captured.

5) Image I1 is converted to lightspace image L1.

6) Image IM is converted to lightspace image LM.

7) Histogram H1 formed from L1.

8) Histogram HM formed from LM.

9) Number of saturated pixels s1 calculated from I1.

10) Number of saturated pixels sM calculated from IM.

11) Affine function derived from s1 and sM, and its intercept is calculated at a predicted value of zero pixels saturated.

This leads to a new value of EM.

12) Number of zero-saturated pixels u1 calculated from H1.

13) Number of zero-saturated pixels uM calculated from HM.

14) Affine function derived from u1 and uM, and its intercept is calculated at a predicted value of zero pixels saturated. This leads to a new value of E1.

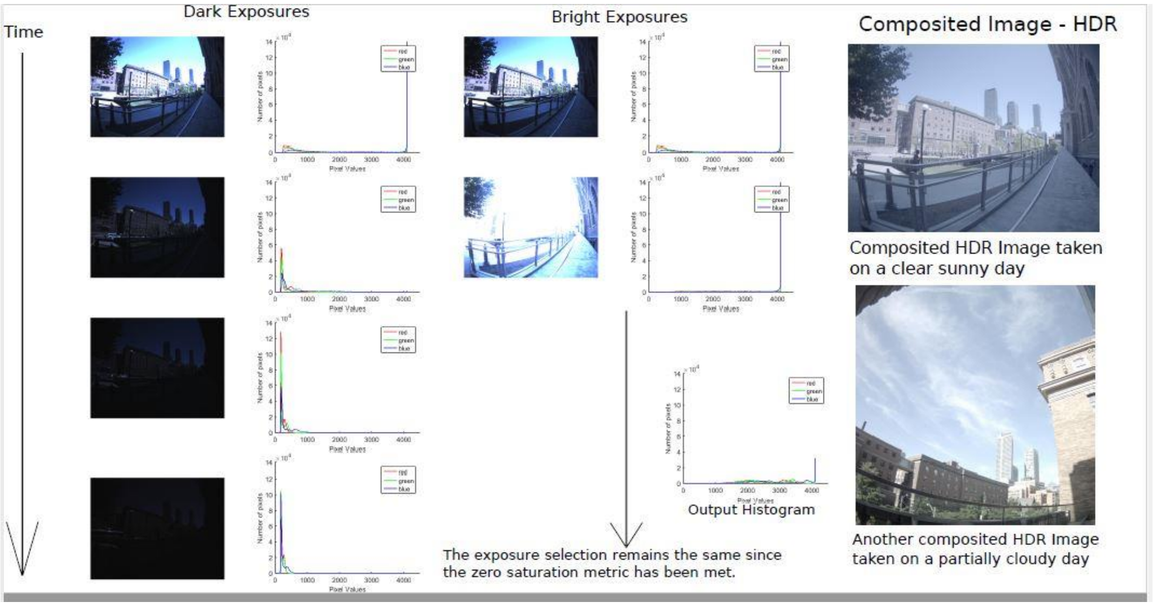
15) Repeat to (3).

3.6 Results

We used an ONSemi NT9P031 image sensor interfaced to EVB1005 development board, which outputted 12-bit images whose pixel-values ranged from 0 to 4095 in each of the red, green, and blue channels.

An example of the system's operation is illustrated in Fig. 1.

Fig. 1 shows the time evolution of two exposures (one dark and one light), until the algorithm is satisfied that sufficient information is known about every pixel, i.e. no pixel is saturated in both input exposures. The final result is a composited image, where each pixel is composed of tonal information from at least one of the two corresponding input exposure pixels. In all cases, the two corresponding input exposure pixels are combined by first converting the 12-bit imagespace pixel values to lightspace by reversing the camera's response function, merging, and re-doing the response function to convert back to imagespace. Fig. 1 also shows another image composited using the presented algorithm under different environmental conditions.



Composited HDR Image taken on a clear sunny day

Another composited HDR Image taken on a partially cloudy day

The exposure selection remains the same since the zero saturation metric has been met.

Figure 1. System operation illustrated, showing the dynamic adjustment of two exposure settings, combined into an HDR image. The exposures are combined in a process from left to right in the diagram. Time evolves from top to bottom in this diagram.

3.7 Conclusion

The new method proposed has been used to automatically select exposure values in order to optimize the exposures of multiple images captured for the purpose of HDR compositing. By choosing the exposure values with the algorithm presented, a high dynamic range is maintained irregardless of the environment, for example on both a sunny and a cloudy day.

Thus, we have devised a new method for automatic exposuresetting control, to enable HDR compositing in any situation.

Chapter 4

SWIM Paper

A research paper was written about the work done on sequential wave imprinting machines during this thesis. This paper will be published at the ACM International Conference on Tangible, Embedded and Embodied Interaction 2017.

4.1 Title

Phenomenologically Augmented Reality With New Wearable LED Sequential Wave Imprinting Machines

4.2 Abstract

The Sequential Wave Imprinting Machine (SWIM), invented by Steve Mann in the 1970s, offers an augmediated reality experience which a group of people can all see with the naked eye (i.e. without the need to wear any special eyeglass).

The SWIM is waved back-and-forth in space, and, through persistence of exposure (to either human sight, or to a camera such as by way of photographic film or sensor array) makes waves visible. Unlike displaying waves on an oscilloscope, SWIM displays waves arranged in space in such a way that they are registered not only in real-time but also in real-space, providing a naturally augmented reality.

This paper outlines improvements in SWIM which are made possible by a simple circuit (with only 2 transistors per element), and recent improvements in LED technology. The result makes possible greater resolution and denser packing, making it more

wearable, and thus more accessible in general. Photos and scientific results of the new SWIM are presented.

4.3 Introduction

Augmediated reality is an experience where by the means of a system of technology, people are able to seamlessly improve or otherwise alter their perception of reality, while situated in reality, which is real-time and real-space.

Where for reality dB = 1, augmediated reality systems may be organized into three types:

1. dB>0 - Those of augmentation, which involve amplification / enhancement / addition of information, such as the system presented here. These systems are augmented reality.
2. dB<0 - Those of diminishment which involve attenuation / subtraction of information, such as HDR for welding. [11]
   These systems are diminished reality.
3. dB E R - Those which are dynamic and can do both, as needed.

Many augmediated reality systems are of the third type, designed as a generalized platform with the intention of supporting a variety of applications, which is in line with the way most personal computers (including smartphones) are thought of as being interacted with [12]. These systems consist of input and output devices, often cameras and aremacs respectively, with computer processing in between [13]. Thanks to ongoing advancements in miniaturization and wearable computer technology, there is large scale interest and commercial development ongoing in these areas [14]. The challenge with a system of this complexity is for it to embody the principles of humanistic intelligence [15] which are key to a system which will provide a seamless and convincing experience which can advance technology for humanity. [16]

The augmediated reality system in this paper is strictly additive (type 1). It is also purpose built for the specific application of the visualization of radio waves, in the same fashion as early augmediated reality experiments carried out by Steve Mann in the 1970s. [17] Recently, with the availability of high efficiency and small SMD LEDs, the SWIM no longer relies on incandescent bulbs and has thus become more practical.

This paper presents two new incarnations of SWIM. The first is based on the LM3914 and provides high resolution (10pixels/cm) at the price of a larger board size. The second is a novel circuit which is used to make a small wearable SWIM which is unprecedented in volume, making these experiments in augmediated reality ever more practical as a wearable.

Head mounted displays, [18] have been used extensively as the output device of choice for augmediated reality systems, [19]. This is natural because they are usually already designed to work as computer displays. These types of devices are well suited to personal augmediated reality experiences, but do not work as easily for activities where multiple people or groups of people are involved and wish to partake in the same experience. For everyone to participate, everyone must wear their own pair of glasses, and high level software/networking systems are required to render the experience for everyone. This creates bottleneck points and opens up opportunities for delays and other issues which can strip the system of its humanistic intelligence, making the experience anything from less convincing to illness inducing to painful. [20] The SWIM system forfeits the complexity imposed by the need for a general purpose system, and instead focuses as a singlepurpose-built augmediated reality system which makes visible normally invisible radio waves. In order to achieve this effect, the SWIM is simply driven with the doppler return output of any low power X band microwave radar set. The SWIM works similarly to an oscilloscope with no timebase generator, by painting out a sensed/measured wave in light so that it is made visible. Instead of the effect of the oscilloscope phosphor we have the phenomenon of persistance of exposure [17]. An oscilloscope works in realtime but virtual-space, on its own 2D display, like most AR systems, while the SWIM uses a 1D display to produce an image like a 2D holograph, which is registered in real-time as well as in real-space, as the user sweeps the SWIM device itself through the waves in space. Last and perhaps most importantly, the augmediated reality experience SWIM creates is easily shared among a group of people, all of whom may bear witness with the naked eye.

4.4 Recent Advances in SWIM

Recently new interest has been raised over SWIM, and several have been built. The first and simplest to implement were digital, with a microcontroller driving cascaded serially programmable WS2812 RGB "neopixels", which can conveniently be purchased in a strip, but pixels are large (greater than 0.5cm) and they suffer from a limited refresh rate. Next SWIMs were built around the LM3914 cascadable 10 segment dot/bar graph display driver IC, which produces excellent results with a high degree of accuracy, tested up to at least 100 cascaded ICs for HD pixel counts and large scale size, the modular design used is seen in Fig.2. The LM3914 was measured to have a bandwidth around 2Mhz, which translates to a very high "refresh rate" and the simple analog system controlling it approaches linear time invariancy, eliminating the possibility of any lag, so the system always responds instantly and the experience is seamless and convincing: humanistic integrity is maintained.

LM3914 ICs were used to make a wristworn "microswim" pictured in Fig.5, which is a 60 pixel SWIM, utilizing 0603 size SMD LEDs, which fits on a 6cm square PCB. An image produced with thisSWIM is found in Fig.4. A novel discrete transistor circuit has been devised, pictured in Fig.3, which makes a low pixel count SWIM smaller and cheaper than is possible with the LM3914. Pictured in Fig.7, an 8 pixel discrete SWIM fits on a 1.25cm by 1.9cm PCB small enough to be worn a ring. An output image from the Ring SWIM is found in Fig. 6.

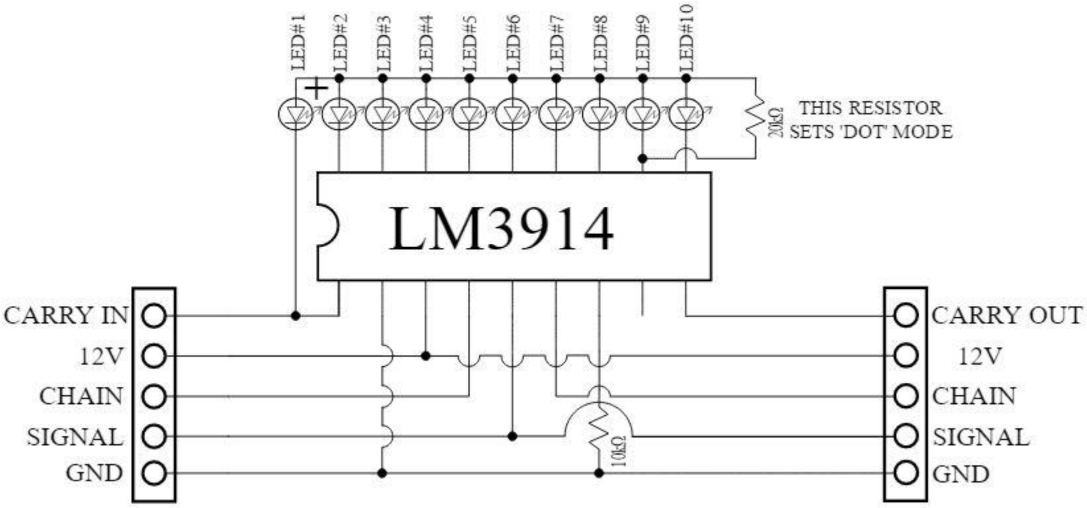


Figure 2: Schematic of modular LM3914 SWIM device.

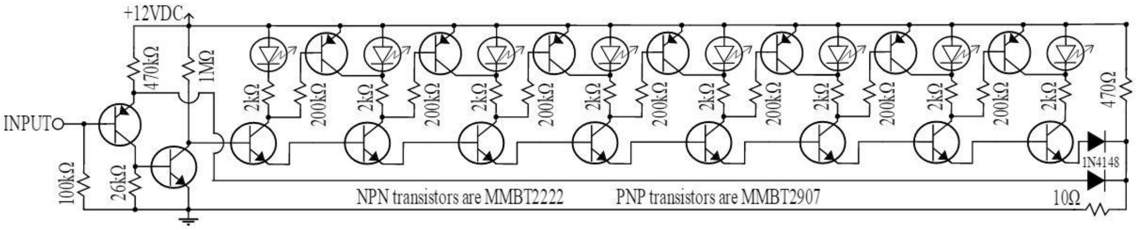


Figure 3: Schematic of novel discrete transistor LED SWIM device.

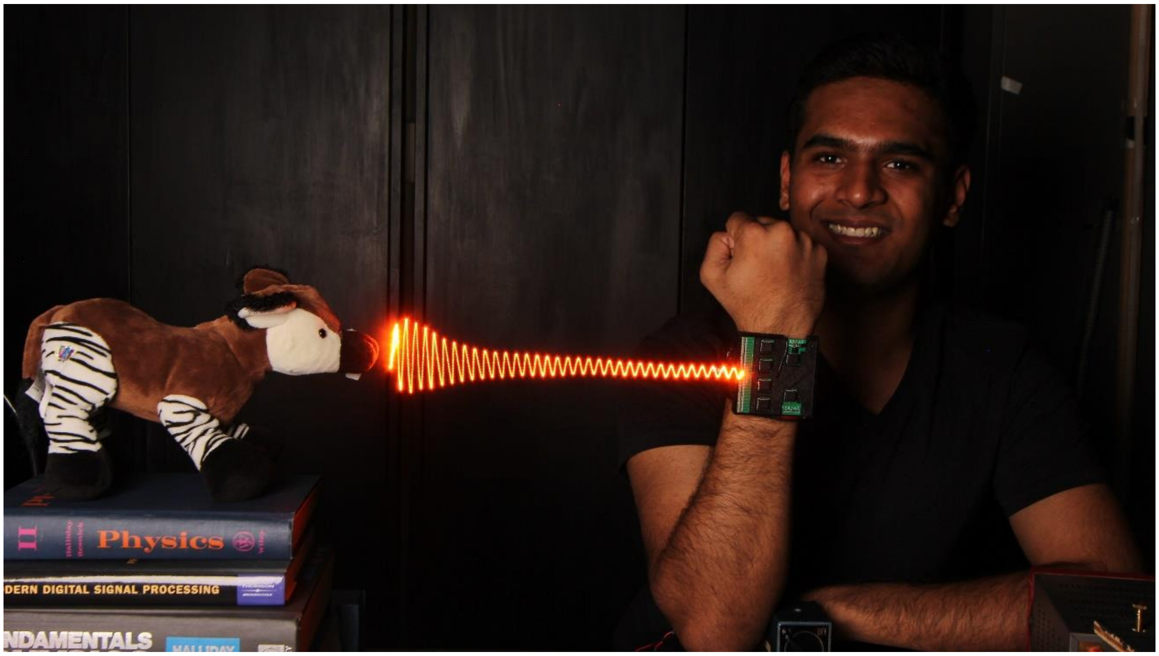


Figure 4: microSWIM visualization

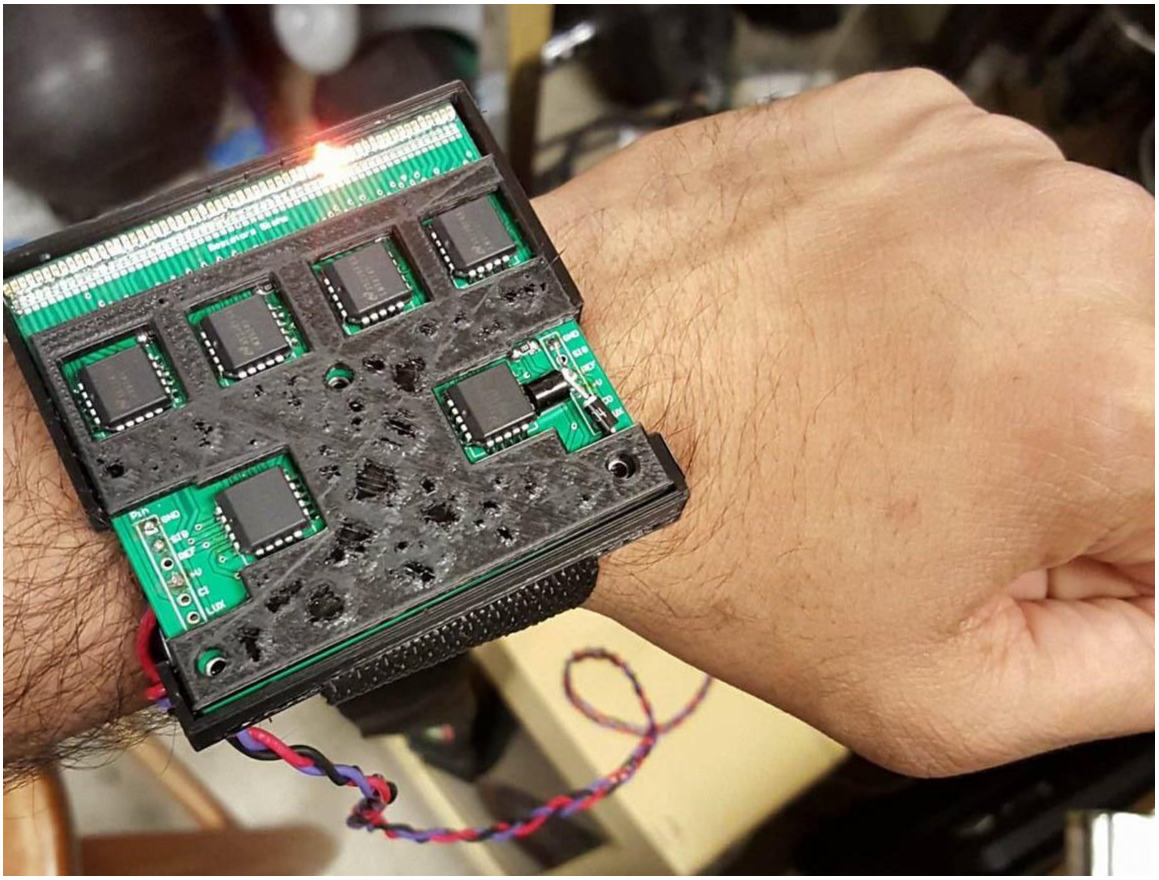


Figure 5: microSWIM

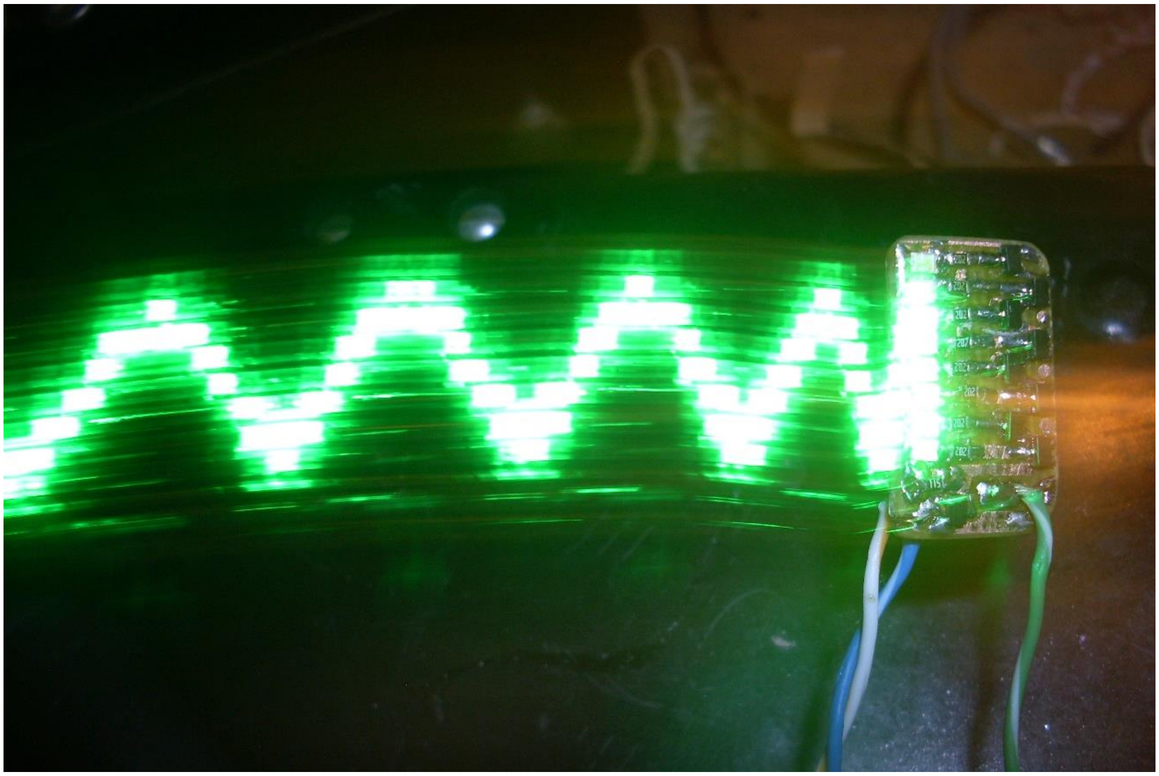


Figure 6: ringSWIM visualization

Figure 7: ringSWIM

4.5 Conclusion

New wrist and ring worn SWIM devices make the SWIM device more wearable than ever, and LEDs allow high resultion and high luminosity with low power consumption. As a result, clear and bright images are produced in order to visualize waves with phenomenologically augmented reality.

Chapter 5

The Sequential Wave Imprinting Machine

The Sequential Wave Imprinting Machine (SWIM), was invented by Steve Mann in the 1970s, as part of the invention of wearable computing and used as an output device for his computer in some of the world's first experiments in augmediated and augmented reality. The SWIM was used for different visualization experiments, but most scientifically notably to make invisible electromagnetic waves visible in real-space and real-time.

The SWIM works by the phenomenon of persistance of exposure and produces a 2D holographic display in space and time using lights. The SWIM may be seen broadly as a general puspose 1D display, simply put, a row of addressable lights. Used in the correct experimental setup, the SWIM becomes a device capable of generating an augmented reality experience. The major example demonstration in this work is the visualization of soundwaves and radiowaves. In this setup, a user interacts with the SWIM by physically sweeping the SWIM device itself through space, much like a broom. By this action, a resulting image is formed which is observable by the naked eye. The images may also be recorded by way of a digital camera or photographic film, and such results are included.

Work presented here outlines new Sequential Wave Imprinting Machines which have been developed as new incarnations of Steve Mann's original SWIM which utilized incandescant light bulbs as the individual pixels. because that is what was practical at the time, see fig. Incandescant lightbulbs work well but are large and inefficient compared to new LEDs. Thus, the defining hallmark of the new SWIMs is that they have been designed with LED type pixels. Along with IC and discrete transistor technology, LEDs have allowed the miniturization of SWIM, making it evermore practical as a wearable and bringing the wearable SWIM into a new era.

One notable improvement made by the miniturization of SWIM is that it can now more easily be swept through space, and waves are more readily observed in realtime by the naked eye. This was possible in the past, but required more effort to move a more cumbersome piece of apparatus fast enough to create the persistance of exposure effect. Miniturized SWIMs presented in this work progress from something looking close to Mann's original SWIM, to a wrist-worn wearable SWIM, to a ring worn wearable SWIM.

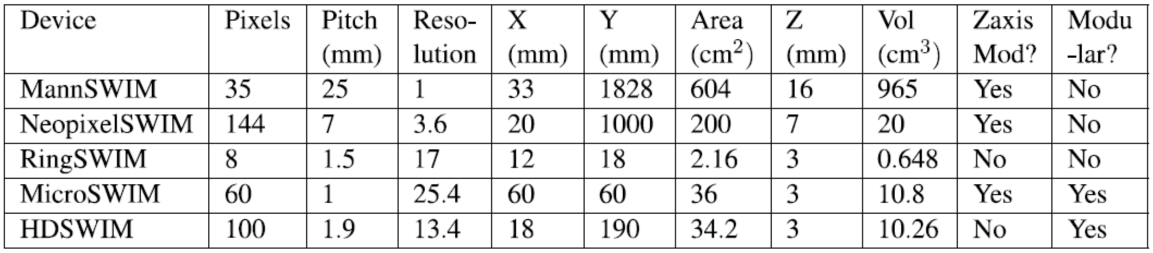
5.1 How does SWIM work and what is it capable of?

The SWIM is a display device based on principle on the oscilloscope. Any oscilloscope may be used as a SWIM device if its timebase is simply switched off and no X deflection applied. The lights on the SWIM act the same way an oscilloscope would, with the usual vertically deflected input, but with no horizontal deflection. The LED pixels of the SWIM are driven in the same manner as a dot graph display, and only one light is illuminated at any given time. The light to be lit is chosen based on the voltage of the given input signal. For a vertically oriented SWIM, a higher input voltage will result in a light lighting which is physically spatially higher than the others, the max input lighting the top light, and consequentially, a lower input voltage will result in a light lighting which is physically spatially lower than the others, the max input lighting the bottom light.

The SWIM is a visual output device, which works much like an oscilloscope, in that it is used to view waves. Radio or sound both work well.

5.2 ringSWIM

The most recent implementation of the SWIM is as a very small wearable, in the form of an 8 pixel SWIM device which may be worn as a ring on the finger. This is made possible by the invention of a novel circuit found in fig. made of discrete transistors and resistors in lieu of the LM3914 IC. In this design, modularity and expandability is traded for smallness of size. Where the other SWIMs are designed to be large, this one is designed to be small, making it more accessible as a wearable.



Device	Pixels	Pitch (mm)	Reso-lution	X (mm)	Y (mm)	Area (cm^2)	Z (mm)	Vol (cm^3)	Zaxis Mod?	Modu-lar?
MannSWIM	35	25	1	33	1828	604	16	965	Yes	No
NeopixelSWIM	144	7	3.6	20	1000	200	7	20	Yes	No
RingSWIM	8	1.5	17	12	18	2.16	3	0.648	No	No
MicroSWIM	60	1	25.4	60	60	36	3	10.8	Yes	Yes
HDSWIM	100	1.9	13.4	18	190	34.2	3	10.26	No	Yes

Table 1: Comparison table for various SWIM devices. X, Y and Z represent the 3 physical dimensions of each SWIM device. Z axis modulation refers to intensity modulation. Resolution is given in pixels/inch.

5.3 Code of Ethics on Human Augmentation

One of the applications of the SWIM device is to visualize the ability of sensors to sense. This ties with the idea of sousveillance and surveillance coined by Prof. Mann. We came up with a Code of Ethics on Human Augmentation in relation to it this summer. Please see Appendix A for the paper.

5.4 Kineveillance paper

I was mentioned as one of the collaborators in Prof. Mann’s paper on Surveillance (oversight), Sousveillance (undersight), and Metaveillance (seeing sight itself). In 2016 IEEE Conference on Computer Vision and Pattern Recognition Workshops. Please see Appendix B for the paper.

Chapter 6

Exposure Selection for High Dynamic Range Imaging

Fig. 8 below shows another result obtained using the exposure selection method presented in this thesis. It can be noticed that there are details in all the shadowy areas of the scene. It can also be noticed that there are details in the entire sky, which normally would be completely overexposed.

Figure 8: A result obtained using the exposure selection method.

6.1 A simple in-flight experiment

On my flight to Boston I saw a beautiful landscape of clouds spreading till the horizon, lit in the golden light of the sunrise. So I decided to take a picture of it with my Samsung Galaxy S6, a phone which was supposed to be one of the best commercially available mobile camera in 2015, with the HDR ON (Fig. 9), HDR AUTO (Fig. 10) and HDR OFF (Fig. 11) options.

Figure 9: HDR ON mode in Samsung S6

Figure 10: HDR AUTO mode in Samsung S6

Figure 11: HDR OFF mode in Samsung S6

It can be observed that the clouds don’t look golden (even though they did in reality) and the area around the window frame is not visible.

I was quite confident that the exposure selection method would do a better job at choosing the right exposures. So I took a sample set of 34 images taken from my phone where the shutter opening times varied between 1/6000s and 1s. I then passed these 34 images in the presented exposure selection method. The algorithm returned the exposure choices shown in Fig. 12, 13 and 14.

Figure 12: Lowest exposure chosen by the algorithm

Figure 13: Mid exposure chosen by the algorithm

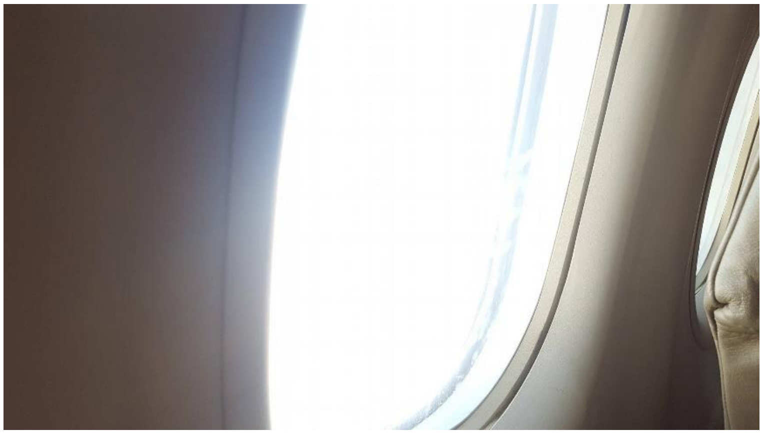


Figure 14: Highest exposure chosen by the algorithm

The composited image is shown in Figure 15.

Figure 15: Final composited image from the in-flight experiment

It can now be observed that the clouds look golden as expected and there are details in the region around the window frame. Thus reaffirming that the exposure selection method works and also beats the current available industry standard in its high dynamic range imaging functionality.

Chapter 7

Ongoing and Future Work

7.1 High Dynamic Range Imaging

The future work in this project will involve the implementation of the exposure selection method in a device that integrates the exposure selection method with the comparametric camera response function high dynamic range image composition algorithm and the camera interface. This device will be an application-independent augmented vision system, since the exposure selection algorithm makes the hardware the bottleneck as opposed to the implementation in the previously seen systems. The block diagram for this system is shown in Fig. 16 below.

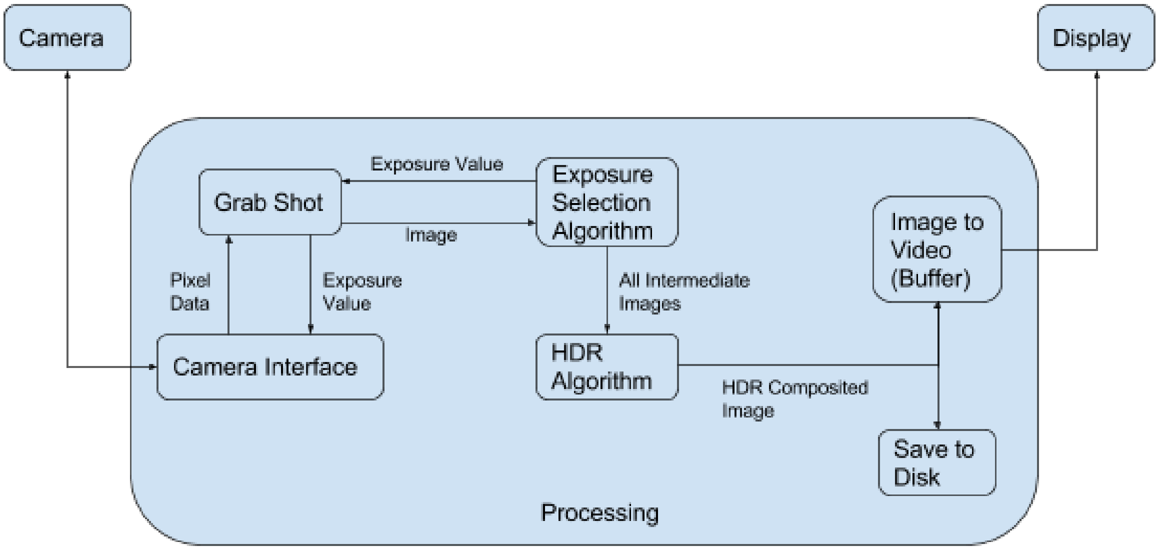


Figure 16: Block diagram for an application-independent augmented vision system

7.2 Sequential Wave Imprinting Machine

The current smallest design of the sequential wave imprinting machine, the ringSWIM, has a limitation. The input voltage has to scale up as the number of LEDs is increased. This is not an ideal condition. The future work in this project should involve the design of a sequential wave imprinting machine which has a simple design that is scalable, without the input voltage limitation.

Chapter 8

Conclusion

- A method for optimal selection of exposures for high dynamic range imaging was developed.
- A novel circuit design for a smaller/ more wearable sequential wave imprinting machine was developed

Chapter 9

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Appendix A

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Appendix B

My work is mentioned here as a collaborator: Steve Mann. Surveillance (oversight), Sousveillance (undersight), and Metaveillance (seeing sight itself). In 2016 IEEE Conference on Computer Vision and Pattern Recognition Workshops.