NEW SEQUENTIAL WAVE IMPRINTING MACHINES VISUALIZE WAVES IN REAL-SPACE AND REAL-TIME BY AUGMEDIATING REALITY

by

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A thesis submitted in conformity with the requirements for the degree of Masters of Applied Science Graduate Department of Electrical and Computer Engineering University of Toronto

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Abstract

New Sequential Wave Imprinting Machines Visualize Waves in Real-Space and Real-Time By Augmediating Reality

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New wearable Sequential Wave Imprinting Machines (SWIMs) based on Steve Mann’s invention, have been designed, built and used as augmediated reality oscilloscopes, to teach concepts of wavelength measurement in real-time and real-space in an immersive and convincing way, by means of phenomenological augmented reality.

Several new SWIM devices are reported on, which are made to meet objectives of wearability, high luminosity and high resolution. Presented are a wrist-worn SWIM device, as well as a ring-worn SWIM device.

A new modular wearable lock-in-amplifier is presented, which completes a wearable SWIM system allowing for visualization of soundwaves in nearly any setting desired.

A systems level analogy is realized between the concepts of the lock-in-amplifier, and of power measurement.

The idea of an electrical efficiency meter is explored and a combination efficiency meter/lock-in-amplifier has been designed and built which has several advantages over existing power analyzers which are reported on.
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Chapter 1

Introduction and Background Information

This thesis highlights a portion of the work carried out over the course of the last 3 years by the author, while working with professor Steve Mann, and enrolled as a Masters of Applied Science student for the past 2 years. A wide variety of projects were contributed to, and several were brought to a stage of fruition, where they were able to be used as demonstrations or teaching tools.

Some of this work contributed to published research findings, such as the recent publication in TEI 2017, the 10th International Conference on Tangible, Embedded and Embodied Interactions: Phenomenologically Augmented Reality With New Wearable LED Sequential Wave Imprinting Machines[1], as well as two recently submitted conference papers currently under review, which are included.

The author was also a co-author on two published conference papers which are not examined in depth in this thesis, because they are not directly related to the works which form the focus. One paper was Integral Kinematics[2] which outlines a new formulation of kinematics, introducing new concepts such as absement, the time-integral of displacement. The second paper was The Code of Ethics on Human Augmentation: the three ‘Laws’,[3] where important implications of advanced human augmentation including augmented reality are examined and related ethical issues discussed.

The research results presented in this thesis are defined by two major objectives, presented here
along with their associated requirements:

1. To improve the function and accessibility of the SWIM device as a wearable augmented reality oscilloscope, chiefly by making the device itself physically smaller and thus more wearable than previously possible. This objective includes designing and building a wearable lock in amplifier to complete the wearable SWIM wave visualization system. The new SWIM should meet the following specific requirements:

   - Small enough to be worn easily.
   - High luminosity, to maintain clarity even for fast sweeps.
   - High resolution, provides high dynamic range, to see small details amongst large ones in the waves.
   - Low power consumption for wearable reasons.
   - Modular such that it may be small and body-worn, or large for demonstrations.
   - High enough bandwidth or "refresh rate" to look convincing and provide correct output, even at high sweep rates.

2. To create a machine which measures and reports the electrical power or energy efficiency of any power converter in a convenient fashion, that is, one which fulfills the following requirements:

   - All in one standalone unit, which is small enough to be easily portable or wearable.
   - Accurate within 2%.
   - Low power consumption, for portability.
   - Requires no programming for basic functionality, such that it is easy to use.
   - Provides realtime buffered outputs from all important signals, for more advanced analysis of power flows and efficiency with an oscilloscope, SWIM or other output device.
The connexion between these objectives is also discussed.

1.1 Background of Objective 1: What is Augmediated Reality and How is it Related to this Work

A large portion of this thesis centers around the topic of augmented and augmediated reality, which is a major area of work for the Steve Mann group, it is also clear that a significant portion of work has been done in relation to power electronics, this is due to the fact that power electronics is a longtime and major area of expertise and interest for the author.

When referring to augmediating reality, we are generally referring to an experience where a person’s perception of what is normal, usual reality, is enhanced by a system made possible by technology, which is somehow able to enhance the participant’s perception of some particular aspect of reality. Augmediated Reality is a subset of mediated reality, and contrasts with virtual reality.

Many varying forms of mediated reality exist, and are often organized into the following categories: augmediated, augmented, diminished, or modulated reality. Many systems of mediated reality are purpose built and often this works best because of a focused design. However, general purpose systems also exist, and have recently roused great interest and funding.

Augmented reality systems are probably most common, and often the simplest possible to implement in any profound or convincing way. An elemental example of an augmented reality system would be a thermometer. The thermometer reports the temperature of its immediate surroundings, and delivers that report from approximately that same particular point in space, which may be difficult to discern otherwise. New information is presented to the user which enhances their perception of reality, by allowing new and more accurate or colourful understanding to result, from the supply of new previously
unknown information. The thermometer thereby augments reality for the user, and it does so in an easy to understand fashion, because the information is presented in the same space to which it pertains. This is in contrast to a potentially more complicated thermometer system, one tending towards virtual reality, which might report in some space, the temperature of some arbitrary different space. Here by complicating the system, it may become more difficult to understand.

Perhaps an important point to make is that true augmented reality is difficult to achieve, since augmenting some aspect of reality will often inherently diminish other aspects, and augmediated reality experiences are more typical.

What makes augmented reality exciting is new and emerging technology which can report on new and ever interesting metrics, far beyond the simple temperature.

New sensors and systems constantly provide people with new information about their surroundings in a variety of scenarios, which is powerful on its own, when the information is presented in any fashion, but presenting this information in an augmediated reality sense means that the information must be presented in situ, where the information itself originates from. This sort of information presentation, somehow overlaid over reality is one ultimate goal of augmediated reality.

This chapter focuses on one specific type of augmented reality system, the SWIM, which is utilized here for the purpose of performing augmediated reality experiments which make visible, normally invisible waves, such as radio waves or sound waves.

1.2 Backround of Objective 2

On the topic of sensors and information, rising environmental concerns have resulted in a great thrust for “greener” technology, with a growing populus becoming conscious of the impact that machine efficiency can have on their carbon footprint and electricity consumption among other things. Power converters are ubiquitous, with many existing for every person in North America. Every laptop, cellphone, and
LED lightbulb for instance, requires a power converter to operate, and the overall power consumption is impacted by the efficiency of the power converter.

One eventual goal of the internet of things would be efficiency metering built into every power converter. This would allow things like future energy audits done in augmented reality, if used along with powerful augmented reality systems such as the Metaview company’s Spaceglasses product. While this pursuit greatly complicates the systems in question, the general trend is on the upswing. Generally put, with the spread of the internet of things, combined with a push for green technology, eventual interest in efficiency metering in augmented reality is a certainty.

One major benefit of widespread efficiency metering, is in device failure prediction. It is known that many forms of component degradation which lead to failure, manifest initially in excess power consumption, and thus first appear as an unexplained decrease in efficiency. This observation may be especially useful for systems which are highly depended on, such as medical systems. If the efficiency is continuously monitored, by watching for an unusual drop which would be indicative of device degradation, device failure can be predicted and better dealt with than if it were to happen by surprise.

1.3 Chapter Outlines

1.3.1 Chapter 2: Augmented Reality and The SWIM

This chapter goes into detail on the background of the SWIM device. Different types of augmented reality experiments that may be performed with SWIM are discussed, and the collection of new SWIM devices which have been built are presented and validated with resulting images of waves.

1.3.2 Chapter 3: SWIM Ring Conference Paper

This chapter is a paper written by the author in collaboration with undergraduate engineering student Sarang Nerkar. This paper centers on the design of a novel circuit which is used to make the smallest
wearable SWIM device to date. This paper is currently under review and submitted to the IEEE ISM International Symposium on Multimedia to be held in December 2016.

1.3.3 Chapter 4: Lock in Amplifier: A Connexion between Augmediated Reality and Power Measurement

This chapter outlines the modular lock in amplifier which was built for the wearable SWIM, and the images that were produced as results are presented. The interesting connection made between augmediated reality and efficiency measurement is discovered to be the lock in amplifier, which happens to be a piece of generalized hardware capable of carrying out both tasks.

1.3.4 Chapter 5: Efficiency Measurement and Analysis

This chapter goes more into detail on efficiency measurement and important considerations in the design of the efficiency meter, such as using the AD734 divider IC, over all 4 quadrants, while it normally only operates in 2 quadrants.

1.3.5 Chapter 6: Efficiency Meter Conference Paper

This is a paper currently under review and submitted to the IEEE APEC Applied Power Electronics Conference to be held in March 2017.
Chapter 2

Augmediated Reality and the SWIM

2.1 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 designed for and used for a variety of visualization experiments, but most scientifically notably, it was used by Mann to produce an effect whereby invisible electromagnetic waves are made visible, much like an oscilloscope does, however markedly different, by being situated in real-space and real-time, where and when the wave exists, as opposed to on a virtual screen. These were some of the first reported experiments in augmediated reality.[12]

The SWIM works by the phenomenon of persistence of exposure and produces a 2D holographic display in space and time using a linear array of pixel style light sources.[13] The SWIM may be seen broadly as a general purpose 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 demonstrations brought to light in this work centre around 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.

The author’s contributions are presented here as the conception, design, prototyping and validation of new LED Sequential Wave Imprinting Machines which have been inspired by Steve Mann’s original SWIM. The original SWIM can be seen in Figure 2.1 and it utilized incandescent light bulbs as the individual pixels, because that is what was practical at the time. Incandescent lightbulbs work well and have enough luminosity, but are large and power 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 ever more practical as a wearable and bringing the SWIM in general 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.

2.2 SWIM Outreach

Given the improvements in wearability and general usability of SWIM, the various new LED SWIM devices have been extensively demonstrated by the author along with Professor Steve Mann, to many hundreds of people over the past few years. SWIM was able to be demonstrated in a very wide variety of settings, with a wide array of onlookers including many students, children and adults alike. Demonstra-
Figure 2.1: Self-portrait of Steve Mann in 1981 with wearable computing apparatus and original incandescent SWIM device.
CHAPTER 2. AUGMEDIATED REALITY AND THE SWIM

Figure 2.2: Professor Mann describes the SWIM device at a TEDx talk this year, while wearing a new LED wristworn SWIM device. The SWIMbot was also presented.
Figure 2.3: Professor Mann wears the new LED wristworn SWIM for his special on Discovery Channel’s “Inventor’s Week” and the SWIMbot is featured as well.

...tions have been given at events like hackathons, and keynote speeches given by Professor Mann on the University of Toronto campus, and off campus, such as at the We Are Wearables Wednesdays meetings at the MaRS Centre. The SWIM was featured by Professor Mann in a TEDx talk this year as seen in figure 2.2. The SWIM was also presented this year on the Discovery Channel as part of “Inventor’s Week” and this event is documented in figure 2.2. The SWIM was filmed this year included in Morgan Freeman’s new science program for television, “Through the Wormhole.” The SWIM has been used to teach children about waves during a visit to Professor Mann’s daughter’s grade 3 class for a demonstration and lesson on wave theory for children. And this year the SWIM was on display and featured at the Canadian National Exhibition in an exhibit on augmented reality.
2.3 How Does SWIM Work and What is it Capable Of?

The SWIM is a visual display device based on the same principle as the oscilloscope, and used for much the same purpose: observation and analysis of otherwise unobservable waves and wave phenomenon. Any oscilloscope may be used as a SWIM device if its timebase is simply switched off and no X deflection applied. Then the oscilloscope itself is simply moved through space and observed from a consistent position. The SWIM is designed as a wearable, such that it is small and light and easy to sweep through the air. The SWIM may be seen as an oscilloscope which is designed for the world of augmediated reality, with a tangible interface. We could call it an augmediated-reality-oscilloscope.

The lights on the SWIM act the same way an oscilloscope would, with the usual vertically deflected input, but with no horizontal deflection supplied. The LED pixels of the SWIM are driven in the same manner as a dot graph display, and the system may be considered basically as an analog to digital converter (ADC), its operation is essentially the same as a flash or direct conversion ADC, with a one-hot encoded output, also known as a ripple output, where the defining characteristic is that 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. So, explained further, 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.

2.4 SWIM for Education

Again broadly described, the SWIM is an output device, similar in function to a computer or oscilloscope monitor. However, by being designed as a 1 dimensional monitor, it takes the form of a wand. The advantage of this improvement is that it allows the SWIM device itself as a physical object, to be
CHAPTER 2. AUGMEDIATED REALITY AND THE SWIM

Figure 2.4: Sarang with wrist-worn microSWIM illustrating the detection of imaginary waves but actually using hidden 40kHz ultrasonic transducers.

the user interface, which makes for a very tangible user interface. What is meant by this, is that the SWIM paints out detected waves only as it itself, is swept through space. As it is swept, its LED output reacts fluidly to the users movement, and this is easily observable by the tangible physical interaction of simply moving the SWIM in space. For instance, by sweeping faster, the waves painted will be larger with a higher amplitude, and by sweeping slower the waves will consequentially be smaller, but the wavelength will always be true to the wavelength of the actual wave being detected. If objects are placed in between the radar and SWIM it is clearly observed that the amplitude is reduced as the waves become attenuated and smaller. It is easily demonstrated that 1 sheet of paper attenuates less than several sheets, or a human hand for that matter.

Most importantly, these waves which are painted as the output of the SWIM device, are registered in real-space and real-time, like an overlay, but actually painted in situ, at the location in space the wave itself is detected, and is continuously painted in a continuous detection process. An oscilloscope or lock in amplifier is capable of displaying a detected wave in real time, but by displaying on its screen
which may be in an arbitrary location, or using an arbitrary timebase, they readout in virtual space. The SWIM device reads out in real space and real time, in a seamless experience that is for these reasons convincing for the user.

Further, embodied as a simple analog circuit, which is inherently a linear time invariant system, there is no ordinary possibility of lag, which is often a problem with digital systems which are more commonplace in this field than analog ones. The SWIM always reacts, and always reacts instantly and predictably. Furthermore by avoiding any cumbersome hardware like electronics eyeglasses can be, the user is free to experience something which is closer to reality, or at least experienced with a smaller barrier. It is much easier for a user to pick up a wand and wave it through the air to make invisible things become visible in space where they exist.

What is more is that the waves painted by the SWIM are easily measured with any ruler, and the wavelength measured is precisely equal to the wavelength of the actual wave being measured. This is what is scientifically valuable about the phenomenon of the SWIM.

For radio waves this means that the precise frequency $F$ of the energy being detected can be measured, according to the formula:

$$F = \frac{V}{\lambda}$$

Where the velocity of the wave is equal to $c$, the speed of light, approximately $3.0 \times 10^8$ m/s:

$$F = \frac{3.0 \times 10^8 \text{m/s}}{\lambda}$$

$\lambda$ is the wavelength which is measured physically using the SWIM and a ruler of any sort. Simply
dividing the speed of the wave in m/s by the wavelength in meters, produces the Frequency \( F \), expressed in cycles per second.

For sound waves a similar experiment was constructed which allows the velocity \( V \) of sound to be precisely measured, again based on the measurement of the wavelength of the wave produced by the SWIM, but with a wave of known frequency. Using the same equation as above, and taking the experiment illustrated in figure 2.4 as the example. The black numbers on the ruler are in inches, and the entire wave can be seen to stretch from the 3 inch to 18 inch mark. Within this 15 inch stretch, 11 cycles are counted. This means that the wavelength \( \lambda \) as measured is \( \frac{15}{11} \) inches. The frequency \( F \) in question here is provided by a function generator and known to be \( F = 10kHz \). Thus if:

\[
\frac{V}{\lambda} = F
\]

\[
V = F \cdot \lambda
\]

\[
V_{\text{SoundInAirMeasured}} = 10kHz \cdot \frac{15}{11}[m/s]
\]

\[
V_{\text{SoundInAirMeasured}} = 13705[\text{inches/s}]
\]

\[
V_{\text{SoundInAirMeasured}} = (13705[\text{inches/s}] \cdot 2.54)[m/s]
\]

\[
V_{\text{SoundInAirMeasured}} = 348[m/s]
\]

The speed of sound is theoretically calculated by the following formula:

\[
V_{\text{SoundInAirCalculated}} = (331 + .606\Delta T)[m/s]
\]
Where \( T \) is the temperature in degrees Celsius and was measured with a thermometer to be 25.0\(^\circ\) Celsius.

\[
V_{\text{SoundInAirCalculated}} = (331 + 0.606 \cdot 25)[m/s]
\]

\[
V_{\text{SoundInAirCalculated}} = 346.15[m/s]
\]

Calculation of measurement error based on theoretically calculated speed of sound in air is as follows:

\[
\text{MeasurementError} = V_{\text{SoundInAirMeasured}} - V_{\text{SoundInAirCalculated}}
\]

\[
\text{MeasurementError} = 348 - 346.15
\]

\[
\text{MeasurementError} = 1.85
\]

\[
\text{MeasurementErrorPercentile} = \frac{\text{MeasurementError}}{V_{\text{SoundInAirCalculated}}} \times 100
\]

\[
\text{MeasurementErrorPercentile} = \frac{1.85}{346.15} \times 100
\]

\[
\text{MeasurementErrorPercentile} = 0.5\%
\]

In these ways the SWIM is ideally suited as a teaching tool for demonstrating some of the effects of how waves work. By having this tool to interact with waves such as either electromagnetic or radar waves, or also sound waves, students are able to experience and learn about waves on a fundamental scientific level.[22]

2.5 New Neopixel Based SWIM

New interest was raised in part by the ability to rapidly prototype a new SWIM. LEDs allow for low power consumption, high luminosity and are available in small SMD packages, therefore allowing close
packing and high resolution, making them the obvious choice of light output device (or pixel), helping to fulfill most of the objectives listed. The only major remaining objective to be fulfilled is bandwidth.

Given the local availability of digital solutions and the ability to very rapidly prototype, the first new SWIM built was a digital SWIM based on the WS2312 RGB "Neopixel"\textsuperscript{TM} \cite{neopixel}, simply because it allowed for the prototype to be very rapidly produced and tested. Neopixels are conveniently available from AdaFruit\textsuperscript{TM} already in strip form, with a pixel pitch of 70mm. The neopixel’s high level of integration allows for ease of application, but comes at other costs.

The neopixel is an integrated circuit LED containing red, green, and blue LEDs, as well a controller IC which pulse width modulates (PWMs) each of the three (RGB) channels in accordance with programmed values. All RGB pixels are programmed by a cascaded serial interface, where any number of WS2812 neopixels may be daisychained in a string and programmed just like one large shift register or
FIFO (first in first out) buffer which is divided into 3 bytes for every pixel, one for each of the colour channels. By transmitting a sequence of bytes totalling 3 times the number of Neopixels, the entire display will be redrawn. Easily driven by any microcontroller with an asynchronous serial port, an Arduino microcontroller was used as a multipurpose display driver for the SWIM. The Arduino and Neopixel strip were mounted on a common strip of hardwood, and thus a complete SWIM device was built, as pictured in Figure 2.5.

![Figure 2.6](image.png)

Figure 2.6: The digital Neopixel-M SWIM with arduino inside blue box which programmes Neopixel LED strip. Modes of operation are selected with two toggle switches and two potentiometers.

Several programs were experimented with for various SWIM experiments, some with success and some with limited success. The limited refresh rate of the Neopixels severely affected the Neopixel SWIM’s ability to react instantaneously to the user’s interactions, which breaks the human/machine feedback loop necessary for a well behaved machine experience which embodies humanistic intelligence[24], [25].

Avoiding the issues of refresh rate, experiments were turned to those involving long exposure pho-
tography, since by using slow sweeping speeds, this is something the Neopixel SWIM excels at, by allowing for a high degree of information to be represented with its RGB colour display. As a group along with the other members of the lab, the SWIM was dubbed a "bugbroom" and used in various experiments and published research involving computer vision and the emerging fields of metaveillage, veillametrics [26] and sightfields [27][28]. The best images were published by Steve Mann in this work. [29]

The digital SWIM was also programmed to do augmediated reality overlays, by displaying an image to be captured during a long exposure photograph while the SWIM device is swept through space. Each column (or row) of pixels from the image, is sequentially displayed on the SWIM, over a period of time. By selecting the appropriate sweeping speed and delay in between row/column advancement, the image to be overlaid can be made small or large. Where most of the other SWIM images seen in this work are over a short distance, less than a metre, Figure 2.5 below shows an example of a large scale SWIM where the word "META" was overlaid in reality for a long exposure photograph with the employees of the Metavision company in 2015.

2.6 Considerations on Neopixel Based SWIM

One major issue with using neopixels for a SWIM device is that the neopixel adjusts LED brightness by the principle of pulse width modulation, which means that the LEDs flicker or turn on and off rapidly, meaning that if the device is swept through space beyond some speed, the flashing on and off will become visible as the traces painted out by the SWIM will appear as dotted lines, instead of solid continuous lines.

Another issue with the digital SWIM is its bandwidth or speed, which equates to its refresh or update rate. As a result of the inherent delay in the cascaded serial programming scheme used by the Neopixels, with any large number of pixels, it is very difficult to make the Neopixel SWIM react
quickly enough to be used in a convincing augmediated reality experiment such as the visualization of waves. The maximum refresh rate or bandwidth for the digital Neopixel SWIM with 144 pixels was experimentally determined to be about 200Hz.

2.7 New LED SWIM, Requirements and Prototyping

Given experiences with Steve Mann’s original SWIM and the pitfalls experienced with the neopixel SWIM, new SWIM requirements were determined:

- Small enough to be worn easily.

- High luminosity, to maintain clarity even for fast sweeps.

- High resolution, provides high dynamic range, to see small details amongst large ones in the
waves.

- Low power consumption for wearable reasons.

- Modular such that it may be small and worn, or large for demonstrations.

- High enough bandwidth or "refresh rate" to look convincing.

Thus, in an effort to fulfill these requirements, new avenues were explored and several analog solutions were developed, each with its own advantages and disadvantages, with different objectives traded off for. Importantly, all of these designs overcome the issues mentioned of the Neopixel SWIM, at the expense of a general purpose reprogrammable design, and RGB functionality. The new designs are purpose built analog devices, more like an analog oscilloscope.

The first new analog version of the SWIM is based on the LM3914 Dot/Bar Display Driver IC\textsuperscript{\textregistered}. By using this IC in dot mode, any waves to be visualized, may simply be input as a voltage signal, and the output is encoded as one illuminated LED, corresponding to the voltage.

The LM3914 Dot/Bar Display Driver IC is essentially designed for this purpose, and with a careful design, allows the modularity, efficiency and size requirements to be met with a very simple circuit,
Figure 2.9: The author looks into the camera in early experiments which validated the new LED SWIM.

requiring only two resistors in addition to the LM3914 IC itself for every 10 pixels. The modular design conceived for this project may be found in Figure 2.7. Thus a SWIM prototype based on the LM3914 was built with 10 LM3914s and 100 LED pixels. The performance of this SWIM was validated by the quality of the images it produced, like Figure 2.7 below for example.

Encouraged by the results, the author mentored another student to design the new PCBs, which were created of the same circuit design, but with SMD parts. 0805 size LEDs were used, spaced 120 thou apart, for a board which is 18mm x 190mm in size with 100 pixels. The key to this board design is that it is modular and there is no gap in between LEDs on separate boards (modules), so the row of LEDs begins and ends exactly at the edges of the board (within 5 thousands of an inch), and connectors are provided at both of these edges which provide enough mechanical connection to keep the boards in line and tight with no gap. A gap will cause an obvious abhorration in the image produced, which can be quite distracting.
The connectors chosen are standard 0.1” spaced machine pin headers, with the male connector being the bottom of the segment, which receives power and signal. With a female connector on the top of the board, additional boards simply cascade one on top of another. Boards were assembled with green LEDs, since green is the most common colour of oscilloscope phosphor. One board was made with red LEDs, in order for experiments with 2 dimensional data to be carried out.

One detail worth mentioning is that each of these SWIMs made up of any number of modules, requires a small “endcap” with a male machine pin connector to be plugged into the top of the topmost board. The purpose of this endcap is to provide the reference voltage for the common resistor ladder through all the cascaded ICs, which determines what the full scale voltage will be.

The great advantage of the LM3914 is that it allows for a convenient modular design and its datasheet from Texas Instruments quotes: ”Expandable to Displays of 100 Steps”[30] however, displays up to 1000 steps (100 ICs) were successfully produced, by cascading 10 of the above boards to achieve approximately HD video resolution. More boards need to be built in order to test the limits of cascading.

With this design, the boards are simply connected together, as many as desired, an endcap is inserted into the connector on the topmost board, and 5V to 12V power as well as signal are applied to the bottom connector. By adding additional SWIM modules, the display will automatically expand to use the full scale for the same voltage input.

Lastly, the fullscale voltage is determined by the voltage applied to the top of the resistor ladder mentioned which is usually taken care of by the endcap. The scale is easily adjusted by custom endcap, or by supply of a reference voltage directly into the top of the resistor ladder.

With a conventional and simplest endcap which simply connects the top of the resistor ladder to the power supply pin, the input is sensitive to some degree to the noise present in the power supply. This may not be an option when a small number of modules are used and the pixel count is low, or when the power supply used is of a very high quality and is sufficiently noise quiet. However when the display is
expanded to a high degree, the resolution is higher and noise becomes more visible as a thick band of lit lights, as opposed to only 1 LED appearing lit at a time which is the case when absolutely no noise is present. Thus, custom endcaps were made with voltage regulators, in order to provide the top of the resistor ladder with a clean reference, which stop the power supply noise from coming through to the output. LM78L05 regulators were generally used, and in a pinch before a demonstration, one could simply be inserted directly into the female machine pin socket at the top of the SWIM with success.

2.8 Multidimensional (Colour) SWIM

One aspect of the design which was considered was to have the row of LEDs as close to the edge of the board as possible. This allows two SWIMs, each with a different colour for its LEDs (each SWIM possibly made up of any number of SWIM modules), to be fixed alongside each other with the two rows of LEDs lined up parallel to each other and as close as possible. The effect is that two different quantities can be represented simultaneously, in two differentiable colours, much like a modern multichannel
oscilloscope. Two separate coloured traces are possible, or one single trace with colour information, which becomes much more expressive with the ability to modulate the intensity.

2.9 Z Dimension - Intensity Modulation

At this point, a new requirement was considered, which is the modulation of the light output intensity from the SWIM. This would make the SWIM more versatile since then the luminosity could be adjusted for best contrast in different lighting situations, or also modulated as another dimension of information to be displayed by the SWIM. This allows the SWIM to be more readily observed by the naked eye, and also enables the production of better photographic images, with the new provided degree of freedom.

The LM3914 has a constant current regulator for each output, and provides a brightness control pin, which must be loaded with a reference current, which it keeps the output current proportional to. This provides some control over the brightness, but there is a minimum programmable current; the circuit does not allow control anywhere near zero. With perception of light so exponential, the lower register of the control is most important. Thus, the SWIM was modified such that its brightness can be modulated to zero. The solution is elementary, a resistor was added in parallel with each LED, in order to sink the quiescent current and quench the LED at the minimal brightness setting. This somewhat impacts the maximum brightness, but there is enough brightness in reserve.

A 6th pin was added to the end of the standard 5 pin SWIM connector for optional brightness control. Brightness can now be modulated by external current signal, or also by simple rheostat, connected to ground.
2.10 MicroSWIM

Another SWIM which is pictured in Figure 2.10 was developed in co-operation with an undergraduate engineering student from the ECE516 class, Sarang Nerkar, mentored by the author, using 0603 SMD packaged LEDs allows the resolution to be nearly two times that of the previous version based on the 0805 size LEDs. MicroSWIM is basically the same circuit as the previously described SWIM, based around the LM3914, but designed such that higher resolution is obtained. It is also the first SWIM to have adjustable light output intensity. An intensity control pin is included in the design. The major design tradeoff for high resolution was that the PCB although it shrunk in one dimension, became larger in another. It was also decided to make the board slightly bigger even to accomodate for the ICs on the top along with the LEDs, such that the bottom could be left clean and the board easily mounted flat to various devices. Also again the LEDs are placed at the edge of the board, permitting two boards of different colours to be mounted side by side and dual colour dual trace SWIM is made possible.
2.11 SWIMbot

The SWIM needs to be interacted with by a user to work, for instance it needs to be waved through space in order to make the waves appear visibly. In order to make the SWIM a piece which can simply be observed without the need for user interaction, which is impractical at some forms of exhibit, a machine was created to swing the SWIM through space automatically, without the need for a user to attend to it. The machine was named the SWIMbot and is pictured in Figure 2.11.

The SWIMbot works by a pair of solenoids which are driven in a push pull configuration. A simple power oscillator circuit was created and mounted within pipe fittings to drive the solenoids alternately and swing the arm back and forth. Two potentiometers are used to program the frequency and duty period of each cycle which the oscillator operates at. The SWIM arm is mounted on a bearing pivot and held to the centre by a spring. The mass of the SWIM and arm and the spring form a resonant system,
and by adjusting the frequency potentiometer on the power oscillator, the resonant frequency is easily found, as the point where the amplitude of swing is the greatest. Then the duty period control may be adjusted to obtain better efficiency. Since a certain minimum duty period will be necessary to sustain oscillation, but any more results in wasted power.

A new SWIMbot based on this design and built on contract, has been presented at an exhibit on Augmented Reality at the Canadian National Exhibition this year.

2.12 Smallest, Ring SWIM

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
Figure 2.14: 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.

<table>
<thead>
<tr>
<th>Device</th>
<th>Pixels</th>
<th>Pitch (mm)</th>
<th>Resolution</th>
<th>X (mm)</th>
<th>Y (mm)</th>
<th>Area (cm²)</th>
<th>Z (mm)</th>
<th>Vol (cm³)</th>
<th>Zaxis Mod?</th>
<th>Modular?</th>
</tr>
</thead>
<tbody>
<tr>
<td>MannSWIM</td>
<td>35</td>
<td>25</td>
<td>1</td>
<td>33</td>
<td>1828</td>
<td>604</td>
<td>16</td>
<td>965</td>
<td>Yes</td>
<td>No</td>
</tr>
<tr>
<td>NeopixelSWIM</td>
<td>144</td>
<td>7</td>
<td>3.6</td>
<td>20</td>
<td>1000</td>
<td>200</td>
<td>7</td>
<td>20</td>
<td>Yes</td>
<td>No</td>
</tr>
<tr>
<td>RingSWIM</td>
<td>8</td>
<td>1.5</td>
<td>17</td>
<td>12</td>
<td>18</td>
<td>2.16</td>
<td>3</td>
<td>0.648</td>
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<td>No</td>
</tr>
<tr>
<td>MicroSWIM</td>
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<td>1</td>
<td>25.4</td>
<td>60</td>
<td>60</td>
<td>36</td>
<td>3</td>
<td>10.8</td>
<td>Yes</td>
<td>Yes</td>
</tr>
<tr>
<td>HDSWIM</td>
<td>100</td>
<td>1.9</td>
<td>13.4</td>
<td>18</td>
<td>190</td>
<td>34.2</td>
<td>3</td>
<td>10.26</td>
<td>No</td>
<td>Yes</td>
</tr>
</tbody>
</table>

A novel circuit found in Figure 3 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.[21]
Chapter 3

Ring SWIM Paper

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 more dense packing, making it more wearable, and thus more accessible in general.

![Figure 3.1: Novel circuit designed by author which makes possible smallest SWIM as of yet, worn on the finger as a ring.](image-url)
Photos and scientific results of the new SWIM are presented.

### 3.1 Introduction

Augmented 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 $\text{dB} = 1$, augmented reality systems may be organized into three types:

1. $\text{dB} > 0$ - Those of augmentation, which involve amplification/enhancement/addition of information, such as the system presented here. These systems are augmented reality.

2. $\text{dB} < 0$ - Those of diminishment which involve attenuation/subtraction of information, such as HDR for welding. [31] These systems are diminished reality.

3. $\text{dB} \in R$ - Those which are dynamic and can do both, as needed.

Many augmented 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 [32]. These systems consist of input and output devices, often cameras and aremacs respectively, with computer processing in between [33]. Thanks to ongoing advancements in miniaturization and wearable computer technology, there is large scale interest and commercial development ongoing in these areas [34]. The challenge with a system of this complexity is for it to embody the principles of humanistic intelligence [25] which are key to a system which will provide a seamless and convincing experience which can advance technology for humanity [24].

The augmented 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 augmented
reality experiments carried out by Steve Mann in the 1970s [12]. Recently, with the availability of high efficiency and small SMD LEDs, the SWIM no longer relies on incandescent bulbs and has thus become much more practical.

This paper presents two new incarnations of SWIM. The first is based on the LM3914 and provides high resolution (10 pixels/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, [5] have been used extensively as the output device of choice for augmediated reality systems [35]. 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 [36].

The SWIM system forfeits the complexity imposed by the need for a general purpose system, and instead focuses as a single-purpose-built augmediated reality system which makes visible the 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 persistanlce of exposure [12]. An oscilloscope works in real-time 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 augmented reality experience SWIM creates is easily shared among a group of people, all of whom may bear witness with the naked eye.

### 3.2 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 very poor refresh rate (kHz).

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 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 invariance, 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.3, which is a 60 pixel SWIM, utilizing 0603 size SMD LEDs, which fits on a 6x6cm square PCB.

A novel discrete transistor circuit has been devised, see schematic Figure 3, which makes a low pixel count SWIM smaller and cheaper than is possible with the LM3914. Pictured in Figure 3.2 an 8 pixel discrete SWIM fits on a 1.25cm by 1.9cm PCB small enough to be worn a ring. A resulting wave image is seen in Figure 3.2.
Figure 3.2: RingSWIM as worn.

Figure 3.3: RingSWIM painting an augmented reality wave.
Chapter 4

Lock in Amplifier: For Augmented Reality and Power Measurement

4.1 Introduction

The lock in amplifier is a fundamental piece of scientific test equipment, which performs the function of phase coherent detection on any wave of interest, given a reference wave which is related to the wave of interest. The wave to be detected is supplied to the instrument by way of an electrical signal which usually originates from some type of transducer, or in some cases may also be a raw electrical signal. The lock in amplifier acts overall as a narrowbandpass filter, selecting only signals which are very close to the frequency of the reference wave.

The Lock in Amplifier has been used in this work as part of an augmented reality system first demonstrated by Steve Mann in the 1970s which makes visible, normally invisible waves[12]. In order to reproduce the experiment of visualizing sound waves in air, the only components needed are the SWIM device along with a signal generator, lock in amplifier and transducers, such as a microphone and speaker. By use of different transducers, different phenomenon may be experimented with, for
instance here we have also used a doppler return radar set for the experiment of visualizing radio waves.

One way of understanding the lock in amplifier is as a form of homodyne receiver. This means that it simply multiplies its amplified input by a reference wave which corresponds in frequency and phase to the wave which is being sensed for. The technique is the same as the one employed by the homodyne receiver (see homodyne figure), to multiply the input wave by the reference wave, which results in the action of signal detection, producing high order harmonics, but also producing the wave of interest itself at the output, but only when it is detected in the input signal. The signal path includes a low pass filter, which eliminates all the high order harmonics, passing only energy which is at the frequency of interest.

The result or output is simply a signal which is fed to the SWIM device, (just like an oscilloscope) in order for it to be visualized.

### 4.2 Lock in Amplifier Background

Lock in Amplifiers (LNAs) were studied in depth. It was found that the lock in amplifier was developed at Princeton Applied Research in the 1950s. It seems that minor but important developments were made on their initial designs which eventually resulted in their flagship product the PAR124A, which is even today touted on the front page of the Stanford Reseach Systems website to be the most sought after LNA ever produced. A dysfunctional PAR124A was acquired at the closing sale of a local surplus electronics store, Active Surplus, and was fixed by replacement of 13 Philips electrolytic capacitors which had each failed in a low impedance state. When the capacitors replaced with new ones, the device began to work properly, and was used extensively to perform augmediated reality experiments, inspiring much of the work to come. The PAR124 uses a discrete transistor multiplier, has a built in reference oscillator and minimal circuitry otherwise. A newer state of the art LNA from the 1980s which was experimented with was the Stanford Research Systems SR510 \[39\]. By examining the internal workings, it was discovered that the heart of the SR510 is an Analog Devices AD534 analog multiplier IC. New but similar and pin
Figure 4.1: ECE516 class student Matt Kim holds the microphone for the modular SWIM which is used to paint out a soundwave using a regular balanced dynamic microphone connected as the input, directly to the modern SR7124\(^37\) digital Lock in Amplifier, and a regular dynamic loudspeaker as the reference output.
Figure 4.2: A screen capture from the SR865 digital lock in amplifier. This screenshot was captured while the SWIM was simultaneously painting out a wave as in Figure 4.1. Note: This demonstrates how the SWIM with a space-base maintains the same frequency of wave, the frequency being detected, while the SR865 uses an arbitrary timebase, which results in changes in frequency as observed in the waveform.
compatible 10Mhz analog multiplier ICs by Analog Devices, AD734[40], were acquired as free samples from Analog Devices.

### 4.3 Modular Lock In Amplifier

Several "blocks" were made in order to make a general purpose and modular lock in amplifier which still had high performance, but ran with low power and could be small enough to be wearable, since generally lock in amplifiers are built in a rack mount form factor.

General purpose multiplier blocks were built. Binding posts were used for the differential inputs, as well as the output, in order for ease of connection in any situation. A differential output is provided along with a grounded binding post such that a single ended, ground referenced output is conveniently selected by connection to ground. The multiplier has +/-10V full scale input range, and produces a maximum output swing of +/-10V, in proportion such that a 1V signal applied to both inputs will produce a 1V signal at the output. Meaning that the maximum input swing if both inputs are the same is $\sqrt{10} = 3.3V$.

Gain blocks were made based around the AD8429[41] instrumentation amplifier, which provides a gain up to 10000 (80dB). As signal connectors for these blocks, BNCs were used, 2 for the differential inputs and 1 for the ground referenced output. A grounding BNC cap is provided with a chain for using a single ended input. By capping either input, a function of either A, or -B can be selected, and with the cap left dangling the default A-B. A heavy duty soviet made rotary switch is used to select the gain, available in choices from unity, to 10k(80dB), in steps of a 1 : 2 : 5 ratio sequence.

The AD8429 instrumentation amplifier although it states on its datasheet no minimum input impedance[41] however in practice was found to require a minimum impedance to ground from each input in order for them not to drift away and the output to saturate. As being the input of the device, a very high impedance is desired, and 10MΩ was attempted but still exhibited the saturation issue. 1MΩ resistors however provided enough stabilization to fix the problem, and matches most oscilloscopes for they generally have
a 1MΩ input impedance. However in terms of lock in amplifiers, it is several orders of magnitude low, the PAR124A has an input impedance of 1GΩ\textsuperscript{[42]}.

The multiplier must be followed by a low pass filter in order to attenuate potential higher order harmonics. Initially Krohn and Hite 3202 filters were used, but eventually a simple low pass filter block was made to follow the multiplier.

The filter is made by single pole R-C circuit whose output is buffered by a high performance op-amp in order to provide a low output impedance and thus more ideal operation (can drive a lower impedance with less signal degradation). The pole position may be adjusted to obtain different filter corner frequencies in steps of 1 : 3 : 10 ratio from 1Hz to 1MHz. A high quality soviet made rotary switch is used to select which capacitor is used in the circuit, thus keeping the input impedance seen by the op amp more constant to avoid errors due to input offset current.

All the blocks were designed to run off of a common 12V power supply, but each contains a small isolated power supply inside, such that each box is electrically floating and there is no possibility of incurring ground loops because of power supply connections. It is thus easy to connect the boxes signals together with BNC cables and be sure that there will be no ground or reference related power or noise issues.
Figure 4.3: The modular HD SWIM in operation with the modular lock in amplifier to visualize soundwaves, as a demonstration at the VRTO (Virtual Reality Toronto) Conference 2016. The system here is still using the Krohn Hite filter as seen in the image.
Chapter 5

Efficiency Measurement and Analysis

5.1 Efficiency Meter

With the push for green technology, rising electricity prices and a growing mass of people becoming aware of the benefits of energy savings, both economic, social, and environmental, efficiency is perhaps a more timely topic than ever. The literature on efficiency analysis was examined in depth and measuring electrical efficiency is of widespread interest [43][44][45][46][47]. Various types of efficiency meters are patented[48][49][50] including several which are designed to measure electrical efficiency by electromechanical means[51][52][53].

Power analyzer machines exist, and may be programmed to measure efficiency, but are complicated computerized laboratory instruments that do not lend well to field usage. The machine presented here is small in size and consumes little power, but more importantly, it is purpose built for plug and play efficiency analysis, thus not requiring the user to do any computer programming or other complicated user interaction. This is surprising, especially since power analyzer machines do exist which can
CHAPTER 5. EFFICIENCY MEASUREMENT AND ANALYSIS

Figure 5.1: This block diagram illustrates how the lock in amplifier is used to detect soundwaves and display them on the swim. The general blocks also represent the blocks of the modular lock in amplifier: gain block, multiplier block, filter block.

Figure 5.2: This block diagram illustrates how a heterodyne receiver generally operates. Note the similarity to the lock in amplifier.

measure efficiency, and are produced commercially by major manufacturers, Tektronix, Yokogawa, Fluke. All of these power analyzer machines however suffer from a common flaw, which is that they are designed with the purpose of power converter development and laboratory based use only, and are not easily portable. All available models are designed to be rack mounted and require 120VAC power, clearly not designed with the intention of portability. Portability is what makes field measurements

Figure 5.3: This block diagram illustrates how an average power measurement circuit is built, which is another circuit of detection, and thus very similar to the heterodyne and the lock-in amplifier.
possible, which are certainly important to efficiency savings measures in many different places.

Given the author’s experience in power electronics, it is noted that the system architecture of the lock in amplifier or heterodyne receiver, bears a strong similarity to a system designed to measure average power. See Figures 5.1, 5.2, and 5.3 to compare. The systems are identical, if current and voltage measurement signals are taken as the wave of interest and the local reference wave. Common to all three systems, these quantities are multiplied, and the result is low pass filtered in order to produce an average result, lacking higher order harmonics.

An interesting mathematical analogy can be drawn from this connection, where average power measurement is like coherent detection of current against voltage, that is they must be the same frequency and phase for there to be real power flow, and this becomes all the more important when considering AC power flows.

In the realm of AC power flow, when energy storing elements are present in a circuit, (which is often) it can be said that reactive power flows in addition to the real power, however reactive power does not contribute to average power flow, and the power analyzer presented inherently accounts for this. For instance, with an oscilloscope and the power analyzer, reactive power may be observed in real time, from the instantaneous power measurement channels.

Average power can just as easily be monitored, and a phase angle calculation can also be performed using the ratio function.

These functions along with harmonic analysis are the basic functions of a power analyzer, which have existed since the very early days of electricity. Detecting power flow is in fact one fundamental way to detect electricity. With the dawn of digital power analyzers, with their ease of math, it became commonplace to program math functions and power analyzers with two channels can often be made to divide the two quantities and produce an efficiency measurement.

Given the novelty and interesting connection to lock in amplifiers/heterodyne receivers a device was
designed and built.

Requirements were considered and determined regarding noisefloor, gain, voltage swing input/output, features, and functions, while working around major design decisions, such as the use of AD734 multiplier ICs.

Several op amps were experimented with including the OP484 with good results, but the MC33708 has very similar characteristics and is a fraction of the price.

In order to accommodate for efficiency measurement, two independent "lock in amplifier" style detection (multiplication/filtering) stages are incorporated, to measure both input and output power simultaneously. Also a ratio function is included, to compute the efficiency which is of course the ratio of output to input power:

\[
\eta = \frac{P_{\text{out}}}{P_{\text{in}}}
\]

\[
P_{\text{out}} = V_{\text{out}} \cdot I_{\text{out}}
\]

\[
P_{\text{in}} = V_{\text{in}} \cdot I_{\text{in}}
\]

\[
\eta = \frac{V_{\text{out}} \cdot I_{\text{out}}}{V_{\text{in}} \cdot I_{\text{in}}}
\]

The system architecture for an efficiency meter seems to coincidentally be identical to that of a 2 channel lock in amplifier with a ratio function, which have been available from the major manufacturers such as Stanford Research Systems and Princeton Applied Research.

The major difference is that a lock in amplifier is generally used with small signals, that is, in the range of several volts down to microvolts, or milliamps down to nanoamps lock in amplifiers are often used to detect very small signals. While power meters and likewise power converter efficiency meters, are generally used to measure larger signals on the order of several volts to several hundred volts, or up to hundreds of amperes of current.
In order to allow for general purpose use, the device built includes both voltage attenuators for measuring high voltages as well as a high gain preamplifier for measuring small voltages, either of which is selected as the mode of operation by way of a toggle switch.

### 5.2 4 Quadrant Divider

The AD734 integrated circuit is named as a ”10Mhz 4 Quadrant Multiplier/Divider IC” which is slightly misleading because it should more precisely be named a 4 quadrant multiplier or 2 quadrant divider. This discrepancy became apparent when the AD734 was used as a ratio divider to compute the measured electrical power efficiency of AC power. This is not an issue for average efficiency measurements, or for DC power, where measured power flows may be constricted to only positive numbers, and a correct
result may be produced by a 2 quadrant divider, which is much more common than a 4 quadrant divider.

With the vast majority of division being carried out digitally in this era, the demand for an analog 4 quadrant divider seems to be low, since even though dated as well as recent research demonstrates several different methods of achieving 4 quadrant analog division [54][55][56], no commercial product is available.

A small microcontroller with ADCs and a DAC, could be programmed to act as a 4 quadrant analog multiplier or divider block, but it would be a difficult to meet the 10Mhz specification of a true analog solution such as the AD734 IC. The issue is of course not with the time it takes to do the computation itself, but with the interfacing time; the time it takes for the ADC and DAC to convert the signals between the analog and digital domains.

The reason that a 4 quadrant divider is necessary to measure the efficiencies of AC power flows is the existance of a reactive power component, in addition to the real power, which accounts for the actual power delivered to a load. Reactive power may be explained whereby "extra" power flows at regular times within the AC cycle, to charge and discharge the reactive elements (inducatances and capacitances) of the load circuit, with no net power flow, that is, the resultant average is simply equal to the amount of real power flow measured. This results in power measurements for AC having portions of

<table>
<thead>
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<th>Switch Position</th>
<th>Frequency (3db cutoff)</th>
<th>Time Period (67% settling)</th>
<th>Capacitor Value (C1)</th>
</tr>
</thead>
<tbody>
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<td>100kHz</td>
<td>10µs</td>
<td>100pF</td>
</tr>
<tr>
<td>2</td>
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<tr>
<td>6</td>
<td>300Hz</td>
<td>3ms</td>
<td>30nF</td>
</tr>
<tr>
<td>7</td>
<td>100Hz</td>
<td>10ms</td>
<td>100nF</td>
</tr>
<tr>
<td>8</td>
<td>30Hz</td>
<td>30ms</td>
<td>300nF</td>
</tr>
<tr>
<td>9</td>
<td>10Hz</td>
<td>100ms</td>
<td>1µF</td>
</tr>
<tr>
<td>10</td>
<td>3Hz</td>
<td>300ms</td>
<td>3µF</td>
</tr>
<tr>
<td>11</td>
<td>1Hz</td>
<td>1s</td>
<td>10µF</td>
</tr>
</tbody>
</table>

Figure 5.6: Table of filter frequency range options as selected by rotary switch on efficiency meter.
time where the power goes negative, which must be accounted for in order to obtain accurate real time measurements of AC power which contains a reactive component. A 4 quadrant divider is necessary because a 2 quadrant divider cannot handle a negative divisor.

In order to overcome this obstacle, a circuit was devised [figure] to make the AD734 work as a divider over 4 quadrants, instead of just 2. The operation of the circuit may be explained as inverting (multiplying by negative 1) both divided quantities when necessary, to produce the same quotient result, without needing to divide by a negative number.

The circuit measures the divisor in comparison to zero, and when the divisor cross below zero (within some tolerance), the polarity or sign of both inputs is flipped, thus keeping the divisor positive, and maintaining the correct quotient.

The quotient output relies on the limited gain of the divider itself to be able to produce the correct quotient. The result is a limitation in minimum allowable divisor voltage, and the AD734 is specified to work properly down to a divisor input of 10mV. Taking this into account, the circuit must also prevent the divisor from entering the region below 10mV.

The circuit devised is based on an op-amp circuit which can reverse the polarity of a signal of interest at the command of another signal. A comparator is used to detect if the input to the divisor is negative, and if it is, polarity of the signal to the divisor is reversed, forcing it to be positive, and within the accepted range of the AD734 IC. Simultaneously, the dividend’s polarity is also reversed, making the quotient output correct.

Finally, another comparator along with an error LED indicates if the divisor input is between 0V and 10mV.
Chapter 6

Efficiency Meter Paper

Efficiency Meter

A power analyzer is presented, which is designed for the convenient measurement of power converter efficiency in realtime, for the purpose of power converter understanding, development and characterization.

Along with the use of a display/recording device, such as an oscilloscope or datalogger, the system described provides a means of producing XY graphs of efficiency, as a function of either voltage, current, instantaneous power, average power, or energy, and any of these can be either input or output.

In another mode, and combined with a swept frequency oscillator and output filter, the system is also capable of power spectrum or harmonic analysis, and can be used to produce spectrograms of power.

Lastly, the system has a fixed, non-volatile, non-reprogrammable, user interface with large rotary switches for ease of user operation and understanding.

6.1 Introduction

Those dealing with power converters may benefit from a convenient means of measuring the efficiency of a given power converter, convenient as in quickly and with minimal equipment setup. Presently,
one can set up volt and ammeters or wattmeters and by some means perform a ratio calculation, or use a power analyzer machine. Power analyzers, which are systems for the measurement and analysis of power and energy flows, are fundamental instruments, and are commercially produced by companies such as Yokogawa, Fluke, and Tektronix. Power analyzers are unfortunately a generally cumbersome piece of digital laboratory equipment that is versatile and may be programmed to do many things including analysis of a given power converter in terms of its power or energy efficiency, and harmonic analysis by FFT. There is some recent work regarding the need for smaller scale power analyzers but the literature on power analyzers is sparse. Most power analyzers until recently have had only one channel for power measurement, limiting their use to harmonic/power quality analysis.

The power analyzer presented in this paper is purpose built to measure and analyze efficiency. It is designed with two power measurement channels, such that input and output power can both be simultaneously measured, and subsequently divided for efficiency analysis, with an internal ratio computer. Despite the fact that industry performs efficiency measuremets using commercial power analyzers, this seems to be the first mention of an efficiency meter, efficiency analyzer or efficiency computer in the literature.

State of the art production power analyzers, such as Yokogawa WT3000E, have a bandwidth of 1Mhz. While the majority of power analyzers found recently in the literature are implemented using National Instruments Labview and/or CompactRIO, and have a sampling rate of 50kS/s. A 2013 DSP implementation runs under 10kS/s. High bandwidth is desired in order for measurements to accurately account for the high frequency components of power flow, and the push for higher switching frequencies in modern power converter development mandates higher bandwidth power analysis.

In response to these above issues, the system presented in this paper is designed around the following criteria:
• Functions as a standalone efficiency meter; power or energy efficiency of a power converter may be directly read in realtime as a percentile on an internal moving coil meter, with no need for any peripherals.

• All in one unit, smaller than rackmount, all controls, inputs, and outputs accessible on the instrument’s face.

• User interface with dedicated functions, employing large rotary switches for ease of user selections.

• Bare minimum complexity, high bandwidth signal path, using On Semiconductor MC33079 operational amplifiers with 16Mhz gain bandwidth product and Analog Devices 10Mhz AD734 multiplier/divider ICs.

• Buffered output from any signal point within system available on BNC connectors.

• Voltage attenuation and gain both available, increasing instrument flexibility for general purpose science.

• Output stage has two modes of operation, divide or multiply:
  
  – Divide for efficiency measurement, to measure efficiency directly as a percentile, or to produce graphs of efficiency versus voltages, currents, or powers which are measured.

  – Multiply for harmonic/spectrum analysis, for lock in amplifier style phase coherent analysis, or to produce spectrograms of voltages, currents or powers measured as a function of frequency.
Figure 6.1: Efficiency Meter perspective shot.
Figure 6.2: Efficiency Meter face.
Figure 6.3: Depiction of front panel control options.
Figure 6.4: Rear view of Efficiency Meter with cover removed, exposing circuitry. Note inputs and blue LEM transducers on left, outputs and display meters on right.

Figure 6.5: Block Diagram of Efficiency Meter.
6.2 Design Details

The 2 voltage measurement channels are differential and may be set by toggle switch into gain or attenuation mode. Attenuators are in 1:2:5 steps, for direct measurement of high voltages up to 1000V. User selectable gain settings are available in lieu of attenuation up to 80dB allowing analysis of small signals down to the sub uV range.

The 2 current measurement channels are isolated by use of LEM hall effect current transducers, and have user selectable sensitivity in steps from 500mA to 10A full scale. Sensitivity is selected by rotary switch choosing the number of turns of wire through the current transducer. Internal LEM current transducers provide a minimum 200kHz bandwidth, however if more bandwidth should be desired the current input may be set by rotary switch to accept a differential voltage instead, so that any modern current probe can be used, or so that any voltage signal in general may be input as well. Additionally, a toggle switch allows the voltage gain to be set to 1, 10, or 100. Lastly, virtually any current range may be accommodated for if it is done by means of a simple shunt resistor placed across the inputs and its differential voltage sensed. The signal path is as follows:

Each pair of voltage and current channels are multiplied together by use of AD734 multiplier ICs to produce two signals which represent quantities of power.

For purposes of time-averaged signal analysis, such as for average power measurements, these two outputs are fed into two independent active first order low pass filters, with user selectable corner frequency in 1:3:10 steps from 1Hz to 100kHz.

For cumulative analysis of signals over periods of time, such as for energy measurements, the filter outputs are successively fed into two independent time integrators, with reset buttons, and user selectable time rate of integration from 1Vs to 1uVs.

A final AD734 stage processes the quantities generated by the previous stages. It may be set to compute either the product or the quotient (Multiplier or Ratio computer), and both inputs to this stage
may be selected from any signal point mentioned above (voltage, current, instantaneous power, average power, energy).

Thus, ratios may be computed for any combination of quantities, for instance energy efficiency over a period of time may be observed and recorded. If however the computed ratios are to be made direct sense of, care must be taken to have the numerator and denominator in the same units. In multiplier mode, lock in amplifier style phase coherent detection is possible. Likewise, frequency selective harmonic analysis is possible, and with the use of a swept frequency oscillator and filter, the system may be used to produce spectrograms of power.

Lastly, a total of 5 independently buffered outputs are available on BNC connectors, signals selectable from any of the signal points. 3 of these outputs also drive 3 built in moving coil type signal monitors (2 bipolar, 1 unipolar) for direct measurement and observation of DC and low frequency phenomena. Switches add diodes into the feedback loops of the buffers driving these meters making them respond roughly to peak AC voltages as well.

### 6.3 Results

The efficiency meter has successfully been used to analyze the overall efficiency of the 12V output of a common ATX computer power supply. As a result, a graph of efficiency versus output current has been created. The accuracy of points on the graph has been verified by Fluke 177 volt-ammeters as well as a Weston 432 wattmeter, which all agree within 2%.

The system was also used to qualitatively analyze the harmonic frequency power content of the input power and the resulting spectrogram is shown below, contrasted alongside a similar spectrogram for an incandescent lightbulb.
Figure 6.6: Graph of mains input AC Voltage and Current as a function of time. Voltage waveform is 50V/division. Current waveform is 0.1A/division.

Figure 6.7: Efficiency graph for ATX power supply 12V output, as a function of output current from 1A to 7A. Efficiency is 10% per vertical division, and current is 1A per horizontal division. Origin, bottom left.
Figure 6.8: Spectrogram of power into an incandescent lightbulb. Sweep setup for 100Hz per horizontal division. It can be seen that the majority of energy is at 120Hz.

Figure 6.9: Spectrogram of power into ATX power supply. Sweep setup for 100Hz per horizontal division. Higher order harmonics are present compared to the incandescent lightbulb.
Figure 6.10: Photograph of experimental setup showing efficiency meter analyzing ATX computer power supply. Efficiency measurement is visible on centre display within efficiency meter. A Weston 432 Wattmeter verifies input power, Fluke volt and ammeters verify output power. Adjustable power resistor used to sweep load.
Chapter 7

Conclusion

Within this thesis, a focus is made on two projects and also their interconnexion which forms a new idea. The first project is related to improvements made to the design of Steve Mann’s SWIM device for visualization of waves. New SWIM devices were designed and prototyped and are presented, including wrist-worn and ring-worn style SWIM devices. A conference paper which was recently submitted to IEEE ISM 2016 Symposium on Multimedia is included, where the physically smallest and therefore most wearbale SWIM to date has been made possible by the author’s invention of a novel discrete transistor circuit, see Figure 3. Other new SWIM devices were built and presented with results which fulfill all the objectives of being modular, consuming little power, having high resolution and having high luminosity. The results are improvements to the augmented reality visualization of waves with the SWIM, by producing a clearer, brighter and thus easier to understand image than was previously possible. The smallest SWIMs to date have been created, in the form of a wearable ring, along with the largest, tested over 1000 pixels, nearly 2 metres high, for large scale demonstrations to large crowds of people.

In order to visualize sound waves a lock in amplifier is used along with a microphone and a speaker and the SWIM device. Since the only available lock-in amplifiers are rack mount units, a new minia-
turized and modularized lock-in amplifier is designed and built to be worn along with the SWIM device for a completely wearable wave visualization system.

As a result of the author’s inherent interest in power electronics, it was noted that the general lock-in amplifier system is directly analogous to an average power metering system. The concept of an electrical efficiency meter was explored, and simplistic electromechanical devices exist, as do commercial power analyzer machines, but these are similar to the modern lock-in amplifier in that they are only available as rack mount form factor laboratory equipment. Here an efficiency meter has been designed which is a better compromise of simple yet high performance. It is designed such that it is portable, and may act in as simple a fashion as the electromechanical efficiency meter, but is also designed to be used with an oscilloscope, datalogger, SWIM device or any other output device, for in depth analysis of power flows and efficiency. For instance by direct connexion to an oscilloscope in XY mode, the efficiency meter may be used to produce real-time oscillographs of efficiency versus any other measured quantity within the system, such as for input or output: power, average power, voltage or current. The device may be seen as a generalized analog computer which performs functions of multiplication and division in real-time, among other things. Any of the measured quantities may be sent into the ratio computer stage (divider), and all inputs may be voltage signals. To extend the range of the unit from power measurements down to small signal measurements, additional gain stages are also included, allowing up to 80dB of gain on the voltage channels and 40dB on the current channels, in either voltage or current mode.

Further results of the efficiency meter are summarized in the included conference paper which was recently submitted to IEEE APEC Applied Power Electronics Conference to be held in March 2017. As an example case it was used to characterize and graph the load dependant efficiency of an ATX computer power supply, as well as qualitatively analyze the harmonic content of its input power. The efficiency meter has been created in a smaller than rack mount form factor and has been tested to have a
3db bandwidth of 500kHz which is better than what is found in the literature, but not quite as good as the best commercial power analyzers. Since the analog hardware is all rated at minimum 10Mhz, the next step is to figure out how to claim that full bandwidth. Likely, a slightly different design which avoids all the wires seen in Figure 6.1 and uses smaller switches, may help. One certain next step improvement which is also expected to improve the bandwidth, is the addition of another input buffer stage to each channel, to increase the input impedance as mentioned in Chapter 4.

In conclusion, the author’s work over the past 3 years has contributed to both the worlds of augmented reality with the SWIM and electrical power efficiency metering with the efficiency meter. Two seemingly disparate areas, yet given the generalized common nature of both, in that they both seek to measure a quantity, it is not so surprising that they share such a similarity in their system architecture. It is noted that given the trajectory of technology and especially the rise of the so called Internet of Things, or Things That Think as some prefer to call it, efficiency metering is bound to meet augmented reality on a mass scale in the near future.
Acknowledgments

First thanks to my parents Gus and Donna, and sister Mary who have been a continual source of support throughout my entire life, in all of my endeavours. Nothing I do would be possible without the food, housing, emotional and spiritual support they provide.

Secondly it must be noted that the connexion to the present state begins with a variac interface. The author had previously been working on a project where the exercise bicycles of the hart house gym were modified such that they were grid-tied, and delivered harvested electrical energy to the utility grid as users pedalled.[62] A presentation and demonstration session at Dr. Mann’s rooftop greenhouse within the faculty of Forestry, had been organized for a group of visiting dignitaries judging the World’s Top 7 Laboratories. This event brought Steve Mann and the author together. Within one day of preparation for the World’s Top 7 Laboratories demonstration, the exercise bike was connected through a variac autotransformer directly to the hydraulophone, as its new power source.

Needless to say, a deep thanks toward Steve Mann for all of his help, guidance, and wisdom, without Steve none of this work would even be possible. Thanks also to Steve’s wife Betty, and daughters Christina and Stephanie who have always been around for support.

Special thanks to the other lab members who have helped me on this journey, Ryan Janzen and especially Mir Adnan Ali for showing me latexmk among so many other things.

Thanks also to Max Hao Lu and Kyle Simmons for their help, and a special thanks to Sarang Nerkar for all of his great help. Thanks also goes out to Jared Mikkelson, and Dave Jeong of GB449 and especially the founding father Wesley Sacher who has always been a stable pillar of support.

Many thanks to the professors who participated on my thesis defense committee, Andreas Veneris and Andreas Moshovos, as well as Stewart Aitchison.

And a special thanks to all teachers and professors I have had the pleasure of learning from, many of whom have played important roles along the way, your continued service is invaluable to society.
Chapter 8

Appendix
Figure 8.1: The two LEM current transducers within the Efficiency Meter. The windings depicted in the schematic page 1 are clearly visible.
### Time Averaging Filters and Time Integrators

**Table: Switch Positions, Frequency, Time Period, and Capacitor Value**

<table>
<thead>
<tr>
<th>Switch Position</th>
<th>Frequency (kHz)</th>
<th>Time Period (ms)</th>
<th>Capacitor Value (C1)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>100</td>
<td>10</td>
<td>100pF</td>
</tr>
<tr>
<td>2</td>
<td>30</td>
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<td>3000</td>
<td>3pF</td>
</tr>
<tr>
<td>11</td>
<td>1</td>
<td>10000</td>
<td>10pF</td>
</tr>
</tbody>
</table>

**Diagram:**

- **Product (Power) Signal Input**
- **Switches and Resistors:** 16kΩ, 10kΩ
- **Capacitors (C1):** Various values
- **Averaged Filtered Product (Average Power)**
- **Time Integrated Product Energy**
- **Integrator Reset Button**

**Efficiency Meter Schematic:**

- **Page #2 Filters**
4 QUADRANT DIVIDER

DIVIDER

BASED ON AD734, 2-QUADRANT DIVIDER IC

QUOTIENT (RATIO) OUTPUT
ALSO: EFFICIENCY OUTPUT

EFFICIENCY METER SCHEMATIC
PAGE #3 DIVIDER
Chapter 9

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