Wearable Bluetooth Brain-Computer Interface for Detection and Analysis of Ear-EEG Signals

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***Abstract*—Epilepsy is the fourth most common neurological disorder. Despite decades of research into the subject, there currently does not exist any non-invasive device that can continuously monitor epileptic seizures. Such a device would provide doctors and patients with a means to optimise medication dosages by tracking the instances and types of seizures This could reduce the side effects of medication while minimizing the occurrence of epileptic events. The device could also provide insights into the causes of epilepsy when correlated with diet tracking apps or other behavioral/location based data. Lastly, a continuous epilepsy monitoring device could eventually be used to predict epileptic seizure before they occur. In this study, we specify a proof of concept device that will realize this specific goal. Our approach to obtaining data is through an in-ear device that places four electrodes inside the ear canal and outer ear. This device picks up brain waves below 30 Hz, which then get amplified and sent over Bluetooth to a laptop (eventually, it will transmit to a smartphone). This information is passed through a classifier that detects the occurrence of temporal lobe seizures. On the detection of a seizure, the classifier saves the last hour of EEG signal to a remote server for further analysis. The long term goal of this project is to use the database of patient specific EEG data to create personalized predictive models to alter the patient of seizures before they occur.**

***Index Terms*—EEG, Epilepsy.**

I. Introduction

EPILEPSY is a hugely prevalent neurological disease, potentially infecting 1 in 26 people at some point in their life. Epileptic seizures are mostly unpredictable, prohibiting everyday tasks such as driving due to the significant risks involved. This paper proposes a discrete wearable device which sits on a patients head and continuously collected electroencephalography (EEG) data which can be analysed and used to predict epileptic seizures. Like other wearable devices, the device is designed to be paired with a Bluetooth-enabled smartphone which can process the EEG data. Additionally, patient data can be relayed back to their doctor for analysis, whereby medication dosages can be adjusted more effectively to reduce side effects.

There does not exist a device on the market which performs EEG in a discrete fashion, and thus nothing is currently suitable for continuous medical use as an epilepsy tracking device for patients. This provides motivation to develop a solution which is discrete - a key requirement in such devices which must be worn for prolonged periods of time. In order to achieve this we needed to develop a large portion of the project from scratch due to the lack of suitable off-the-shelf components. Fortunately the remaining parts of the device use very standard parts and did not present a significant challenge

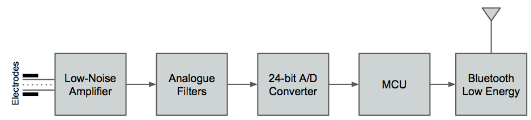

Fig. 1. System Block Diagram

thanks to ample documentation and resources available on these subjects.

Brain-Computer Interfaces (BCI) are still a relatively new concept, fortunately an open-source BCI project (OpenBCI) provided a very good starting point much of the content presented here builds upon work done by the OpenBCI team. Here we introduce a design which can be used to discretely and wirelessly transmit EEG data back to a central processing device for analysis.

A. Approach

Our approach consists of predicting epiliptic seizures by using electroencephalography (EEG) to monitor brainwaves. Normally EEG signals are collected using electrodes placed on the scalp, however the objective is to improve the users quality of life, so we are opting for the more discrete option of in-ear EEG. A hearing-aid-like device will have small electrodes embedded on the surface which make contact with the skin inside the ear canal and pick up brainwaves. Due to space constraints, in-ear EEG is usually limited to two channels of data. The signals are very small (10 V) and need amplifying before they can be analysed - this requires a high-gain, low-noise amplifier.

Once amplified, the signals are digitised using at least a 10-bit ADC, and then buffered into a low-power microcontroller where any additional pre-processing occurs. The microcontroller uses Bluetooth Low Energy to maintain a data connection with a smartphone for analysis, however that is beyond the scope of this project and we shall relay the data back to a laptop instead, where we will simply display a real-time frequency plot of the two channels. The analysis software is being handled by a separate team.

II. Technical Material

A system overview is illustrated in figure 1.

Four electrodes are connected to a high-performance low-noise amplifier and further filtered before being digitised by a high-resolution 24-bit Analogue-Digital converter. The ADC triggers an external interrupt on the microcontroller indicating

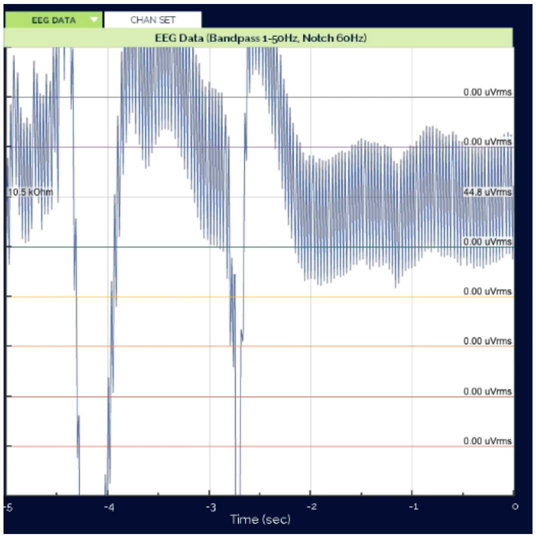

Fig. 2. Electrode impedance on the custom earpiece measured at 10 kOhm

a new sample is ready, which the microcontroller fetches and transmits over Bluetooth to a central device.

A. EEG Fundamentals

Electroencephalography is the process of recording electrical potentials generated as a result of large-scale brain activity. Neuron activity in the brain causes electromagnetic fields the result of action potentials to be radiated outwards, eventually reaching the surface of the scalp in the form of voltage changes. Electrodes normally comprising of a singular silver-chloride disc with wires attached are placed on the surface of the skin in order to pick up the extremely low-voltage signals emitted from neuron groups. The resulting set of signals is referred to as an electroencephalogram. Although skin is slightly conductive, these signals are mostly localised due to the variance of activity produced by different regions of the brain; thus, signal variation depends mostly on electrode placement[1].

Electrode impedance, resulting from imperfect contact between the electrode and skin, is highly-detrimental to signal integrity. Typically a sub-20 kOhm impedance is considered optimal for EEG. Using the Ear-EEG method presented here, a sub 10 kOhm impedance was achieved. Electrode gel a conductive semi-viscous substance can be used to reduce this impedance by improving skin-electrode contact.

EEG signals look largely random when viewed in the time domain, but become more meaningful when frequency data is analysed. Cognitive state can be determined when the signal is viewed in the frequency domain discrete frequency bands are highly correlated to specific cognitive metrics such as relaxation (Alpha waves, 7-12 Hz) and concentration (Beta waves, 13-40 Hz). By analysing a combination of these frequency bands it is possible to determine far more complex metrics.

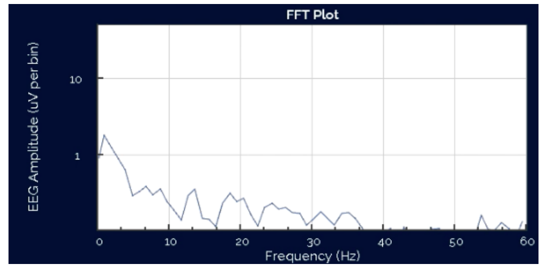

Fig. 3. EEG signals are a lot more meaningful when viewed in the frequency domain, where frequency bands correspond to specific metrics

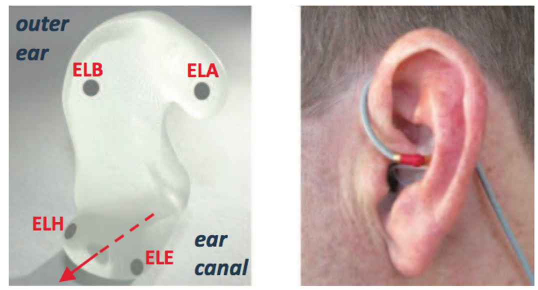

Fig. 4. The personalized earpiece, for the left ear, with electrode positions visible and an arrow indicating the direction in which it enters the ear canal (left) and a photo of the earpiece in the ear(right)

B. Ear EEG

In order to provide continuous patient monitoring it is necessary for the device to be discreet and comfortable. The high number of electrodes used in traditional on-scalp EEG makes this method impractical. Instead, Ear-EEG techniques are employed to vastly reduce the size of the device in order to make it wearable. Implementation details for an Ear-EEG-based earpiece are presented later in this paper. Ear-EEG was chosen due to the ability to integrate it into a hearing-aid form factor which is already common with various medical and consumer devices (wireless headsets etc.).

On-scalp methods use the 10-20 system for a standardised placement of up to 256 individual electrodes, allowing for very high spatial resolution due to the full brain coverage. However, on-scalp EEG is prone to signal attenuation from the skull as well as increased noise from environmental factors such as 50/60 Hz mains interference. Ear-EEG instead opts to place electrodes on the inner ear and ear canal, resulting in a comparable Signal-to-Noise-Ratio (SNR) at the cost of lower overall signal amplitude (to the order of 10 V). Utilising additional electrodes increases complexity exponentially due to the size constraints introduced by Ear-EEG. Such constraints require that electrodes be placed closer together, thus reducing spatial resolution significantly. Additionally, noise rejection techniques result in a single usable channel, thus complicating signal analysis.

C. Earpiece Design

The earpiece design is based on research on the feasibility of an ear-EEG from generic earpieces conducted by P. Kidmose

Fig. 5. The final iteration of the ear-EEG, which is made of rigid cast material from a mold impression.

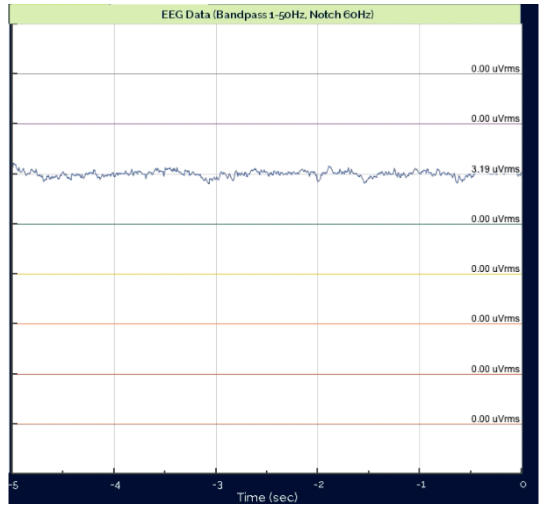

Fig. 6. Ear-EEG signals are lower in amplitude than their on-scalp counterparts

et al. The earpiece is made of a hard resin casting material that is custom made for the users ear using a fabrication process that is similar to creating customized hearing aid ear-plugs (Figure 5).

To record EEG signals optimally, four electrodes are placed strategically on the ear-EEG. EEG signals are recorded from the ELB and ELE electrodes while the ELA electrode is used as ground and ELH is used as the common reference. These four locations, shown in Fig 4 were selected based on the research conducted by P. Kidmose et al [2].

Several design features were specifically implemented to reduce the impedance of the electrodes such as applying conductive paint and ten20 electrode paste to the four electrodes on the ear-EEG. Reducing the impedance of the electrodes improves the signal integrity of the EEG recordings. Ideally, the impedance of the electrodes should be less than 10 kOhm. By applying conductive paint and ten20 conductive paste, the impedance of the electrodes is reduced to 1-10 kOhm whereas the impedance of the electrodes without the conductive paint and conductive gel is 50-100 kOhm.

The plastic material that the earpiece consists of offers a hard surface for the conductive paint to bind to. When compared to our initial earpiece that was made of a flexible rubber, the new rigid material allows for Improved application of conductive paint on our electrodes. Applying the conductive paint to a flexible rubber surface proves to be troublesome with the conductive paint – After drying, the conductive paint cracks due to the flexibility of the earpiece surface.

The ear-EEG interfaces with the brain-computer interface by four wires that make up the electrode and feed out the back of the ear-EEG. These electrode wires are made particularly short to reduce the amount of environmental noise induced on the wires. To get the electrode wires to exit the backside of the ear-EEG, thin tunnels are created using a drill press. This allows for the electrode wires to tunnel from the surface of the ear-EEG that makes contact with the inner ear canal of the user to the back of the earpiece, and into the brain computer interface platform.

D. *Analog to Digital Converter*

When amplifying EEG signals certain attributes must be carefully considered in order to preserve high signal integrity, most notably the common-mode-rejection-ratio (CMRR). Despite variance in placement, multiple electrodes will often contain common elements such as noise which reduce SNR. The information contained in a signal can be quantified by its variance; given that this noise is common among all channels, it contains no useful information and thus it makes no sense to amplify it. To maximise the SNR it is important to try and attain the highest CMRR possible to prevent noise from being amplified. The reduced amplitude of Ear-EEG signals compared to on-scalp EEG mandates the need for exceptional noise-rejection and thus a high-performance analogue frontend. The Texas Instruments ADS1299 Medical Analogue Frontend is specially designed for processing EEG signals and is utilised in the design presented here to ensure signal integrity. While two electrodes are used as inputs, differential amplification has been used to subtract the two signals, thus removing the common-mode signal and only amplifying the difference, which contains the useful information. Unfortunately the effectiveness of differential amplification is somewhat diminished due to the reduced spatial separation of electrodes electrodes in close proximity have low signal variation and thus much of the signal is removed as a byproduct of differential amplification. RIght-leg Drive (RLD) circuitry inside the ADS1299 is able to detect this common-mode signal and inject an inverted signal to cancel it out [3].

The signal is amplified by a Programmable Gain Amplifier (PGA) configured to 24x amplification. Additional filter stages remove any unwanted noise from the system before the signal enters the 24-bit Analogue-Digital converter. The ADS1299 is configured to sample at 250 Hz. Upon sampling, the ADS1299 toggles an external interrupt on the microcontroller to indicate a new sample is ready. The microcontroller is connected to the ADS1299 using a SPI interface to transfer samples and configure the device.

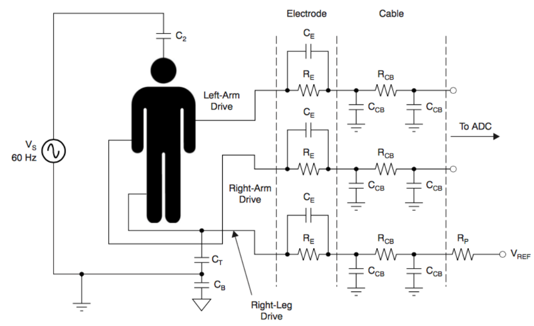

Fig. 7. Applying the Common-Mode Voltage at the Patients Body Using Rp

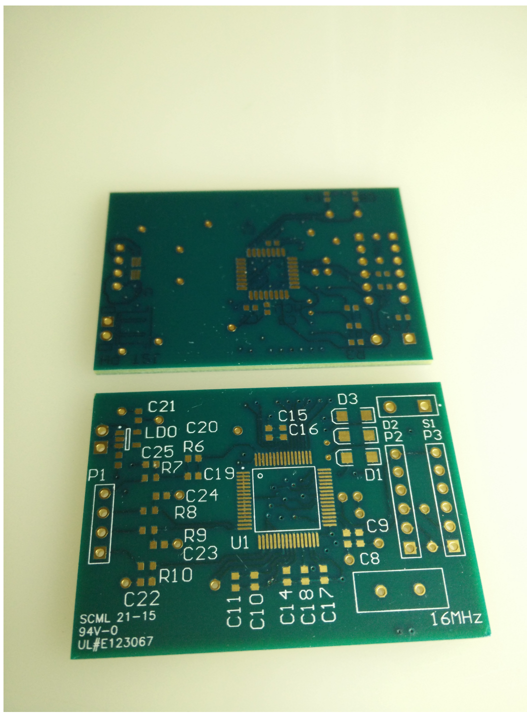

Fig. 8. The image shows the top and bottom view of the custom designed printed circuit board for the ear-EEG system prior to assembly.

E. Printed Circuit Board

The Printed Circuit Board (PCB) is designed with many system optimizations and features in mind – These design choices are intended to reduce the size of the hardware as well as improve the signal integrity of the EEG recordings.

The PCB is designed to have four layers to allow for two signal layers, as well as dedicated power and ground layers. This design specification is chosen to allow for ideal signal return paths. By designing for optimal signal return paths, we avoid discontinuities in the current return path. Discontinuities in return path can cause cross-talk between adjacent traces and causes waveform distortion.

By using surface mount technology (SMT) components, which are much smaller relative to through-hole components, the PCBs dimensions are reduced to 5.1cm by 3.5cm. Reducing the size of the hardware is crucial to the system since the ear-EEG platform is intended to be fitted and worn around the users head near their ear.

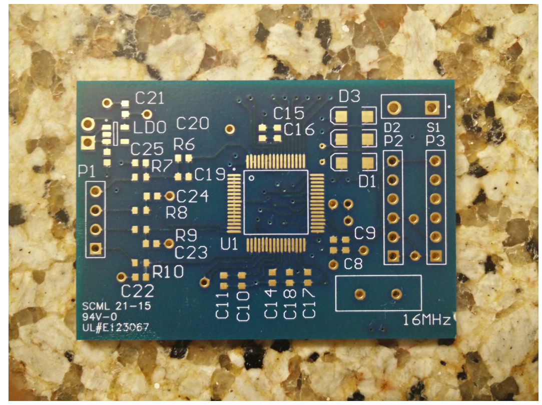

Fig. 9. The image shows a close up of the top of the printed circuit board after assembly.

To improve the integrity of the EEG recordings, the length of the trace from the electrodes to the analog to digital converter (ADC) should be reduced as much as possible. For this reason, the PCB was designed so that the ADC is as close to the electrode interface as possible. By reducing the length of the trace and wire from the electrode to the ADC, the amount of environmental interference and cross-talk between traces is reduced.

An ATmega328p microcontroller (MCU) is chosen to process the EEG recordings due to several features offered by the MCU. The ATmega328p MCU is power-efficient which allows for the use of a small 40mAh Lithium Polymer battery for maximum portability of the ear-EEG platform. Since there is a large online community for the ATmega series of MCUs, references and open-source firmware are widely available – This minimizes the overhead for researching hardware and firmware implementations. Lastly, the ATmega328p is readily available for purchase with the Arduino bootloader pre-programmed on to the MCU. By using an MCU with the Arduino bootloader, the overhead of setting up the MCUs registers and fuses is minimized. This allows for skipping the process of configuring the MCU, which allows for immediately having the ability to upload firmware on to the MCU after powering the device.

F. Bluetooth

Bluetooth is a communication protocol used to send and receive data wirelessly through a 2.4GHz link. It has many benefits, such as low power usage and high security, and it is often used for short-range wireless communications. It can be thought of as an RF version of serial communication. Bluetooth is seen everywhere in consumer electronics due to its wide array of features, making it well-suited for use in a wearable device intended for use with a smartphone.

Devices connect in a star topology, whereby multiple a single Bluetooth central device (acting as the master) connects to multiple peripherals (slave devices). When a connection is established, the resulting network is called a piconet. Therefore a piconet consists of one master, and one or more slaves.

Offset	Name	Type	Size
0x00	Control / Status	enum / int	1 byte
0x01	Samples	int []	18 bytes
0x13	Reserved	void	1 byte

Fig. 10.

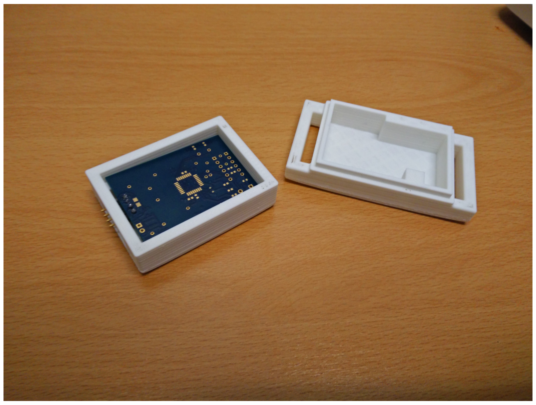

Fig. 11. Casing for the prototype.

Every Bluetooth device possesses a 48-bit identifier, using MAC-48 identifier format. This number is used in the connection process, which consists of 3 main steps: First, the devices are set to discover, where they will scan within their range for any other available devices. Once an appropriate device is found, a connection request is formulated, where both devices must know of each other and accept a connection. After the connection is established, data can be transmitted back and forth, or the devices can be set to power saving modes, where they can afterwards be called back into normal function.

Bluetooth Low Energy (BLE), also known as Bluetooth Smart, is a subset of Bluetooth that provides an appropriate service with significantly less power consumption. It was introduced with the release of Bluetooth 4.0. BLE uses the GATT data protocol to handle its data transmission. GATT Profiles simply contain a predefined set of instructions which will be followed by both the master and slave. GATT Profiles contain Services, and Services contain Characteristics. Characteristics are single data points, and Services are logical groupings of Characteristics.The master device creates what is called a GATT client, whereas the slave device creates a GATT server. The data transmission occurs at every connection interval where the client checks for new data on the server.

For optimised battery performance and throughput, we propose a custom GATT profile in figure 10. BLE has a maximum packet size of 20 bytes to ensure low power consumption, at the cost of data throughput. Despite a modest sample rate of 250 Hz, a throughput of at least 6 kB/s is required. To achieve the highest efficiency possible, the entire 20 bytes is utilised to transmit six samples per packet.

G. Device Casing

The enclosure was modeled with SolidWorks. It was designed to precisely fit the printed circuit board and securely fasten it to prevent any unnecessary movement. The outside of the case featured two loop holes to thread a headband, since the design was meant to be worn near the ear. This is because impedance can be reduced by shortening the transmission wires as much as possible. The current model was 3D printed using ABS filaments. The model looks like figure 11.

Date	Objective	Description	Member(s)
13/4	Order earpiece mould materials	Raw materials required to build earpieces.	MW
13/4	Order cheap Bluetooth earpiece	Bluetooth module to be disassembled and analysed.	ML
13/4	Order Bluetooth serial module	Bluetooth serial module to connect to Arduino for prototype.	RP
20/4	Arduino -> Laptop Bluetooth link	Establish a link between an Arduino and laptop to transfer mock data mimicking EEG samples.	RP
20/4	Teardown cheap BT earpiece	Analyse Bluetooth earpiece for space-saving layout techniques.	ML
27/4	Fabricate earpiece and electrodes	Prototype wired Ear-EEG earpiece which can be connected to OpenBCI board for testing and use by the software team.	MW + ML
27/4	Realtime FFT plot of BT data	Incorporate EEG earpiece into Arduino prototype and display realtime data.	RP
Milestone 1: Mocked EEG data streamed from Arduino to laptop. Wired prototype earpiece working with OpenBCI.			
27/4	High performance amplifier + A/D	Select and implement high-gain low-noise differential amplifier for electrodes.	MW + ML
4/5	Replace Arduino with Nordic devkit	Port code to Nordic Cortex M0 board in preparation for final layout.	RP + MW
Milestone 2: Real EEG data from earpiece fed into ARM Cortex M0 devkit and streamed to laptop.			
4/5	Layout initial PCB	Integrate amplifier / ADC, MCU and BT radio onto a single board.	ML + MW
4/5	Design initial housing (optional)	A small casing to house fabricated board. Design using CAD.	RP
11/5	Print initial housing (optional)	3D print housing.	RP
18/5	Fabricate initial PCB	Send PCB for fabrication.	ML + MW
25/5	Assemble and test initial PCB	Place and solder SMD components.	ML + MW
25/5	Assemble and test initial housing	Fit PCB into housing.	RP
Milestone 3: Assembled custom PCB with all discrete ICs (MCU + BT, amplifier + ADC).			

Fig. 12. Planned milestones

III. MILESTONES

At the beginning of the quarter we created a set of milestones to guide our progress (Figure 12)

Although the dates for the milestones were not always precisely men, we only had one of our milestones modified (Figure 13)

Date	Objective	Description	Member(s)
Milestone 1: Mocked EEG data streamed from Arduino to laptop. Wired prototype earpiece working with OpenBCI.			
4/5	Replace Arduino with Nordic devkit	Port code to Nordic Cortex M0 board in preparation for final layout.	RP + MW
	Maintained the Arduino Prototype	The ARM board proved to be too complex given the timeframe. We decided to keep using the Arduino chip, since it provided enough functionality.	
Milestone 2: Real EEG data from earpiece fed into ARM Cortex M0 devkit and streamed to laptop.			
Milestone 3: Assembled custom PCB with all discrete ICs (MCU + BT, amplifier + ADC).			

Fig. 13. Modified milestones

IV. Conclusion

This paper presents the design and implementation of an in-ear EEG recording platform, and demonstrates that it is possible to create EEG recording platforms that are personalized to the users ear. High signal quality was achieved from the personalized earpiece by reducing the impedance of the electrode and minimizing the length of the wire from the electrodes to the signal processing electronics. Although a working brain computer interface platform was not successfully implemented due to issues with the board bring up of the custom PCB, the project is at a point that it would not take much more effort to get the full system working.

V. References

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