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Physics Independent Study Paper
Commercial Application of Brain Computer Interfaces

Hivemind

Company Overview

Hivemind seeks to create a revolutionary new way to interface with our day to day devices via the power of thought alone. As the cost for EEG (electroencephalogram) and wireless sensors have plummeted, we see a unique opportunity to develop a product that builds on current BCI (brain computer interface) technology to create a novel interface platform for web-connected devices. Currently, we are working to create an arduino based control panel linked to a EEG signal interpreter. LED lights blinking at a certain frequency will be connected to a particular device, be it a computer or a wheelchair, enabling the user to control the device by glancing at a particular LED. Our long-term goal is to create a revolutionary new brain-computer interface platform that allows users to interface with any device via thought alone.

Technical Overview

Powerful low-cost computer equipment, new understanding of brain function, and growing need of people with disabilities has spurred research in the field of brain-computer interface. Potential users are those suffering from severe neuromuscular disorders such as brainstem stroke, amyotrophic lateral sclerosis, and spinal cord injury. The immediate goal is to provide these "locked-in" patients with the ability to communicate basic messages, or even to use a word processor.[1] Brain-computer interfaces (BCIs) are used to communicate a user's intent by converting brain signals into outputs. This method of communication does not require the use of muscles and nerves, which makes it ideal for people with motor disabilities.[11]

Brain Computer Interfaces

There are several techniques for measuring brain activity: magnetoencephalogram (MEG), near infrared spectroscopy (NIRS), electrocorticogram (ECoG), functional magnetic resonance imaging (fMRI), and electroencephalography (EEG)[14]. Some BCIs are invasive, while others are noninvasive. Invasive BCIs require a surgical procedure, during which electrodes are placed directly on the brain. Invasive BCIs offer benefits such as several degrees of freedom and higher spatial resolution, but come at the cost of implanting electrodes within the cortex, which creates difficulty in achieving and maintaining stable long-term recordings, not to mention the expense and inconvenience of a surgical procedure. They function by recording single neuron activity within the brain. Some neurons, such as pyramidal neurons, are large and easily recorded, and are thus a prime target to recording via invasive BCI, but small displacements of the electrodes can cause the electrodes to shift away from these easily recorded neurons.[11]

One form of invasive BCI is electrocortography (ECoG). (ECoG) could prove to be a practical and powerful alternative to the other recording methods. It offers higher spatial resolution (tenths of millimeters vs centimeters) and a broader bandwidth (0-200 Hz vs 0-40 Hz), less vulnerability to artifacts, and higher amplitude (50-100 µV max vs 10-20 µV). It is safer than single-neuron recording because ECoG is recorded by subdural electrode arrays, thus not requiring electrodes within the cortex. However, this method is still invasive and requires surgical placement of electrodes on the subdural region of the brain. The results of a study by Leuthardt *et al* suggest that ECoG-based BCI could provide more precise control than EEG-based BCIs.[7]

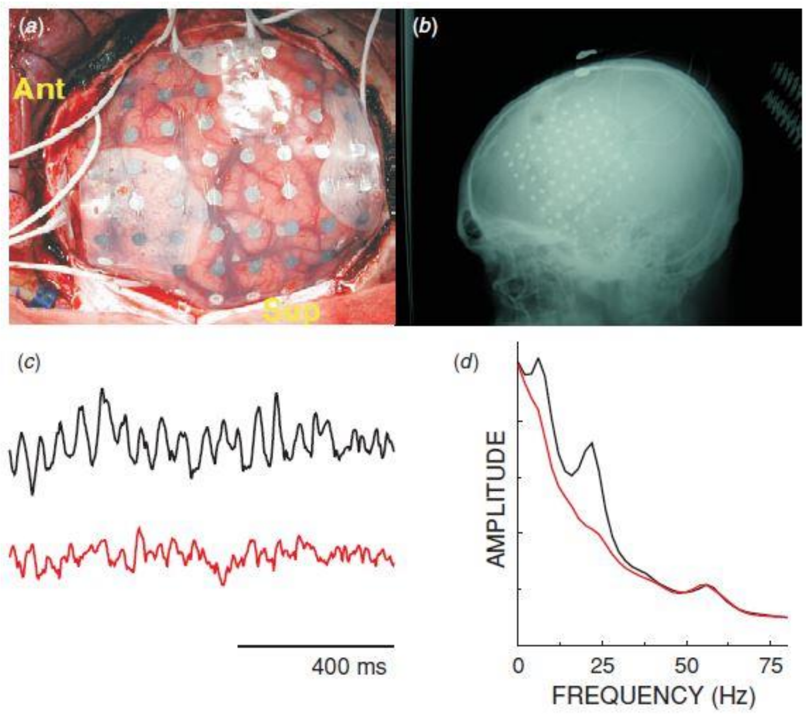


Figure 1. a) Placement of a 64-electrode subdural array. b) Radiograph showing electrode grid post-surgery. c) Raw ECoG signals from patient moving cursor. The black line represents the patient resting, while the red line represents the patient imagining saying the word "move". d) Spectra from corresponding conditions

Noninvasive BCIs simply requires placement of electrodes on the scalp. Electroencephalogram (EEG) is a noninvasive form of brain computer interface which operates by monitoring EEG activity recorded from the scalp. Compared to fMRI, EEG offers high temporal resolution, but low special resolution.[14] EEG can detect six brain rhythms: delta (1-4 HZ), theta (4-7 Hz), alpha (8-12 Hz), mu (8-13 Hz), beta (12-30 Hz), and gamma (25-100 Hz). Delta and theta occur during the sleep stage and high emotional conditions. Alpha rhythms occur when one is awake and has eyes closed in a relaxed condition. Oscillations of the alpha rhythm are smooth in pattern, while beta rhythms are desynchronized, and occur while one is in a normal awake state with eyes open. Gamma rhythms are acquired from the somatosensory cortex, which is located in the lateral postcentral gyrus region of the brain. It is the main sensory receptive area for the sense of touch. The mu rhythm can be acquired from the sensorimotor cortex, an area of the brain which includes the precentral gyrus and the postcentrul gyrus, and associated with combining motor and sensory functions.

Though EEG devices are safe to use, relatively inexpensive, and convenient, the limitation is that they have relatively low spatial resolution and require extensive training. They are also susceptible to artifacts such as electromyographic (EMG) signals.[11] Due to the low-cost, portability, and ease of use offered by EEG, it is the main platform we will use for developing the Hivemind product.

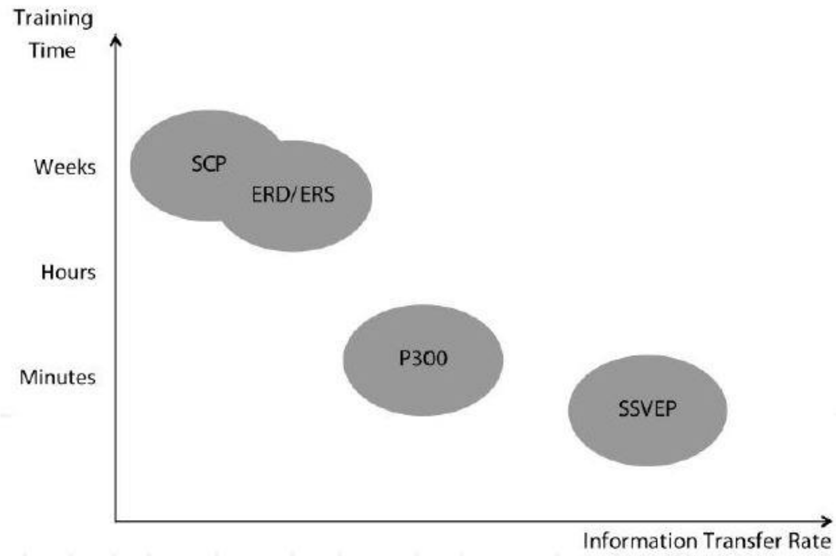


Figure 2: A comparison of the information transfer rate and training time of SCP, ERD/ERS, P300, and SSVEP

Brain-computer interfaces bypass the brain's normal output pathways (muscles and nerves) in order to communicate with the external environment. Currently, BCIs are categorized into four different types: steady state evoke potentials (SSVEP), P300 component of event related potentials (ERPs), event related desynchronization/synchronization (ERD/ERS), and slow cortical potentials (SCPs).[14] Figure 2 shows that there is an inverse relationship between training time and information transfer rate (ITR) between these BCI interfaces. There are two classes of BCI: dependent and independent. Dependent BCIs require activity in the normal output pathways, though those pathways are not used. An example of this would be visually evoked potentials (VEP), where the user still needs to glance at a visual stimulus. Cranial nerves and extraocular muscles are still required to generate the EEG signal. Independent BCIs do not depend on the brain's normal output pathways at all. The user's intent is all that is required to activate the EEG, by using a method such as P300. This is useful for those suffering from conditions which allow absolutely no motor control whatsoever.[14]

SSVEP stands for steady state visually evoked potentials. Due to high signal-to-noise ratio and higher information transfer rate, SSVEP is attracting more attention by researchers.[11] Gazing at a repetitive visual stimulus, usually a flickering LED (light emitting diode), creates stable voltage oscillation patterns in the brain, which can be detected by the EEG. When the retina is excited by the flickering stimulus, the brain creates electrical activity at the same frequency as the stimulus.

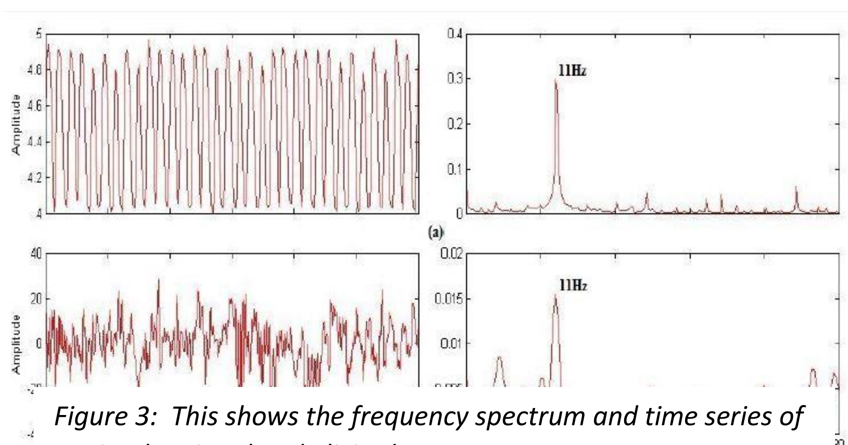


Figure 3: This shows the frequency spectrum and time series of a stimulus signal and elicited SSVEP at 11Hz

These visually evoked potentials are called SSVEP. Flickering stimuli flickering at different frequencies with constant intensity evoke the SSVEP in different amplitudes. Low frequencies range from 5-12Hz, medium frequencies range from 12-25Hz, and 25-50Hz represent high frequencies. SSVEP is more accurate at low-frequency stimulation. The amplitude of SSVEPs peaks at 15, and gradually declines at higher frequencies. The minimum detectable difference in frequencies is 0.2Hz, so several stimuli can be implemented in a relatively narrow range of flickering frequencies without the risk of interference. Since the occipital region of the brain is where the brain generates the majority of the electrical activity with SSVEP, this is where the majority of the electrodes must be placed. SSVEP is most useful when high reliability of recognition is required, and a large number of BCI commands are necessary. SSVEP also requires little to no training compared to other BCI methods. [14] For this project, we will be using a SSVEP based BCI.

Though the EEG will be used to detect the brain signals, a signal processing method is required to filter the signal. Methods for signal processing include power spectral density (PSD), autoregressive spectral analysis (ASA), canonical correlation analysis (CCA) and frequency stability coefficient (SC). PSD is the most widespread technique, and entails extracting SSVEP responses from the raw EEG data using fast-Fourier transform (FFT) of a sliding data window with a fixed length. ASA and SC provide a better power spectrum for short data windows. CCA requires shorter data window length, so is also an efficient method for SSVEP.[14]

Emotive EPOC

There are several EEG devices on the market, but most of them are prohibitively expensive for use on this project. The Emotive EPOC is an EEG device that costs only $299. It is a high fidelity wireless headset with 14 channels. Its lithium battery provides 12 hours of life allowing it to be used continuously throughout the day. It requires the user to drop a special solution on the electrode sponges connected to the headset, prior to directly wearing it.[3] The Emotiv system has the static electrode locations: AF3, F7, F3, FC5, T7, P7, O1, O2, P8, T8, FC6, F4, F8 and AF4. It offers a 128 bit/s sample rate. It is easy to use even by those that are unfamiliar with BCI, and does not require one to clean the scalp. However, it is difficult to implement SSVEP BCI system on the Emotiv, due to its not being open source and having limitations on Matlab programming. It comes packaged with Emotiv Testbench, which allows for recording and converting of EEG data into Matlab format.[8] Due to its low cost and ease of use, we will be using the Emotiv EPOC as our EEG device for this project.

Project Technical Description

The EEG uses the unique properties of Steady State Visually Evoked Potentials (SSVEP) to differentiate lights of different frequencies. From this we can create a classification system that uses a board of different lights frequencies and colors to find out which one the user is focusing on, and from that we map it to a command that can be used for whatever the user desires. The placement of the LED lights is important as the light can interfere with each other by putting nearby frequency lights farther then LED lights with a huge difference in frequency we are able to mitigate this issue.

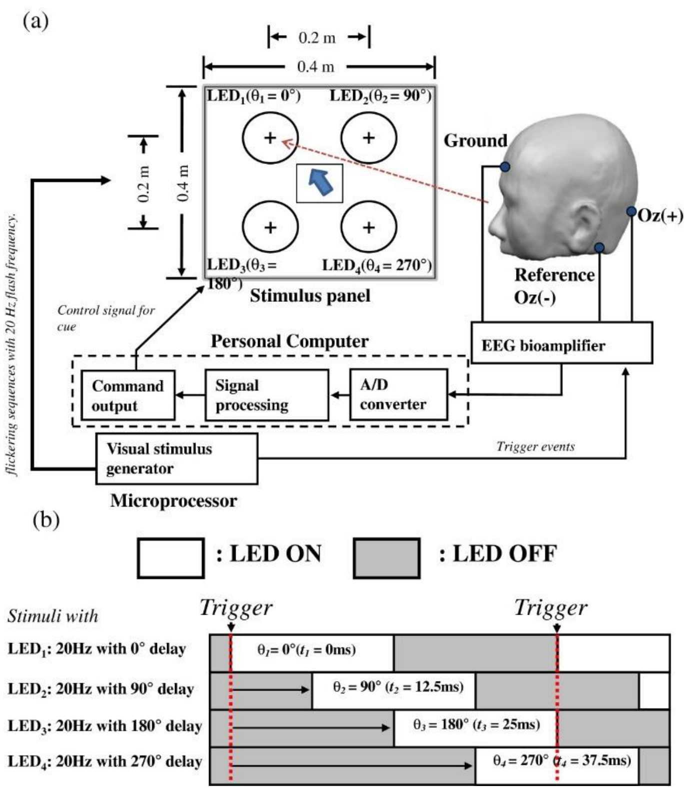


Figure 4: A model of how the proposed closed-loop BCI will work

When a user looks at one of the special SSVEP frequency lights, the brain interprets it as a signal with the same frequency. Using the EEG and filtering the signals, we can determine which LED the user is looking at using pattern recognition techniques such as Support Vector Machines (SVM). Since it has been proven that the SSVEP signal is consistent among users (by having the same frequency) we can compare the current pattern to a previous set of classified data. From this we can send which LED the user looked at to any other program. Figure 4 illustrates this concept. We plan to first demonstrate the usability of the device by attaching two LED lights and switching a light bulb on or off with the EEG and then work on controlling other devices from there. The salable product will be the Emotiv EPOC packaged with our arduino based control panel, which the user can attach to a desired device, such as a computer or wheelchair, to program and control as needed.

Research and Development Plan

We are currently in the process of developing an algorithm to interpret EEG signals with adequate filtering, so that signals picked up that are not caused by brain activity are filtered out. We are also developing the interface node that will be interpreting the EEG signals. The minimum viable product will enable a user that is connected to an EEG device to glance at a light flashing at a certain frequency and trigger a preprogrammed task (i.e. turn a light on or off). As we develop our product, we plan to integrate the technology with more complex appliances, such as a computer screen, so that the user can control a mouse by glancing at lights at the four edges of the screen. We are also considering developing a control panel board of LEDs that trigger preprogrammed actions. This control panel would consist of an Arduino microcontroller with a series of LED lights flashing at various, unique frequencies, which can be programmed for the required application. Eventually, as the technology advances, there is the potential to phase out the use of lights altogether.

Our team is also working to develop Telassist, a quad-copter controlled via a brain-controlled interface (BCI) to assist the disabled with simple tasks, such as opening doors, picking up the newspaper, and checking to see who's knocking on the door. The user will interact with the drone using an electroencephalogram (EEG) machine, a non-invasive device worn like a helmet. They can either directly control the drone or select from a menu of preprogrammed missions, via the EEG interface, which would command the drone to "hover", "land", or "pickup newspaper". The user will be able to see through the eyes of the drone and select missions via our graphical user interface (GUI) on a monitor packaged with the product. The quad-copter will also have a robotic arm attached, which will enable it to pick up and interact with objects via BCI. The real value in Telassist is the BCI interface algorithm, which is why we are developing a product around the interface algorithm before developing Telassist.

<u>The Market and Competitors</u>

Market Size

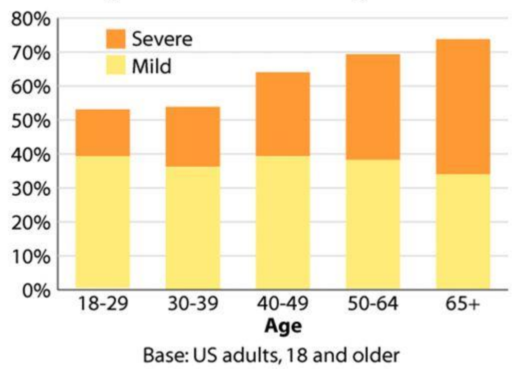
The BCI market was valued at $1.08B in 2012, and is growing at a CAGR of 8.6%, reaching $1.63B by 2017. This market includes devices such as electroencpahlograph, magnetoencephalography, Transcranial Doppler, and cerebral oximeters. The market's growth is being driven by technological advances that are leading to lower costs, ease of use, higher functionality, and miniaturization. More sophisticated technology over the coming years are likely to continue this trend.[9] There are 5,596,000 paralysis patients in America, all of whom would benefit from our technology. [6] 30,000 Americans have ALS at any given time, with 5,600 people diagnosed each year.[5] About twenty percent of people with ALS live five years or more and up to ten percent will survive more than ten years and five percent will live 20 years. We will market and sell to patients that have no motor control, and desire to use our product. The initial model will be sold via our website. Our primary sales channel will be our website.

Target Market - Primary and Secondary Markets

Users that will immediately benefit from our innovation are those that are disabled or elderly, without much or any freedom of movement. Our device will enable them to interact with devices from a distance, by simply glancing at the light source associated with the desired device and function. Victims of ALS, such as Stephen Hawking, often have minimal to no motor control. Our device will offer them a cheap way to do routine tasks such as navigating a computer, turning appliances on or off, without having to depend on personal care or expensive, customized technology.

40 million people in the United States are over the age of 65, a number projected to increase to 89 million by 2050. As the number of elderly Americans increases, many of them will require some sort of assistance around the house. A study by Forrester Research shows that one in five workers in the US will be over the age of 55 by 2020.[13] These individuals will increasingly need to use computers at older ages than generations past, and will have increasing difficulty doing so as they age. The elderly have increasing mild and severe difficulties as they age, and are likely to develop these difficulties if they are not already existent. Difficulties include visual, dexterity, hearing, cognitive, and speech difficulties.[13]

Figure 10: Difficulties and Impairments Increase with Age



Source: Study commissioned by Microsoft, conducted by Forrester Research, Inc., 2003

Elderly individuals no longer in the workforce will also need to interact with their devices, but are currently dependent on nurses or caregivers. Private Nurses and caregivers are expensive, costing upwards of $1,500 per month. Private caretakers also usually work on a part-time basis, meaning that patients are left to their own devices much of the time. Hivemind enables patients to interact with their environment using minimal effort, reducing the need for some of a private caretaker's services. Though Hivemind won't replace the human care provided by a caregiver, it will provide supplementary assistance. Paralyzed patients will benefit from our product even more, as they will obtain a sense of autonomy though Hivemind. One of the potential uses for our EEG control panel is to install it on a motorized wheelchair, enabling the patient to move simply by glacing at specific LEDs associated with a given task.

There are also applications for gaming. Gamers could install our LEDs connected to our control panel on the side of their monitor that are associated with a button on the keyboard, which will enable faster reaction times, a critical factor for hardcore and professional gamers.

Professionals that require use of both hands and extreme concentration while on the job, such as surgeons and pilots, could also benefit greatly from our innovation. A fighter pilot in the middle of aerial combat might not be able to press an important button since both of her hands are in use. Our device would enable her to glance at the required button to activate it. Researchers at the University of California at San Diego are already developing EEG scanners to detect whether the pilot is concentrating or not mid-flight, and our innovation takes this a step further.[2]

Target Market - Growth Trends and Driving Forces

Wireless sensor and microprocessor costs have plummeted in recent years, as has the cost for EEG machines. As with many technologies, performance has increased as costs have fallen. The reduction in costs for sensors have led many to believe that the "internet of things" will finally become a reality within the next 10-20 years, meaning that most of our devices will be connected to the web.[4] This rising trend will make investment in BCI related technology more attractive, as it opens up an entirely new platform and measuring tool. The global brain monitoring device market is experiencing high growth rates due to technological advances that are leading to lower costs, miniaturization, ease of operation, and higher functionality. These trends show that our technology is set to catch the next wave in revolutionary user interface products.

Target Market - Distribution Channels

Following product development and testing, the product would be available on our website, as well as through hobbyist and specialty websites. We will also be seeking partnerships with industry leaders such in the brain monitoring devices market such as Emotiv, Medtronic, Plexon, and NeuroNexus. We could also seek partnerships with video game development companies, computer monitor manufacturers, and motorized wheelchair manufacturers who we could license our product to.

Competitive Overview

Major players in the brain monitoring devices market include Advanced Brain Monitoring, Compumedics, Covidien, PLC, Natus, Integra Life Sciences Corporation, and Nihon Kohden Corporation.[9] Patients with ALS can purchase highly customized augmentive communication technology, such as that offered by Words+, the device used by Stephen Hawking to communicate. This technology is not EEG based however, as is prohibitively expensive for most users. NeuroSky is a BCI manufacturer that is working towards integrating BCI technology with iOS to create software for the paralyzed. Various companies have developed BCI devices targeted to the mainstream market. [1]

Patients also have the option of utilizing a sip-and-puff system. This is a device used to power wheel chairs or other technology by inhaling/exhaling in a pneumatic tube. Speed is controlled by sharp sips and puffs, steering is controlled by lower power SNPs. The problem with this system is that ALS patients have increasing difficulty breathing as their condition worsens. Eventually, they are unable to move a sufficient amount of air in and out of lungs to use the system due to muscle weakness.[12]

Figure 5: An ALS patient in a sip-and-puff controlled wheelchair

Financial Analysis

Pricing and gross margin targets

We plan to sell our product at a 36% gross margin. The total cost for the product is $320, and will retail for $499. This product would include the Emotiv EPOC, the arduino based control panel, and ten LEDs. The EEG device we will be using is the Emotiv Epoc, which retails for $299. We will be using an Arduino Uno as our microcontroller for the LEDs, which retails for $18. The LEDs retail for less than $0.10 each. We project a CAGR of 30%

Though the majority of expenses will be in the form of cost of goods sold, operational expenses are not insignificant. The largest expense in the first year will be founder's salary, which is quite low at $15,000 each. This will grow to $45,000 each as revenues increase. Sales is 5% of revenues, and will entail costs such as hiring marketing staff and developing promotional materials. We will need to bring on two full-time engineers beginning in the second year of operation to help with research and development, adding an additional engineer every year. Office rent is projected to be $750 per month. We will also be purchasing general liability insurance, which will cost $5,000 annually. Research and development equipment will be required to further develop the product.

Revenue Growth Projection						
	Units Sold	Price per unit	Cost per unit	Revenue	Cost of Goods sold	Gross Revenue
Year 1	1,000	$ 499	$ 320	$ 499,000	$ 320,000	$ 179,000
Year 2	1,300	$ 499	$ 320	$ 648,700	$ 416,000	$ 232,700
Year 3	2,080	$ 499	$ 320	$ 1,037,920	$ 665,600	$ 372,320
Year 4	3,328	$ 499	$ 320	$ 1,660,672	$ 1,064,960	$ 595,712
Year 5	5,658	$ 499	$ 320	$ 2,823,142	$ 1,810,432	$ 1,012,710

Income Statement					
	Year 1	**Year 2**	**Year 3**	**Year 4**	**Year 5**
Revenue:	**$499,000**	**$648,700**	**$1,037,920**	**$1,660,672**	**$2,823,142**
Cost of Goods Sold:	($320,000)	($416,000)	($665,600)	($1,064,960)	($1,810,432)
Gross Profit:	**$179,000**	**$232,700**	**$372,320**	**$595,712**	**$1,012,710**
Operating Expenses:					
Engineer Salaries	$0	($60,000)	($80,000)	($120,000)	($300,000)
Sales Staff Salaries	($24,950)	($4,654)	($18,616)	($29,786)	($50,636)
Server Fees	($20)	($100)	($300)	($500)	($700)
Office Rent	($5,625)	($11,250)	($11,250)	($11,250)	($11,250)
Marketing Costs	($27,350)	($14,035)	($21,016)	($32,186)	($53,036)
Liability Insurance	($5,000)	($5,000)	($5,000)	($5,000)	($5,000)
Research and Development	($20,000)	($50,000)	($50,000)	($100,000)	($200,000)
Total Operating Expenses:	**($62,945)**	**($95,039)**	**($136,182)**	**($198,721)**	**($420,621)**
Depreciation & Amortization of PP&E:	($1,000)	($3,500)	($6,000)	($11,000)	($21,000)
Operating Income:	**$115,055**	**$134,161**	**$230,138**	**$385,991**	**$571,089**
Interest Income:	$0	$0	$0	$0	$0
Interest Expense:	$0	$0	$0	$0	$0
Other Income & Expense:	$0	$0	$0	$0	$0
Pre-Tax Income:	**$115,055**	**$134,161**	**$230,138**	**$385,991**	**$571,089**
Income Tax Provision:	$0	$0	($73,004)	($131,237)	($194,170)
Net Income:	**$115,055**	**$134,161**	**$157,134**	**$254,754**	**$376,919**

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