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13. ABSTRACT *(Maximum 200 words)*

The purpose of this Phase I STTR was to demonstrate feasibility for a wireless long-term EEG/EMG recording system for use with mice. Animal testing at Northwestern demonstrated that mice will tolerate a head-mounted unit of up to 1 cm^3 without modifying their running wheel behavior, if the weight did not exceed 500 mg. The effective maximum volume is 5x5x7 mm (0.2 cm^2). The proposal called for an IR power and telemetry link, but after a significant effort, the team determined that this approach is not feasible. All alternative power solutions were considered, and the team settled on a design in which a radio frequency (RF) field remotely powers the system eliminating the need for batteries, and "backscattered" telemetry transmits data. A remotely powered system was developed which can measure 200 uV differential inputs (10 uV noise floor) at approximately 35 samples/sec/channel with a current draw of 500 uA (1.5 mW). This is a significant achievement - however, after completing this Phase I, it is clear that the size, power, cost, gain, and acquisition speed required for wireless long-term EEG/EMG testing on mice is not feasible with current technology, but the design has applications in other areas of manufacturing.

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Executive Summary

A wireless electroencephalographic (EEG) and electromyographic (EMG) long-term recording system for mice, like the one examined in this STTR, would have numerous advantages including reduced electrical noise and animal stress. In other work, Pinnacle has shown the viability of this approach for the amperometric measurement of neurotransmitters in rats and other small animals (NIH 1R43NS37606-01A1 "Biosensor Array, Wireless, In-Vivo Monitoring System," http://www.pinnaclet.com/biq/rathat.htm). The results of this project have been very encouraging, and we are moving toward commercialization

However, a **wireless** solution for EEG/EMG on mice is a much more difficult problem, and the results of our Army Phase I effort have shown that with current technology, there is no feasible approach to building such a device. The most glaring constraints for a wireless monitoring system are size and weight. Animal testing at Northwestern has shown that the mice will tolerate a head-mounted unit of up to 1 cm^3 without modifying their running wheel behavior, as long as the weight did not exceed 500 mg. Practically, the device size has to be significantly smaller. Testing shows that 5x5x7 mm (0.2 cm^2) is the effective maximum. This testing was carried out using eight mice from two different strains (3 BALB/C and 5 C57BL/6J), 4-5 months old and weighing 20-30g. As a point of comparison, a single state-of-the-art surface-mount instrumentation amplifier (required for the first stage signal amplification) measures 5x5 mm. This does not include the additional space needed for multiple channels, routing, telemetry, etc.

One might argue that an Application Specific Integrated Circuit (ASIC) or custom integrated circuit in a miniaturized package might be the best solution. However, mixed-signal ASICs are very time consuming and expensive to design and produce, and in general, they are not cost effective unless the number to be sold is very large (>100,000 units). For the mouse, we project that system sales will be in the thousands. This is large, but not large enough for ASICs. During the course of the Army Phase I STTR, we contacted several ASIC manufacturers and found that the base price for prototyping costs alone is in the \$300,000 range. In fact, this is probably an underestimate since the combination of low power and high accuracy required for this application will force the use of extremely specific (and protected) analog layouts.

Another option is hybrid technology. In this approach, the individual semiconductors (without packaging) are placed on a common substrate. This removes all of the wasted space due to packaging; however, the cost is prohibitive, and the substrates themselves tend to be rather large and heavy. During the course of this Army Phase I, we worked closely with engineers from the DOE Kansas City Plant run by AlliedSignal (now Honeywell). The Honeywell engineers are experts in hybrid design, and yet no viable solution to the size problem was found.

The second main problem is power. To accurately measure EEG and EMG signals, the system must amplify the incoming signals by 5,000 to 10,000 times, and acquire data from multiple channels at approximately 100 samples per channel per second with at least 12 bits of resolution. In many designs, low power can be achieved by turning the power off between samples, but at the data rates required for EEG/EMG measurements it is not possible to shut the system down for long. In our Phase I effort, we achieved a total power consumption of 1.5 mW with two channels acquiring data at roughly 35 samples per second and transmitting the data to a stationary receiver via a telemetry link. This is an amazing result, considering the current state-of-the-art, but it is still not good enough for this application. In short, there is no battery technology available today that will meet the size and weight constraints of a wireless system for use with mice, and other solutions, such as supercapacitors, are also too large at present.

In the end, the team settled on a design which used inductive coupling for both power and telemetry. A radio frequency (RF) field remotely powers an inductively coupled system. This eliminates the need for batteries. A block diagram of the system is shown below. Circuit schematics and printed circuit board layouts are given in Appendix A.

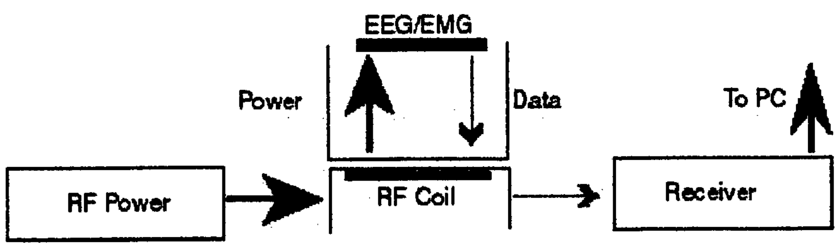


Figure 1: Wireless System Overview

This prototype wireless system coupled power to a very small and lightweight head-mount which contained power conditioning, high-gain amplification, analog-to-digital conversion and telemetry electronics (see prototype - Figure 2). Power was delivered to the electronics as radio frequency (RF) radiation. This power was then used to generate the on-board voltages required by the EEG/EMG unit to acquire data. Once a sample was digitized, it was transmitted back to the receiver by simply detuning the receiving coil. This "backscattered" approach to telemetry is commonly used in RF identification systems, and it has the advantage of consuming very little power since there is no active emission during transmission. The receiver in turn separates the approximately 100 mV data stream from the 200 V RF power link, and sends it on to a PC for analysis. At least two companies, Mini Mitter (www.minimitter.com), and Data Sciences International (www.datasci.com) commonly use this basic approach for implant studies with large-signal sources (temperature, pressure) and even single-channel EEG. Single channel EEG is difficult, but much simpler than the two channel system which is being developed in the Phase I STTR since the output of the first stage amplifier can be directly coupled to a voltage controlled oscillator.

Our benchtop tests demonstrated the proper function of all aspects of the system. In our tests, we obtained high-resolution measurements of 100 uV input signals, as long as the receiving coil was separated from the EEG/EMG inputs by a few inches. Pinnacle successfully conducted a bench-top demonstration of the overall system at NWU on March 3rd. The remotely powered circuit measured 200 uV differential inputs (from a function generator and voltage divider) at approximately 35 samples/sec/channel with a current draw of 500 uA (1.5 mW). This is a significant achievement, however, when the power receiving coil was integrated into the EEG/EMG electronics package, the electrical noise from the power coupling was simply too great, and tended to overwhelm the system. There is no easy way around this problem. The best solution would be to use a small battery to power the unit, but even the smallest batteries currently available are roughly 7 mm in diameter, and if a battery powered solution is used, the power consumption will increase since an active telemetry system will be needed. The prototype size is shown below. As discussed above, the overall size of this prototype is very small (1" x 0.7"), and the projected size of a hybrid solution is less than 0.5" x 0.5". However, our testing with mice has shown that this is too large by roughly a factor of two.

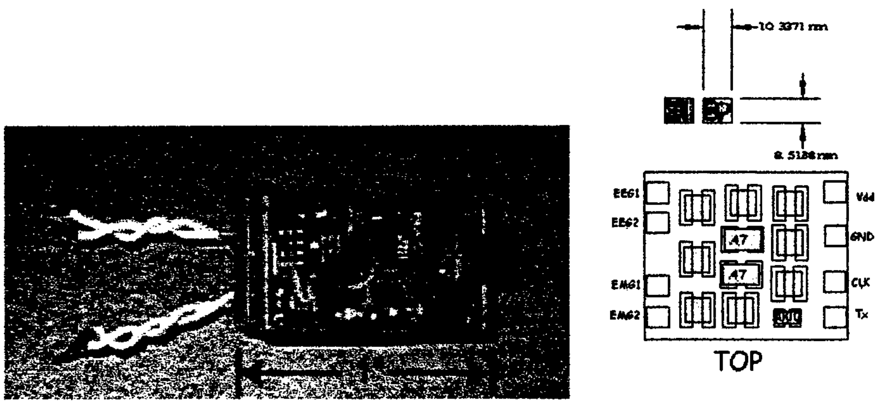


Figure 2: Complete Functional Wireless EEG/EMG Prototype and Hybrid Layout

For all the reasons mentioned above, it is the team's opinion that there is **no viable wireless solution for EEG/EMG untethered monitoring in mice at this time.** However, the results do lead us to believe that a more efficient tethered design is possible and necessary if sleep research in mice is to advance.

Significance of Research

People sleep for about a third of their lives. Sleep disorders of various kinds are known to affect the majority of elderly Americans and a significant percentage of other age groups. At least 84 different sleep disorders are known to interfere with quality of life, degrade personal health and endanger public safety. For example, an NIH study of 913 adults found that individuals with severe sleep apnea were 7.3 times more likely to be involved in multiple motor vehicle accidents over a five-year period compared to those without apnea. The total economic impact of sleep disorders including health care costs, lost productivity and property damage is very difficult to accurately measure, but an overall understanding of the genetic, chemical and environmental influences which affect sleep is clearly needed.

The genomic and genetic resources currently available for the laboratory mouse make it the most important experimental organism for mammalian genetic approaches. The availability of inbred strains, genetic markers, and YAC and BAC (Yeast Artificial Chromosome and Bacterial Artificial Chromosome) clone libraries make it more feasible to positionally clone genes in this species than any other. The methods for transgenesis and gene replacement by homologous recombination also are well-developed in this species, so that so-called "reverse genetic" approaches may be taken. Further, effective chemical mutagens makes mutagenesis screening for genes underlying a variety of phenotypes practical in the mouse. Hence, a number of genetic approaches to identifying genetic (and consequently molecular) elements underlying complex physiological processes such as sleep can be taken in the mouse.

To support research in the areas of sleep, fatigue, alertness, etc. and to take advantage of the molecular genetic revolution in mice, new state-of-the-art EEG recording techniques are required. The research team believes that an EMG channel is also necessary to properly score rodent sleep. In addition to the necessary information that EMG levels provide about wakefulness and sleep, the signal is used within sleep periods to distinguish between SWS and REM sleep. At present, it is estimated that less than a dozen laboratories world-wide are recording sleep in mice. This is not due to a lack of interest in sleep as a biologically challenging and important area for research - sleep disorders affect millions of Americans (National Sleep Foundation statistics). Nor is it the lack of use of mice as a research model. The National Institutes of Health have devoted a broad, multi-institute initiative to development of mice as biomedical research organisms because of this species' value as a genetic organism (see http://www.nih.gov/science/mouse). Rather, it is simply the difficulty of recording sleep in such a small animal, which acts as an impediment to doing this type of research. In our opinion, a large number of research teams will purchase a simple, long-term sleep recording system when it is available.

Currently, sleep recording in the mouse involves monitoring one EEG and one EMG channel via implanted electrodes. EEG electrodes commonly take the form of two small stainless steel screws implanted in the skull while EMG waveforms are recorded using small wires placed under the trapezius muscle. Typically, implantation of these electrodes and their attachment to a small connector that is mounted on the head involves complex surgery lasting about an hour per animal. After surgery, a recovery period of about a week is necessary before any sleep recording can begin. In order to record EEG and EMG waveforms, the implanted electrodes are connected to a flexible tether system which conducts the low-voltage (about 100 μV), unamplified signals to a swivel mount. The swivel allows the mouse a complete 360° range of movement while maintaining the electrical connectivity. The signals are currently amplified and filtered after they have traveled several meters from their source. Following amplification the signals are converted into digital format and archived on a large capacity storage device such as a CD-ROM.

While this "hard-wired" method of sleep recording has been used successfully in the rat for well over 40 years, the field of sleep research is quickly changing and a new animal model is required. Moving away from neuroanatomy and neurochemistry, the study of sleep has come to focus on specific genes which may be responsible for the sleep process. The study of genetics requires the use of a newer animal model, the mouse. Thanks to recent developments in genetics research, the human genome is nearly cloned and a complete map of the mouse genome is not far behind. In fact, specific genes that may be responsible for sleep onset and/or duration have been identified in several recently-published papers [Fang, 1997, Tobler, 1997; Franken, 1999; Chemelli, 1999; Franken, 2000]. The movement towards recording sleep in the mouse has the potential to unlock unprecedented findings about the genetics and molecular biology of the sleep process. However, the extremely small size of the mouse as compared to the rat has revealed several problems with the currently available tether system which are not easily overcome with existing technology. These limitations include:

- High swivel torque which encumbers the mouse under test
- Movement noise which can create artifacts
- Limitation of one EEG channel which makes automatic scoring difficult
- High cost which limits research

If these difficulties can be overcome, and a more streamlined system specially tailored to the mouse is developed, the study of EEG waveforms in this species will become easier and more accessible to scientists outside the EEG and sleep community. Development of a refined, high-capacity EEG system will increase the ability of pharmaceutical companies to screen drugs for seizure and sleep abnormalities. At least two companies whose primary mission is to screen possible sleep-enhancing drugs in a rodent model are already in existence. Genetic screens will also be greatly enhanced by allowing the high throughput needed (on the order of 1000 mice per year) to screen for mutations. More importantly, it will open up the field to researchers who otherwise might not be able to study EEG waveforms

Continuing Research

To overcome the obstacles described above, the team has submitted a Phase I proposal to the National Institutes of Health to continue this work for a **tethered system** ("Integrated, Low-Cost EEG/EMG Recording System for Mice"). The following summarizes the expected results of this work.

Swivel – Mechanical swivels require some amount of torque to rotate. Even the best swivel arrangements, which have torque that is negligible for rats, are not acceptable for use with a mouse. New swivels, which can easily be rotated by a small mouse, will allow the mouse greater freedom of movement throughout the cage and allow the use of a running wheel in conjunction with sleep recording.

Movement Noise – When the mouse is awake and moving around the cage, the movement in the tether cord combined with the low-voltage nature of the signals creates a great deal of noise in the amplified signal. This movement noise overrides the recorded signal and makes evaluation of the waveform during periods of wakefulness impossible. By amplifying the EEG signals at the source (on the head), movement noise will be eliminated. This will allow a better analysis of the waking EEG signal.

Limitation of One EEG Channel – On the rat skull, there is ample room to place four or even six recording screws, allowing multiple EEG channels. The dramatically smaller size of the mouse skull prevents more than two screws from being placed comfortably; allowing for only one EEG channel. A head implant designed to accommodate four screws will allow for two or even three EEG signals to be conveyed back to the recording system. The addition of extra EEG channels will facilitate better analysis of the sleep waveforms. Additionally, extra channels would make it possible to develop an automated sleep scoring algorithm which would dramatically reduce data analysis time.

Cost – It currently costs over $3000 per mouse to set up a sleep recording facility. This includes the cost of cages, swivels, amplifiers, computers and recording software from different manufacturers. A significant cost reduction will allow a greater number of laboratories to enter into the sleep recording field.

A streamlined system specially tailored to the mouse will make the study of EEG waveforms in this species easier and more accessible to scientists outside the EEG and sleep community. Development of a refined, high-capacity EEG system will increase the ability of pharmaceutical companies to screen drugs for seizure and sleep abnormalities. At least two companies whose primary mission is to screen possible sleep-enhancing drugs in a rodent model are already in existence. Genetic screens will also be greatly enhanced by allowing the high throughput needed (on the order of 1000 mice a year) to screen for mutations. More importantly, it will open up the field to researchers who otherwise might not be able to study EEG waveforms

Phase I Research Results

System Design

On September 27, two engineers from Pinnacle traveled to Evanston, IL for a very productive meeting with Fred Turek's group at Northwestern University. The basic focus of this meeting was to make sure that everyone clearly understood the objectives, timelines and responsibilities for this project. Some key points from the meeting are:

- A system which is roughly 10 x 10 x 4 mm will be acceptable for mice
- The software which has been developed by NWU should be adequate with minor modification

- Filtering/gain/sampling rate estimates for the EEG and EMG channels were established
- Power options were discussed including RF and IR.

The tether that is currently used is very large, and obviously the design complexity and cost of the system will decrease as size increases. Therefore, the team decided that in the early stages of this project, one goal will be to determine the maximum size head mount that a mouse can handle without showing strain. To this end, Northwestern prepared a series of experiments to determine the point at which a mouse's running wheel behavior is effected by various head set mock ups. At the same time, Pinnacle designed a preliminary IR test to determine if an IR solution will be feasible under real testing situations. In particular, the communication range and "blocking" effects were to be investigated. At this point, the team was concerned that the mouse might block an IR signal by curling up while sleeping, piling debris, etc. Pinnacle also started to purchase components for initial breadboarding and testing.

On Wednesday, October 6th, Pinnacle had an initial meeting with the engineers at Honeywell to explain the overall design and goals. At that time, Pinnacle delivered an estimate of part count, size and the usage requirements of the NWU team. Honeywell started to investigate the best manufacturing method for both the mechanical and electrical components.

Stage I Electronics Development

Pinnacle developed the electronics and investigated various power and telemetry solutions. First level prototypes were constructed.. At this point, the problem was well understood and the team was entering the first evaluation stage for IR and inductive solutions. The original proposal called for an IR power and telemetry link. From the original proposal Subtask 1.C:

> *In this subtask, all viable power options will be addressed. The power budget can be estimated from previous designs. For a low noise instrumentation amplifier, 100 Hz 12 bit analog to digital converter and IR telemetry, the estimated current consumption at 3V will be around 2 mA (microcontroller 1 mA, IrDA 16bits, 2 channels @ 100 Hz 300 uA, Instrumentation Amplifiers 400 uA, power conditioning 100 uA). One solution is to implant a primary battery. This is a reasonable back-up solution, but an external power source would be much easier for the user, and this STTR solicitation clearly calls for an external power source. The external power source can not introduce appreciable noise into the frequency band of interest. This means that an inductively coupled radio frequency (RF) solution is very unlikely. RF has a secondary problem in that the antenna used for telemetry or power coupling must be relatively large at normal (900 MHz) frequencies. In the long term, shaped polymer batteries might provide an elegant solution. In the short term, an IR power source with IrDA standard telemetry is likely to emerge as the best overall solution. An IR powered system is especially*

suited for this application since the sleep cages are light tight in most cases. This will reduce the noise coupled in from other illumination sources. At the power levels required, the animal will not feel or see the IR power source. One severe problem is that if the IR power source is at the same wavelength as the IrDA device, the power source will swamp the telemetry link. This problem can be addressed by using long wavelength (InGaAsP/InP or other) light emitting diodes to supply power, and a low bandgap receiver to receive the power. Typical IrDA devices operating at 900 nm will not see this radiation. However, the area of the power receiver is very small, even in a stacked structure (4 mm x 4 mm). The incident IR power will have to be relatively large in order to generate the required power (about 5 mW). A charge pump converter will also be required to convert this power to a 3V system voltage. Another problem is the angular dependence of the telemetry. If the mouse curls up while sleeping or rolls over, power, and the telemetry link may be lost. The solution to this problem is to connect each basestation pod to several power/receiver units. Valid data from any receiver will be accepted and essentially omnidirectional power will be available. Experimentation will determine the best number and arrangement of these power/receiver units. An on board capacitor will also be required to handle the > 25 mA surge currents required for the IrDA device.

During this month the team discovered two main problems with the IR solution. It is theoretically possible to use a broadband IR source such as the L523-G Gold Reflector Halogen from Gilway Technical Lamp (www.gilway.com). This would be a good solution since the power could be delivered at long wavelengths which are too low for the IrDA telemetry system to detect, and the power would be "clean" – i.e. free from RF interference. The first problem is that expensive Indium Gallium Arsenide (InGaAs) diodes would be needed to convert the incoming radiation to electricity. InGaAs detectors are very expensive ($180 for 3 mm x 3 mm, http://www.fermionics.com/LargePD.htm), and often not available in die form. A more imposing problem is that there is very little area to work with. For a 4 mm x 4 mm detection area at 10% overall efficiency about 3 kW/m^2 of illumination would be necessary to produce 5 mW of power. It is not clear that any arrangement of lamps will produce this power level in a convenient (easy to use) arrangement for all orientations of the mouse. An additional problem is that two cells in series will produce about 1.1 V, so a charge pump would be necessary.

Batteries can not be used due to the size and weight constraints of the device. The highest energy density commonly available is Lithium Thionyl Chloride (710 Wh/kg, 1300 Wh/l). Assuming a maximum volume of 0.24 mL and a maximum weight of 500 mg, the theoretical limit for this battery would be about 100 mAh at 3 Volts. In reality, the size of the battery would have to be roughly half as large, giving a maximum capacity of 50 mAh. For a circuit with active telemetry drawing 1 mA, this corresponds to a lifetime of roughly 2 days. This is not adequate for the sleep research community, and even if this was suitable, there are no batteries on the market with this form factor. Secondary (rechargeable) batteries do not have a high enough energy density to be useful, and there is on room for the recharging circuitry. Inductive coupling offers the possibility of delivering power and communication over the same link (by detuning the receiving coil), but this advantage is offset by the size and weight of the receiving coil and noise introduced into the overall system. IR power sources in the long wavelength regime have to be coupled into very expensive collectors (InGaAs). Short wavelength IR sources may interfere with the IrDA communications link, and in general, IR is inherently line of sight.

Other power technologies such as supercapacitors were also examined, but although significant advances have been made in recent years the energy density of these devices is still an order of magnitude too low for this application. For a supercapacitor behind a charge pump, initially charged to 3 V, the charge pump will operate down to about 0.9 V, so delta V = 2.1 Volts. For a constant current of 1 mA, a capacitance of 41 F would be required to keep the device on for 1 day. This is well beyond anything the specifications of current devices. At this stage, the team converged on two potential solutions to the power problem IR and Inductive coupling. At this point, we were leaning toward inductive coupling for all of the reasons discussed above. Also, any active telemetry system (IR or RF) would require a rather large storage capacitor to provide surge currents when the telemetry is active. Given the size constraints for this project, it is very unclear where this capacitor would fit in. At this stage, prototypes were developed to test both RF and IR solutions.

Size is also a primary concern and to that end, ASICs were also examined, but the cost for relatively low volumes (< 10,000 units) is quite expensive for a mixed signal design of this type ($300,000 development cost and $50 - $100 per unit).

Mouse Size and Weight Experiments

Northwestern conducted a series of tests to determine the maximum size and weight for the EEG/EMG electronics and telemetry. Work during this period focused on determining the maximum size and weight that mice will support on their heads. The validation technique was based on measurements of the animal's running wheel activity. Eight mice from two different strains were examined; three BALB/C and five C57BL/6J. All animals were full grown adults between 4-5 months of age and weighing 20-30 g. The mice were entrained to a 12:12 LD cycle before entering into the experiment. Baseline wheel running activity was measured in the five days prior to implant surgery. During surgery, four small screws were implanted into the mouse skull in a manner similar to an actual sleep recording implant. A layer of dental acrylic was applied to cover the screws and provide a base for the implant. Creation of the implant was accomplished by taking a plastic base 1 x 1 x 0.5 cm (weighing between 1.3 and 1.4 g) and coating the bottom with dental acrylic. This coating then attached to the acrylic base already in place on the mouse skull. The mouse was allowed to recover from surgery and adapt to the implant for at least seven days before activity measurements were taken. After five days of activity measurements with the smaller implant, another layer was added to increase the size to 1 x 1 x 1 cm and increase the weight by an additional gram.

Again, at least seven days were allowed before wheel running records were analyzed over a five day period.

Individual animals' responses to the first two implant sizes and weights can be noted in Figure 3. The numbers to the right of the lines indicate the final implant weight for each mouse. Two mice were unable to complete the second phase of the experiment but yielded good data for the smaller implant size and were included in this analysis. Figure 4 shows the average running wheel activity over five days for the C57BL/6J mice only. Although a slight downward trend in wheel activity can be noted, an analysis of variance test indicates that there was no significant difference between any of the three time points ($p=0.42$).

Overall, the results indicated that an implant of 1 cm^3 and weighing about 2.5 g did not significantly impact wheel running activity in C57BL/6J mice. However, the decline in wheel running activity by about 4000 revs/day does suggest that the mice were not entirely unaffected by this size and weight. The low number of BALB/C mice in the experiment made a group analysis impossible but the data did suggest that they will tolerate the smaller implant and at least one BALB/C mouse did show promising results with the larger implant. It should also be noted that The BALB mouse showing a severe decline in wheel activity had the heaviest implant of any of the mice. Because mouse strains differ widely in their responses to stimuli it is impossible to say with certainty that the larger size and weight will be as well tolerated in all strains. However, this data, suggests that the maximum dimensions for the head implant be no larger than 1 x 1 x 1 cm and weigh no greater than 2.5 g. Of course, an implant of that size will only be useful on a full-grown adult mouse so smaller is always better.

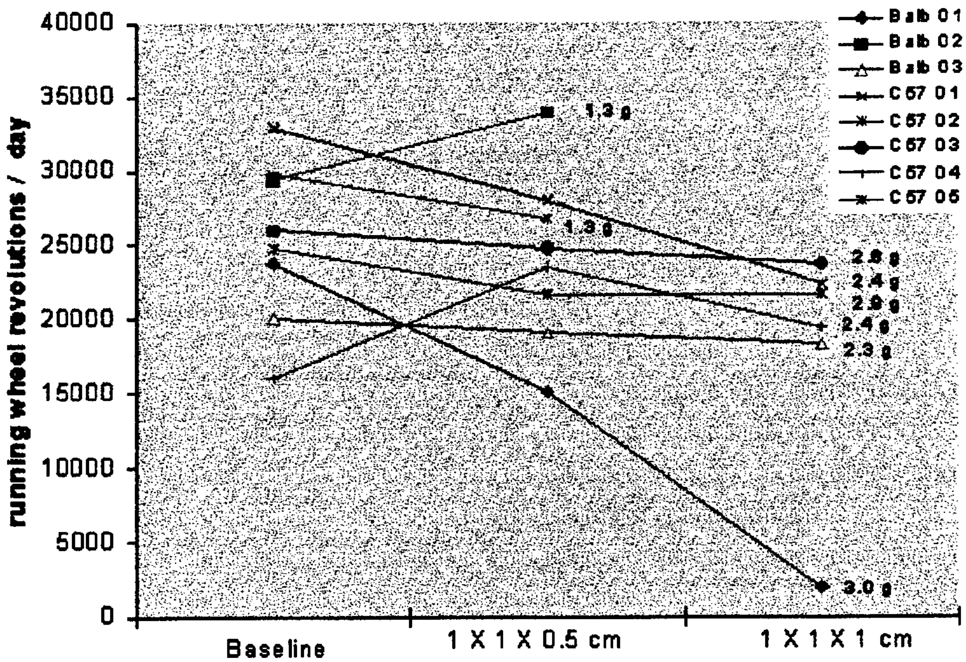


Figure 3: Weight Testing: Running Wheel Activity

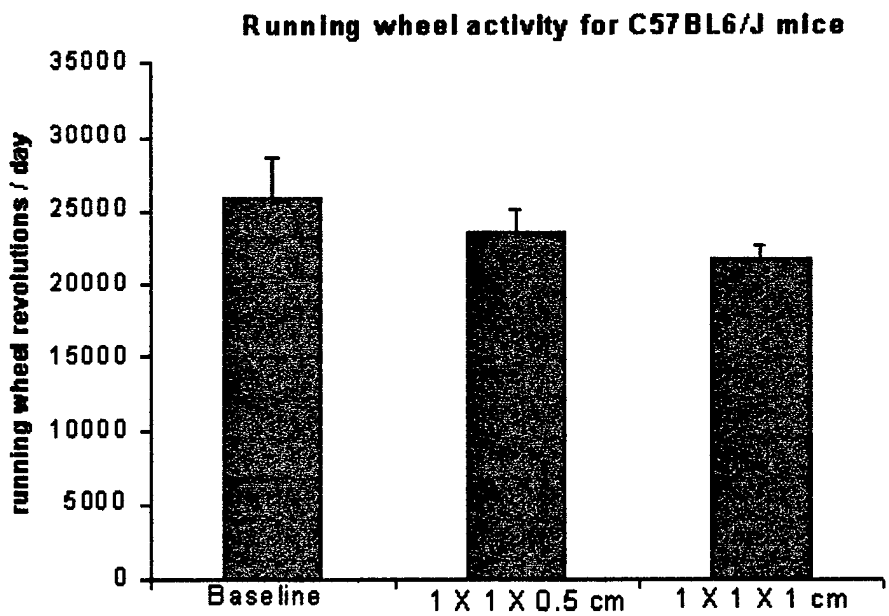


Figure 4: Size Testing: Running Wheel Activity

Based on this information Pinnacle reexamined the system options. Initial testing of the EEG/EMG and basestation electronics was completed. We anticipated that computer renderings and rapid prototyped models of some of their initial designs would be available early in November, but this was pushed back to December. Although unanticipated, this delay allowed Pinnacle to incorporate the NWU size and weight findings into the initial models. Pinnacle also continued to investigate various power and telemetry solutions. From continued testing on IR power and telemetry systems, it was apparent at this point that an RF solution was most probable.

Stage II Electronics Design

Based on Northwestern University's revised size and weight data. Pinnacle and Honeywell engineers reexamined all possible solutions during a December 14th meeting in Kansas City. With this new data, it was determined that an inductive link would most likely yield a working and marketable product. Other companies such as Data Science International and Minimitter are already using this approach for implants. Honeywell's RF design team also examined novel methods of RF antenna design including fractal antennas. Pinnacle completed breadboard testing of a complete inductively coupled data and power link, and began designing boards for second level testing. At this stage, we decided to use a two-stage amplification system prior to A/D conversion in the initial designs due to hardware variability. This added size, and turned out to not be necessary, but at this point the design guaranteed signal integrity that is not IC batch dependent. The power was not significantly affected by the second stage. The receiver/basestation design was proceeding. We decided on a test configuration with simple analog output interfacing with NWU's existing LabView based software. Internet capability was also considered. Pinnacle has used similar solutions in its internet ready datalogging products (www.pinnaclet.com/ez.htm).

Final System Design

An overall functional design using an inductive power/telemetry link was completed. This system measured EEG/EMG at a data rate of 35 Hz per channel and 12 bit resolution. The overall power dissipation for the current design was 1.5 mW. It was clear at this stage of the project that standard surface mount electronics would not meet the size constraints on this project. The preliminary single board layout shown in Figure 5 using surface mount components measured 0.75 in^2.

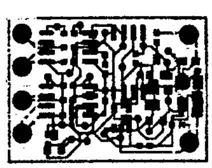


Figure 5: Preliminary SMT layout

During this month a bench solution was demonstrated that met the power and data rate design requirements for this system. A backscattered telemetry scheme allowed low bit error rates and low power operation. The hardware was designed and software written to establish the power, data acquisition and telemetry components of this project.

The team successfully established a very low power system using an indcutively coupled RF data/power link. Initial testing indicated that noise from the inductive link can be effectively filtered from the EEG/EMG signals yielding a noise floor in the 10 uV range. At this stage of the project, the team was still hopeful that a solution with an integrated inductive pickup would be possible.

Testing and Final Assessment

At this point, the team had settled on an inductively powered design with backscattered telemetry as the only possible approach to this problem, and preliminary prototypes had been successfully demonstrated. Initial testing indicated that noise from the inductive link can be effectively filtered from the EEG/EMG signals yielding a noise floor in the 10 uV range. The initial design specification called for a sample rate of 50 Hz on both channels. In the preliminary designs 35 Hz per channel was achieved, but it was clear from this initial testing that a sample rate of at least 100 Hz per channel would be necessary for a practical design. In the long term, the sample rate could be easily increased by moving from a 125 kHz power link to a 13.56 MHz link. 13.56 MHz is also a standard frequency for remotely powered devices. In effect, to achieve sampling rates of 100 samples/sec/channel with 12 bits of resolution a telemetry system with a practical bandwidth of about 5 kHz is necessary. There are a variety of transmission protocols such as frequency shift key (FSK) and phase shift key (PSK) can be used to achieve this data rate with a 125 kHz carrier. However, the bandwidth is much easier to achieve at 13.56 MHz. In addition, the coupling coil size decreases at higher frequencies and the noise coupled into the measurement would be easier to filter.

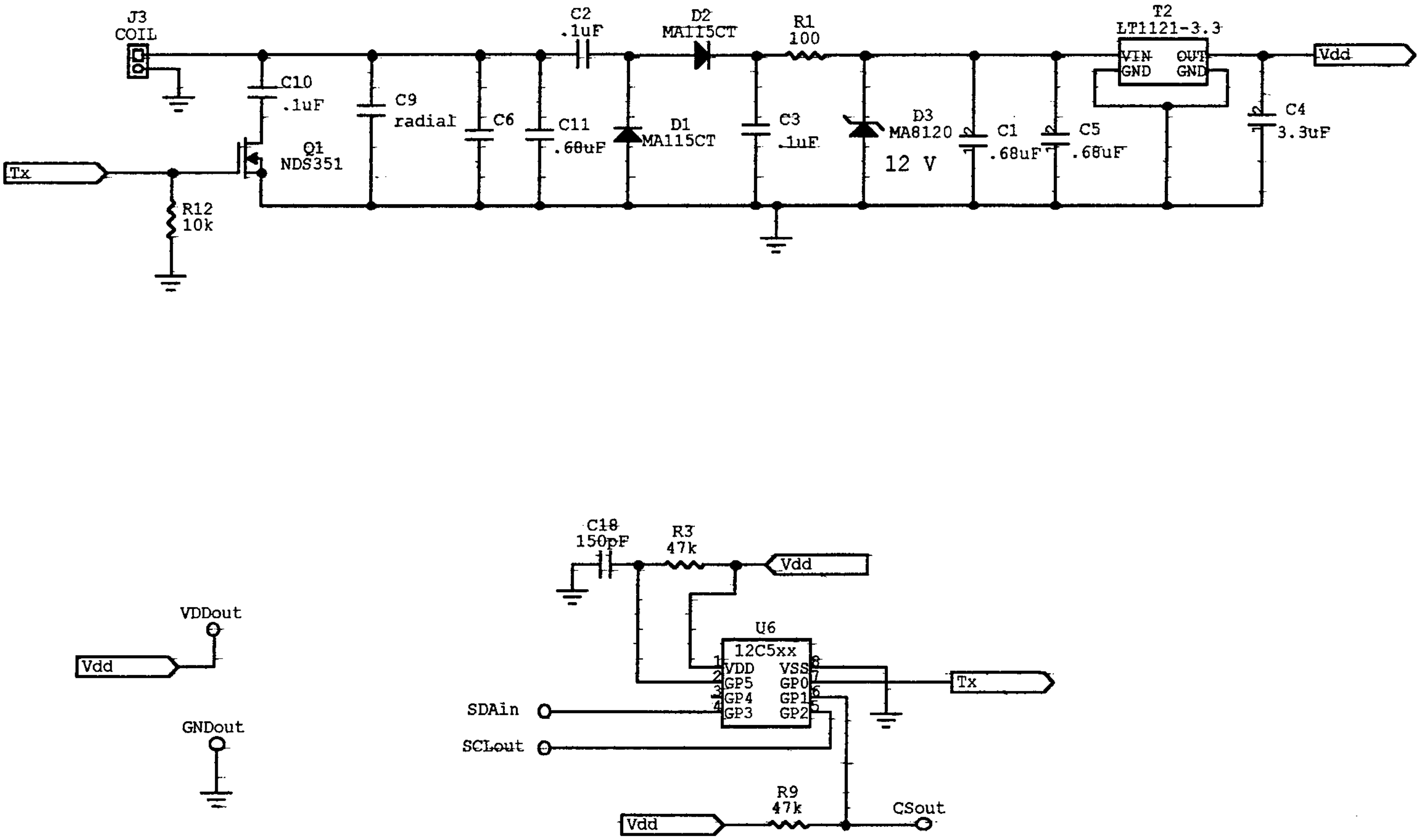
During this period the team struggled to find a design which would meet all of the size and weight requirements for this project. It was clear that this problem can not be easily solved with SMT components, and hybrid designs and ASIC designs are applicable, but expensive. Various chip sized packaging schemes such as National Semiconductor's Micro-SMD packaging may prove to be very valuable as more IC's are converted to this packaging format. However, at present there are few practical options available.

On March 3rd, Pinnacle conducted a successful demonstration of the overall system at Northwestern. It was hoped that the system could be tested on mice, but the surface mount prototype was too large, and the noise induced by the 125 kHz power carrier too great for a fully integrated system. Therefore, although the test of overall functionality was a success, it was equally clear that at this time, there is no practical way to develop a system which will be useful for mice. In short, the size, power, cost, gain, noise, and acquisition speed required for EEG/EMG testing force a design solution that is not possible with Year 2000 technology. As ASIC or hybrid solutions become more commonplace, new battery technologies develop, and costs decrease, the team is confident that a solution will emerge. However, in the short term there is no apparent answer. For these reasons, the team decided to temporarily abandon the idea of a head-mounted wireless design. Instead, we will seek future funding to develop a superior tethered solution. There are many aspects of the current tethered design that can be vastly improved.

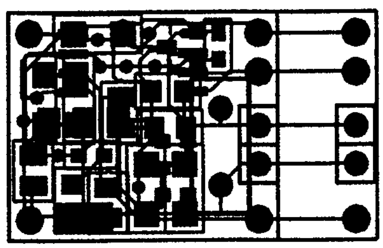
Conclusions:

The system that was developed worked very well, but not well enough for this application. Based on our current knowledge and the results of this Phase I research, the team is in the process of identifying alternative applications, with less severe size and weight constraints, where a remotely powered sensor interface and data acquisition unit would be required. A medical example would be long-term neurophysiological monitoring for larger animals. Another, non-medical, example would be data acquisition in sealed, hazardous environments. Once these areas are identified, the team will develop strategies to actively transfer this technology into those areas.

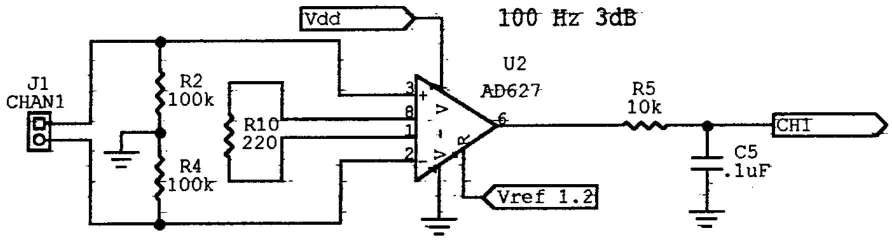
Appendix A: Schematics

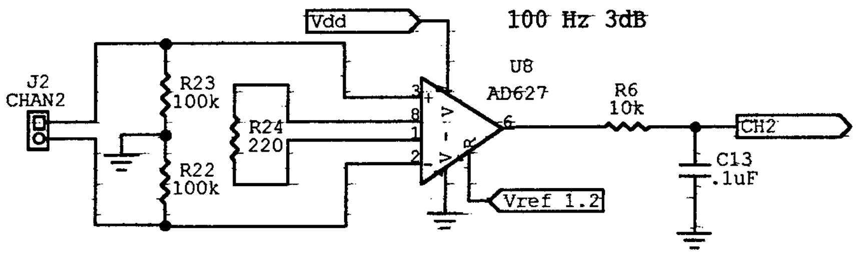


Pinnacle Technology, Inc.	
EEG/EMG Mousehat Bottom Board (Power & uC)	
Rev 4	ID C
Date: 2/19/00	Page: 1 of 1



Mousehat Bottom Board Layout (x2)





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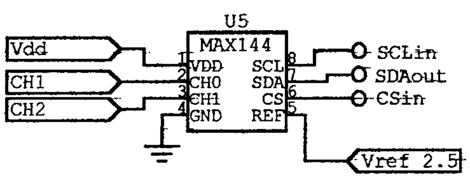
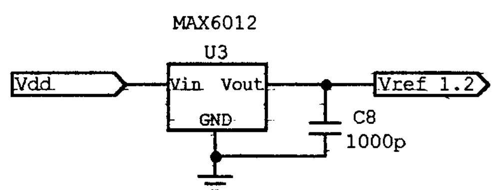
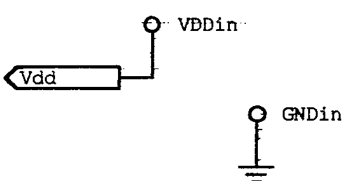
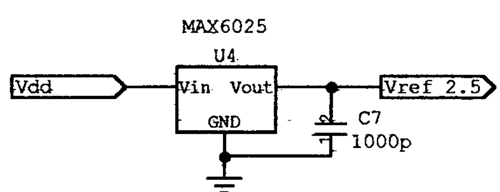
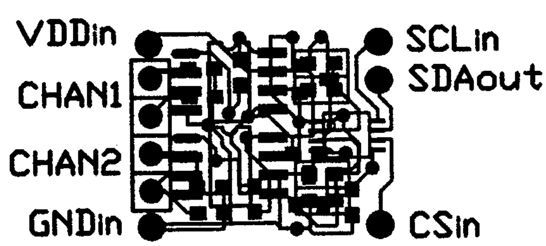




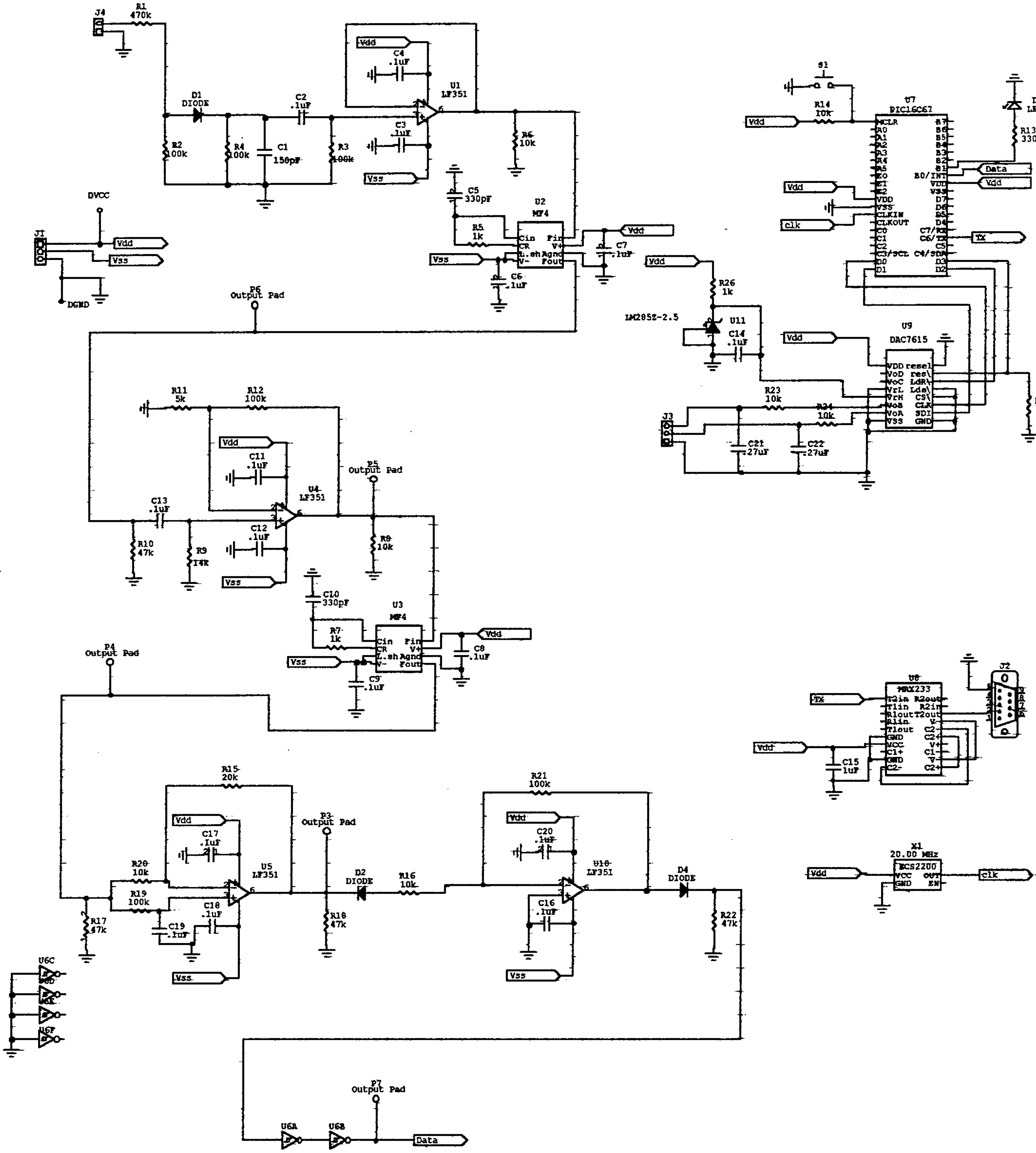




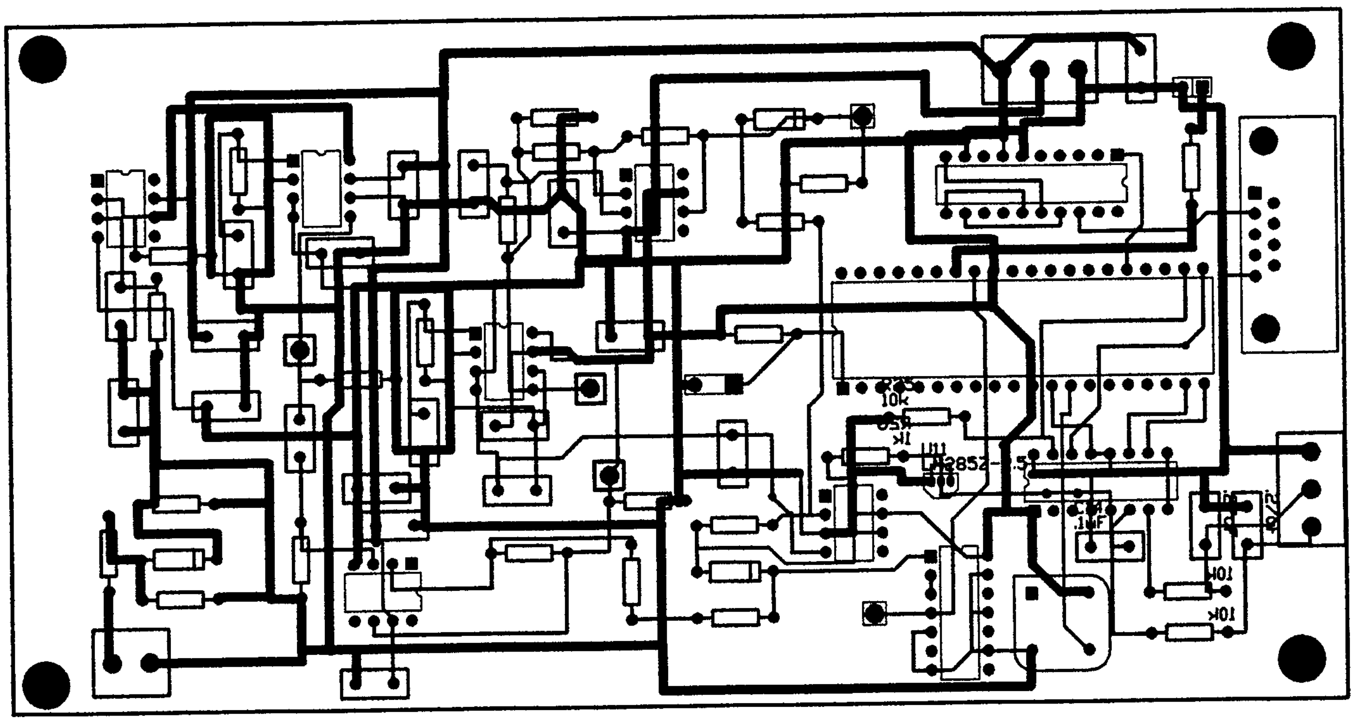
Pinnacle Technology, Inc.	
EEG/EMG Mousehat Top Board (Amplifiers & A/D)	
Rev	ID
Date:	Page: 1 of 1



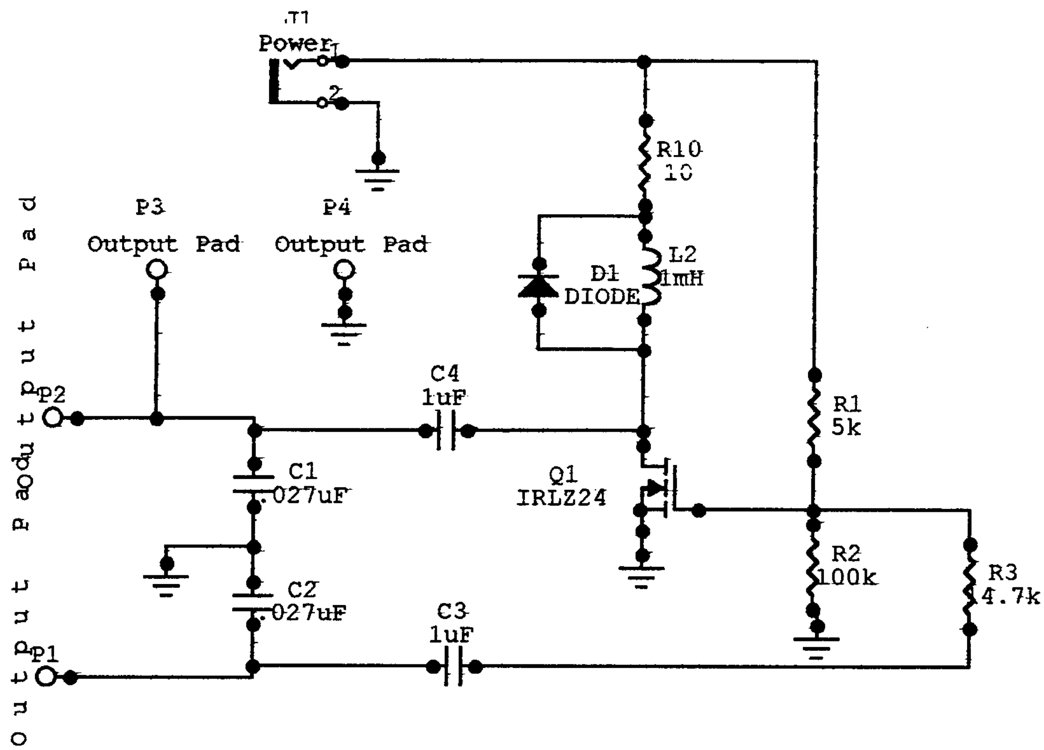
Mousehat Top Board Layout (scale = x2)



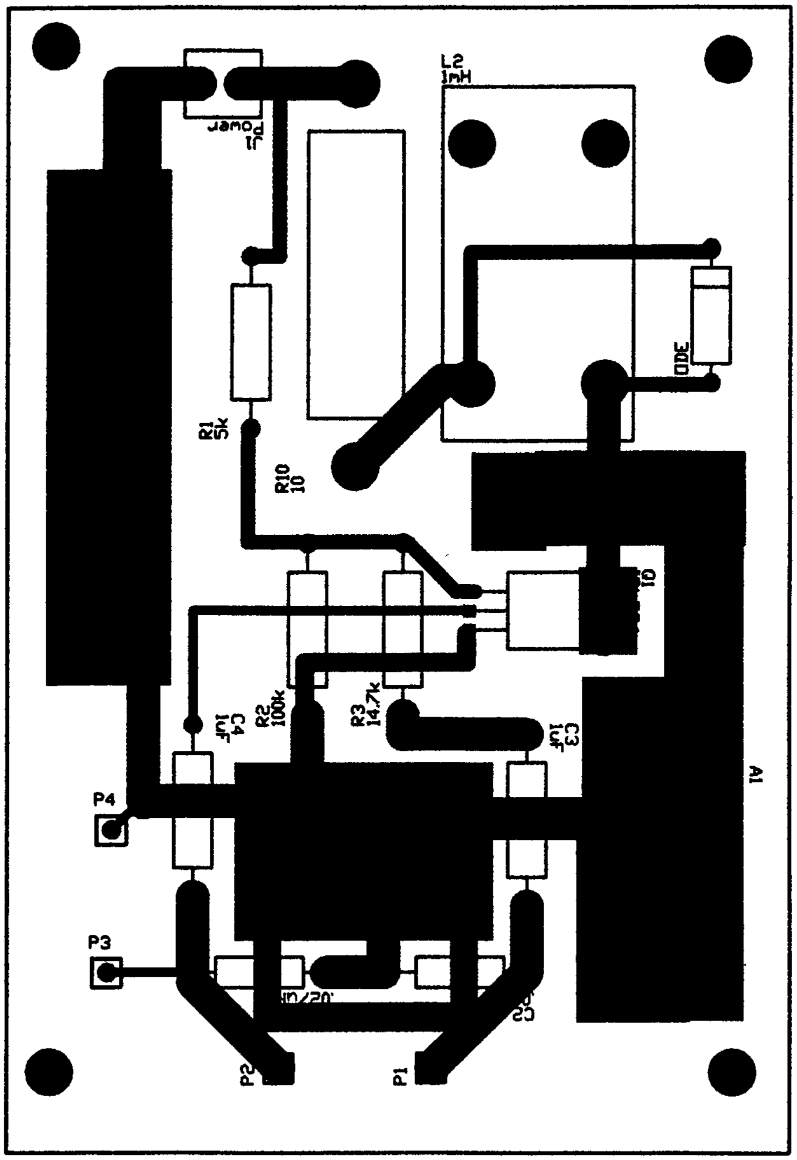
Pinnacle Technology, Inc.	
Backscattered Receiver (125 kHz) EEG/EMG	
Rev 5	ID B
Date: 2/21/00	Page: 1 of 1



Basestation Receiver Board Layout



Pinnacle Technology, Inc.	
EEG/EMG 125 kHz Oscillator	
Rev 3	ID A
Date: 1/14/00	Page: 1 of 1



125 kHz Oscillator Board Layout