Bioelectronic Telemetry System for Fire Fighter Safety

Final Report

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List of Terms and Abbreviations

Physiological Monitoring Board (PMB)- A title given to the system developed by Extreme Endeavors that fits inside of the fire fighters turnout coat that monitors the heart rate and environmental data surrounding a fire fighter.

Software Defined Radio (SDR)- A title given to the system developed by Extreme Endeavors that fits inside of the fire fighters turnout coat that communicates through a digitally controlled transmission.

Inter Beat Interval (IBI)- The time between each individual heart beat. It is noted that this is different from the pulse rate since the pulse rate is an average of heart rate over time, IBI is the time between each individual heart beat.

Army Research Laboratory (ARL)- A US Army research facility that Extreme Endeavors worked with throughout this contract and performed technology transfer of sensors from. http://www.arl.army.mil/www/default.htm

Fort Monmouth U.S. Army RDECOM CERDEC STCD- A US Army research and Development organization that Extreme Endeavors has worked with for inclusion of our developments into a system of wearable fire fighter technology. http://www.monmouth.army.mil

TI6713 Digital Signal Processor - The TMS320C6713 DSPs compose the floating-point DSP generation in the TMS320C6000™ DSP platform, a processor developed by Texas Instruments for advanced floating point computation.

Extended Least Squares Harmonic Analysis (ELSH)- A digital signal processing methodology for breaking apart a signals components into harmonics and analyzing it to extract rate information.

QPSK modulation- Quadriture Phase Shift Keying Modulation is a form of modulation of digital signals that is resilient against phase noise and interference from reflection.

Wearable Antenna- an unobtrusive antenna that is embedded within a jacket or coat that transmits RF energy. The end user may not even know the wearable antenna is present.

Fire Ground Display- Display developed by Extreme Endeavors for the Safety Officer to view the status of their personnel operating on the fire ground.

Abstract

Every year a large number of firefighters are killed while on duty and the main purpose of this SBIR was to assist in the reduction of deaths for fire fighters and to address the occupational safety and health issues among firefighters. This SBIR research was targeted toward the development of a device to monitor the physiology and environment of a fire fighter. This technology is targeting prevention of deaths caused by overexertion and entrapment, which make up 60 to 70% of all firefighter deaths on an annual basis. The design of this personal monitoring system was done to allow firefighters to perform their duties in an efficient and productive manner as possible, the technology could not interfere with the fire fighters normal job duties.

Our approach was to design a state-of-the-art platform embedded in the fire fighter's turnout gear that utilized technology transferred from Army Research Laboratory (ARL) in Aberdeen Maryland. Modifications were performed on gel coupled acoustical sensors to mount inside of the wrist cuff of a fire coat and which gave this sensor significant stabilization. The processing used one of the most powerful Texas Instruments Digital Signal Processors to provide computing power for running complex algorithms on board the fire fighter that extracted heart rate information from the wrist of the fire fighter. This innovative use of wearable computing power was featured in the Texas Instruments 2006 User Conference as a Key note demo. Figure 1 is Extreme Endeavors on stage with Mr. Rich Templeton, CEO of Texas Instruments, demonstrating the fire coat to an audience of thousands.

Figure 1: Extreme Endeavors on stage with Rich Templeton, CEO of Texas Instruments Demonstrating the Wearable Computing

The data, processing and the resulting information detailing the well being of the fire fighter is useless, unless there is a means to use that data and intervene if needed. A software defined radio was developed with this project to allow for more reliable transmission of data out of the burning building and insure data transmission. The research from Phase I of this project showed considerable multi-path issues created from a fire burning inside of a structure. The development scheme is to design a multiple frequency radio that can automatically switch frequencies. However, the scope of this project was limited which lead to the development of only one frequency of operation, with the plan to include other frequencies as the project enters into phase III.

Some of the issues as to why Extreme Endeavors is developing a software defined radio for this application are just now being addressed by The International Association of Fire Chiefs (IAFC). The IAFC has received reports of firefighters experiencing unintelligible audio communications while using a digital two-way portable radio when operating in close proximity to equipment and fires.

Through all the technological advancement and processing power embedded in the coat, what attracts most of the fire industry to our technology is the methodology behind the sensing and there is no different to how the fire fighter dawns their gear with this system. They will never know this technology exists. Other systems on the market today are impractical for the fire industry because they involve adhesives or invasive sensor technology.

Substantial partnerships were developed during this project. Lion Apparel provided us with turnout gear and assisted by educating us in how turnout gear is mass produced and gave us feedback on industry standards. Extreme Endeavors also obtained the interests of NASA Langley Research Center and Entered into a Space Act Agreement and is currently looking into additional acoustical monitoring capabilities that can be added to the system at a later date.

Highlights/Significant Findings

For description purposes the system is divided into three different realms, the sensor system, the Physiological Monitoring Board (PMB), and the Software Defined Radio (SDR).

Sensor

Extreme Endeavors performed technology transfer from Army Research Laboratories to obtain acoustical sensors that are gel coupled to the human skin. This allows us to "listen" for the sounds the blood makes while surging through the body. Extreme Endeavors modified the sensors to fit inside the cuff of the fire coat to enhance the alignment and make better contact with the skin.

PMB

Utilizing a TI6713 Digital Signal Processor, a PIC18F4550 controller and multiple high resolution (greeter than 20 bit analog to digital converters) a prototype of the Physiological Monitoring Board (PMB) was constructed and programmed. This board sampled the pulse rate information, from the gel coupled sensors and provided processing to filter out noise, weight the data in accordance with RMS noise and perform an innovative harmonic analysis of the data. This methodology provided for extraction of pulse rate information when the pulse sounds are 100 times less than the noise applied to it. In addition, development of code and testing of the PIC18F4550 microcontroller allowed this board to sample temperatures from four different locations, communicate with the DSP, communicate with an outside peripheral (either the SDR or directly to a PC).

SDR

The SDR Board was developed utilizing the TI6713 Digital Signal Processor, interconnected with direct digital synthesizer technology and very precise and fast sampling analog to digital converter. A simulation was performed in MATLAB to prototype the algorithms for processing the received signal. These algorithms were then programmed into the digital signal processor and tested. The testing revealed that the analog to digital converter had failed due to the abuse presented in our testing to insure survivability inside of a burning structure. This failure was discussed with Texas Instruments and a new component was selected for this application, one that is more robust and utilizes less power.

Embedding

Extreme Endeavors worked with Lion Apparel in developing a design to embed the electronics in the garment. It was found that the PMB board placed in the right chest region of the fire coat and the software defined radio, placed in the right chest region of the fire coat was most efficient of not hindering the fire fighters movements. Perhaps the most innovative portion of our developments though is the inclusion of a metalized NOMEX fabric around the bottom of the coat to serve as an antenna. Not only is it a flexible antenna platform, but it also is NFPA rated!

Translation of Findings

Fire fighters work in one of the most stressful and demanding environments known. On a daily bases a fire fighter can be subject to intense physical exertion, high temperatures and stress. The culture within the fire industry is undergoing a revolution. In the past, fire fighters would pass their time at the fire house by cooking elaborate meals, watching TV or other small activities that burned off the nervous energy of waiting for a horrific event about to unfold when the alarm goes off. Now every fire department has a gym, training programs are continuously ongoing and fire fighters are becoming more cognitive of their health. The physiological monitoring system by Extreme Endeavors is designed to enhance this revolution in culture.

Through use of the sensor systems fire fighters will learn what effects their work has on them. They can track their physiological response to different conditions and as we analyze data sets, we will be able to quantify different conditions, such as a means to tell the fire fighter they must stop and rest or face a heart attack. In addition to monitoring the physiology of one person, teams of people may be analyzed. This analysis shows shift A has been exerting themselves for hours, while shift B has been on scene assisting with light duty tasks such as traffic control. This provides the incident command with knowledge of who to place in the next physically demanding task.

The other main benefit to this technology is we now have a platform and the effort to embed this technology in an efficient manner, we can include additional sensors and provide the fire fighter with specialized technology. During this Phase II SBIR a partnership with the Fort Monmouth U.S. Army RDECOM CERDEC STCD was initiated to collaborate and display the operational capabilities of our first responder technology demonstration to Congress and the Senate in August. Through this collaboration we plan to integrate this system with tracking, IR viewing, and a heads up display.

Outcomes/Relevance/Impact

When firefighters don their turnout gear the electronics automatically turn on, requiring no input from the users to initiate measurements or communications. Each coat communicates with a base station, either located on the truck or in a small briefcase. Charting of the firefighter's pulse begins almost immediately, as the firefighter climbs onto the vehicle to respond to the scene. The jacket has embedded in it all of the hardware for monitoring physiology and the environment around the firefighter.

The sensors embedded in the cuffs of the coat detect the radial pulse from the heart beat, while temperature sensors both inside the coat and outside begin take baseline thermal recordings, showing the temperature gradient through the coat. Utilizing the latest in Texas Instrument Digital Signal Processing technology the data from the sensors is processed to conserve valuable transmission time and bandwidth, creating a useable and effective monitoring tool.

The transmission of data is performed through a software-defined radio that transmits and receives via a wearable antenna embedded in the sleeves of the turnout coat. This antenna is a conformal metallized fabric that eliminates the problems of an external whip antenna that can be hooked by obstacles. This embedded radio also allows for relaying of data via a custom-designed ad-hoc network. If a firefighter becomes lost or injured, the data relay can direct firefighters to the location by indicating which firefighter is the closest.

The Safety officer can quickly look at a view screen, evaluate multiple firefighters, organize reinforcements, and assess the overall safety of the team. Statistics show that overexertion is one of the most common causes of death for a firefighter. The Electronic Life Line is a system that is intended to reduce this factor all while allowing more efficient and effective operations on the fire ground.

The greatest design challenge of this coat, the user, the firefighter will never even know the monitoring systems are there and in operation. The coat will resemble a normal, everyday turnout coat, dawning the gear will be the same as always done!

The decision to place all of the system components on the upper torso, excluding the head, was to satisfy the design goal of "self-containment." We wanted to avoid interconnections between different parts of the PPE, such as the helmet, bunker pants, boots, gloves, hood, etc. Although conceptually possible, using a wireless network to connect the electronics to the sensors and communication device was less desirable than maintaining everything in one location, i.e., within the turnout coat.

Scientific Report

Background for the Project

Every year a large number of firefighters are killed while on duty. The on-duty death rate for fire fighters has seen no significant decline over the past twenty years, leaving it as one of the most hazardous jobs. Extreme Endeavors goal for the physiological monitoring system is to eliminate as many firefighter deaths as possible, while allowing firefighters to perform their duties in an efficient and productive manner.

Extreme Endeavors has researched the cause of these deaths and found that the leading cause of death among firefighters is due to over exertion. The physiological monitoring system is targeting prevention of deaths caused by overexertion and entrapment, which make up 60 to 70% of all firefighter deaths on an annual basis.

To accomplish this goal and reduce the death rate, departments must effectively monitor the vital signs of a physically active individual. This process must be done on a daily basis, which requires different application procedures than observed in a normal hospital setting. The methodology behind the sensing system must not include shaving, adhesives, or intrusive sensors of any kind.

In a survey conducted by the Office of Law Enforcement Technology Commercialization in connection with Extreme Endeavors and Consulting, twenty fire departments polled from around the country were asked what the most important medical parameters to measure in firefighters while working in extreme environments. Additionally, the poll asked these departments to determine the order of importance for these self-defined parameters. The fire departments ranked the listed items in order of importance and these items were weighted and averaged to determine the most desired features for any physiological monitoring device. Figure 2 exhibits the results of this survey.

The survey also asked the fire departments to prioritize the environmental factors they wished to see monitored concerning firefighters at work. E^2C used the same weighting and averaging for this data. Figure 3 notes these particular results. This data demonstrates the most critical piece of data regarded by these firefighters is ambient temperature.

Figure 3: Fire Department Survey- Medical

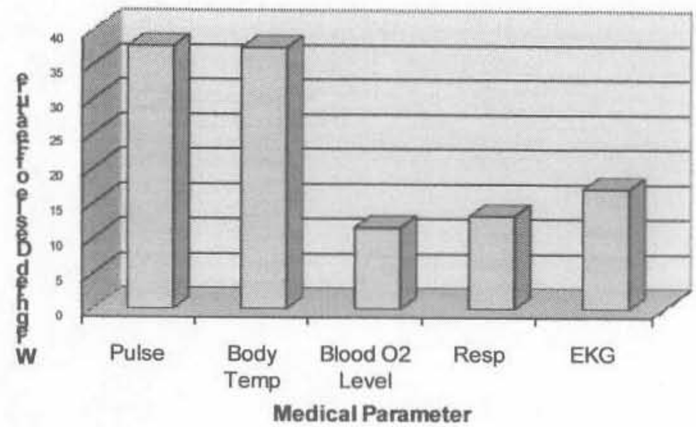
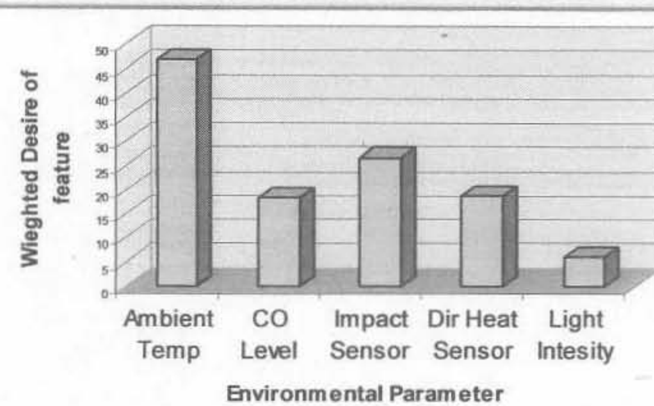


Figure 2: Fire Department Survey- Environmental



The physiological monitoring system aims to provide firefighters with a rugged useable devise that allows a base commander to monitor the actions involving individual and group of firefighters. This system is important because it will allow command officers to recognize life-threatening conditions, including entrapments and falls, and thus provide valuable data to help commanders make important decisions. This system was developed to lower the risks encountered by emergency service workers and aid in research applications, providing further knowledge of the stressors perpetrated on emergency service workers while in the field.

The primary objective for this development is to aid firefighters while working in intense conditions where physiological and environmental monitoring is imperative for reducing stress and environmental related accidents. Since the members of Extreme Endeavors are fire fighters, we understand the operations on scene; we can provide equipment to the fire industry that is functional and robust enough to meet the demand. The physiological monitoring system is directed for use by the safety officer, who is the individual on scene whose sole responsibility is to ensure the safety of the crew during fire ground operations.

Specific Aims

Phase I funding for this project supported the successful development of a proof of concept system for measuring the vital signs of a firefighter and the environmental parameters of their surroundings and transmitting the data in real-time to a receiving station. The ultimate goal of the Phase II project was to refine every aspect of this system and create a prototype product for the fire industry that can increase firefighter's safety and allow them to perform their job duties more efficiently.

Our approach in Phase I was to use ECG electrodes, thermistors, platinum resistance thermometers, and acoustic sensors combined with processing electronics developed in-house to measure pulse rate, ECG waveforms, ambient temperature, body temperature, and movement. This data was collected using a microcontroller and then transmitted out of a structure using IEEE wireless standard and commercially available components. The ability to relay the transmission was incorporated into the system design which allowed us to receive data outside a reinforced concrete structure with 1-foot thick walls and the base station located approximately 100 feet from the structure.

Under Phase II our goal was to develop a sensor suite capable of measuring vital signs and environmental parameters that is coupled to a more powerful processing unit and transmit this data in a more robust and failsafe fashion. In addition, we will incorporate all of these elements into a turnout coat (with the assistance of Lion Apparel) and provide a unified system that can be included in a firefighter's normal gear so that when the turnout gear is donned by the firefighter, the physiological monitoring system is already in place.

The Specific Aims for this project were:

1. Sensor Development: E^2C developed further refinements to the suite of sensors for measuring pulse, ECG, ambient temperature, body temperature, and motion in order to maximize the accuracy, reliability, and power efficiency of these sensors. We continued to work with Offray Specialty Narrow Fabrics to incorporate the sensors into the firefighter's turnout gear provided by Lion Apparel and we will continue discussions with MSA for potential integration into their gear.

2. Processing Developments: E^2C migrated to a more powerful microcontroller and incorporated advanced digital signal processing (DSP) capabilities as well as non-volatile memory directly into our system. This allowed us to perform data reduction and analysis before transmitting data, thereby reducing the bandwidth requirements and allowing us more flexibility to use powerful error-correcting codes (ECC).

3. Transmitter/Receiver: E^2C utilized the Phase I RF propagation test results to forward the design of a dual-band telemetry system, with each of the two bands optimized for transmission from different types of structures and environments firefighters encounter. We selected the two frequencies to be used, developed a compatible antenna system, selected commercially available components and designed the accompanying RF microstrip circuitry, created a simple ad-hoc routing system, and designed the interface between the processing electronics and the transmitter/receiver. We

constructed a prototype employing this telemetry system and rigorously tested the performance in idealized scenarios as well as in fire ground operations.

4. Fire Ground Display: E^2C worked in conjunction with the Clarksburg Fire Department to develop a human-to-machine interface sufficient for operations in a hostile environment such as a fire scene. We then developed a rugged prototype system that displayed the vital signs and environmental parameters transmitted from several firefighters.

5. Testing: The system was tested and analyzed to insure reliability and performance. The testing was divided into three phases. The first phase of testing was in-house testing by E^2C engineers under laboratory conditions. For the second phase of testing, E^2C engineers tested the prototype system in a burning structure. Finally, in the third phase of testing, the Electronic Life Line prototype system underwent external testing by the Clarksburg Fire Department and the West Virginia University Fire Extension. At the end of each testing scenario, a document detailing the results and lessons learned were developed.

Procedures

Extreme Endeavors tracked this project through our project management system, which is initiated by the CFO assigning a project number. This project was assigned a number of 1008. This number describes an account in QuickBooks and a schedule in Suretrack software, from Primavera. The project schedule and finances were updated as needed and reported on a weekly basis. The technical staff at Extreme Endeavors reported tasking completion based on the work breakdown structure that is assigned at the beginning of the project. This project utilized the project management methodologies as defined by the Project Management Institute (see www.pmi.org).

The only other procedures involved the design tools used to develop the system. Developments of the software for the embedded systems were done in C Code while development of monitoring system was in Labview. The project documentation was done in AutoCAD and Altium schematic capture software, which was also utilized to develop the printed circuit boards for this project.

Methodology

1 – Sensor Development:

Extreme Endeavors performed a technology transfer from the US Army Research Labs. The sensor element and gel pad remained the same, however the body of the sensor was curved to fit around the wrist and make better contact with the skin while being held in place by the cuff of the fire coat. The sensor used to monitor pulse also functioned as the motion monitor.

The ECG and respiration measurement system was redeveloped to be smaller and self contained in a single band around the chest. This device connects into the PMB board to allow for direct correlation of ECG signal and respirations with the data from the acoustical sensors for validation of results from a known source.

Previously, Extreme Endeavors utilized a 10 Bit A to D Convertor for the measurement of temperature. To further refine this sensor, we included a 22 bit A to D convertor for added precision.

The sensing network was also altered to provide a range from -40 to 500 Degrees F, with a precision of .1 Deg F.

Extreme Endeavors began discussions with Offray Specialty Narrow Fabrics (OSNF) but was referred to Foster Miller when discussions of the geometry of the antenna arose. It was determined that utilizing OSNF became impractical with the inclusion of Foster Miller, not only was it financially prohibitive but the scope of the project was not a large enough magnitude for Foster Miller. To resolve this, Extreme Endeavors began the development of our own antenna and decided that embedding the wires within the garment would be better accomplished with the help of Lion Apparel during Phase III of the project.

2 – Processing Developments:

Extreme Endeavors selected the Digital Signal Processing (DSP) capabilities of Texas Instruments to use in this system. The TIC6713 floating point processor was chosen since we were uncertain of the processing power needed in the final plan. With most DSP designs it is encouraged to start with the most powerful processor and then step down in size at a later date to minimize power consumption. This tactic came highly recommended from Texas Instruments as the fastest design path.

The basic structure allows four 24 bit analog to digital converters to samples to be pulled into the DSP through the Enhanced Dynamic Memory Access port. A Microchip, 18F4550 microcontroller is used to control basic housekeeping functions around the board, including but not limited to, control boot up conditions for the DSP, act as an interface between the DSP and I/O from the board and sample the temperature channels through four MCP3553 22 bit analog to digital converters.

PMB Board Software

Initial conversations with Army Research Laboratories referred us to Dr. Les Atlas from the University of Washington who had developed an Extended Least Squares Harmonic (ELSH) algorithm for analysis and reduction of data from the acoustical sensors. Upon entering discussions with University of Washington concerning the intellectual property of this algorithm, we determined that it was not a feasible business decision to enter into a partnership with them. This was due to the algorithm had been prototyped in MATLAB and we would have to convert that to a C compiler for an embedded system, which is very labor intensive. Several papers had been published by Dr. Atlas on these algorithms that were public knowledge and hence we could not see paying University of Washington for an algorithm that was already published. In addition Dr. Atlas's MATLAB code that tested this algorithm could not run in real time. There was considerable concern that if the code could not run in real time on a 3 GHz Pentium, we would have a difficult time getting it to run on a 300MHz embedded system.

We developed our own algorithm (based off Dr. Les Atlases' work) that found the heart rate through a harmonic analysis. Performing an Extended Least Squares Harmonic Analysis was too time intensive and similarities were found ELSH data as with a method using several Autocorrelations and a peak detection algorithm. Since the autocorrelation/peak detection method ran much quicker (about five times) than the ELSH method, and provided similar results we went with this method.

3 – Transmitter/Receiver:

Extreme Endeavors researched the most appropriate means of developing a Software Defined Radio and found a DSP and arm micro processor in one package. The TI TMS320VC5510 OMAP was initially selected, but once the development system was tested, we realized that this was inappropriate due to the complexity level required to program this system. It required a standard windows system for programming the DSP and a Linux based system for programming the ARM processor.

In order to stay on schedule and utilize available assets at Extreme Endeavors facility, we began implementing the Software Defined Radio using the TMS320C6713B-225 floating point processor by Texas Instruments. This is the same processor used in the PMB board; our goal was to utilize similarities in the board to reduce the programming needed.

For the basic structure of the Software defined radio, several technologies were analyzed. Such standard transceiver packages limited us in frequencies that are standard to fire ground operations; hence we looked for methods of generating our own signal and detection of that signal. It was found that a Direct Digital Synthesizer IC was ideal for this application, much quicker response time over a phase lock loop and had tremendous flexibility in frequency and modulation techniques.

To receive the signal, we will utilize a low power A to D to sample the signal. There is a trade off in the selection of the A to D Convertor. The trade off speed/power consumption and dynamic range was analyzed and the Texas Instruments ADS8382 was selected for this project.

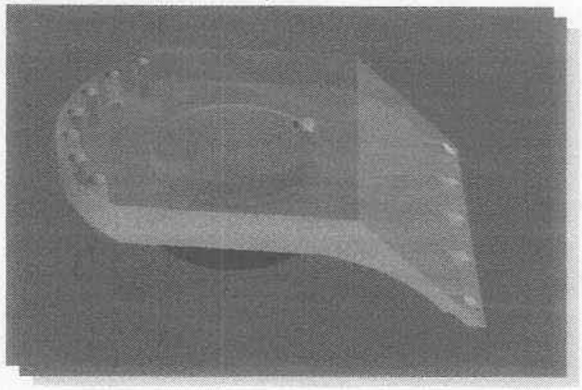


Figure 4: 3-Dimensional Drawing of Sensor Element without gel pad or ceramic material

4 – Fire Ground Display:

For the fire ground display, several software packages were considered for what to use in this development. Since the amount of data was limited, and the display was rather critical, we decided to use a LABVIEW development environment as the software package to meet these needs.

Extreme Endeavors worked with the the Clarksburg Fire Department to develop a human-to-machine interface sufficient for operations in a hostile environment such as a fire scene. A prototype system was developed to display the vital signs and environmental parameters transmitted from a firefighters.

5 – Testing:

The testing is divided into three phases. The first phase of testing was in-house testing by E^2C engineers under laboratory conditions. The second phase of testing, E^2C engineers tested the prototype system in a burning structure. In the third phase of testing, the prototype system underwent external testing by the Clarksburg Fire Department and the West Virginia University Fire Extension.

Results and Discussion

1 – Sensor Development:

Extreme Endeavors transferred the sensor technology from Army Research Laboratory, reconfigured the physical attributes of the sensor to wrap around the wrist and be held more securely by the cuff of the fire fighters coat and connected it with a 24 bit analog to digital converter to all for better data. Figure 4 shows a three dimensional rendering of the sensor that is placed up against the fire fighters wrist. A sample of the data retrieved from one of these sensors is shown in Figure 5.

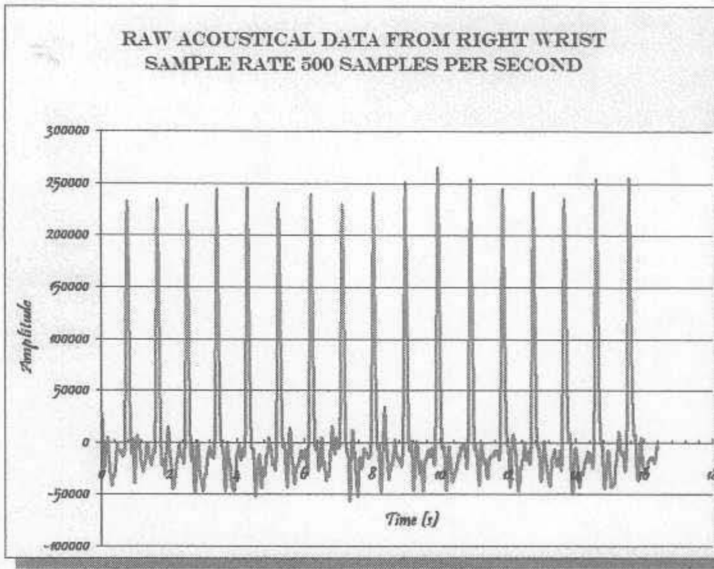


Figure 5: Raw data taken under laboratory conditions

Further research was performed on the sensor system to evaluate performance referenced to an original sensor from ARL and in analysis of motion/noise artifacts from the sensor. One of the benefits to these sensors is their sensitivity in picking up noises inside of the body. One of the drawbacks to these sensors is the noise they pick up from inside the body. Figure 6 shows a typical example of a motion artifact picked up by the sensor. For this reason, significant data processing must be done to give us a qualified result so that we can say the fire fighters heart rate is 183.

2 – Processing Developments:

Development of the physical part of the PMB Board was done in two stages, during the first stage we experimented with the design, construction and mounting of the components. This initial test revealed several requirements that had to be addressed. This initial prototype was used to perform high level trouble shooting of the board, thus enlightening us to several minor alterations needed to operate a sensitive system in such a severe environment. During additional testing of the PMB board we found the inductors used in the power supplies for the core voltage were to be fragile for body worn applications.

Another key issue that required correction was the four MCP3553 22 bit analog to digital converters used to measure the temperature (from -40 to +500 Deg F) were being sent into a undefined logical state upon power up. This condition did not present itself until four Analog to Digital converters were tied together on a single board. This problem was corrected by reconfiguring the SPI communication lines. The next problem arose with these analog to digital converters through shutting down within the conversion cycle. This problem was solved by inclusion of an analog switch on the bias power and performing a system reset for the analog to digital converters on power up. The last problematic issue found with the analog to digital converters was when the communications request came from the Digital Signal Processor the PIC microcontroller must service this request as soon as possible, hence if in the middle of reading the MCP3553's it would have to abort which put the MCP3553's into an unknown state. A software modification that checks this condition and resets the MCP3553's during the abort was developed so this state is never entered into.

After troubleshooting the circuitry and performing substantial programming a revised PMB board was constructed that is pictured in Figure 7.

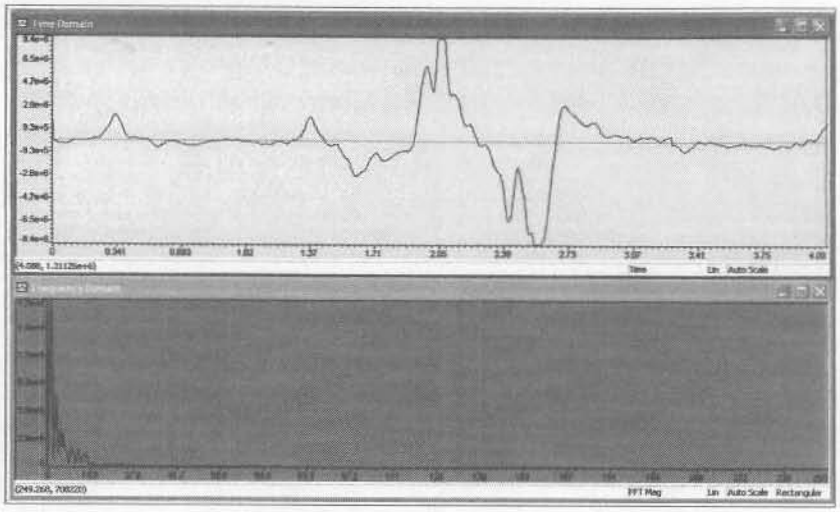


Figure 6: Motion Artifacts measured by the sensor

PMB Software

Programming of the Digital Signal Processor was performed to extract the heart rate from the sensors on the wrist. The goal is to analyze which wrist sensor has the least amount of noise and the hi look at clean sections of data and then process it looking to extract the heart rate information.

Two main techniques were implemented and then several variants of those methods were created. The first one is a least squares harmonic analysis, which was optimized to run in approximately 100 milliseconds. The timing is critical for this application since we have found that the pulse rate can change over a ten second window, hence the ability to expand to an extended least squares harmonic analyses will be needed. The second method implemented was to perform an auto correlation on the data and search within a specific range for the maximum.

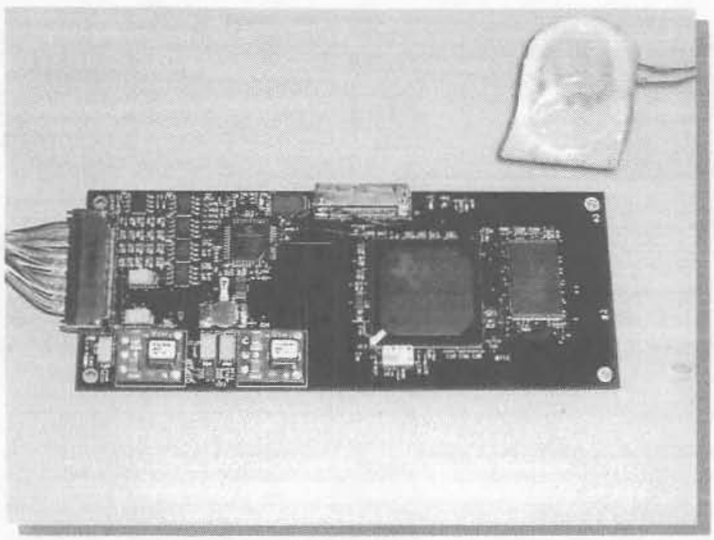


Figure 7: Physiological Monitoring Board and gel coupled wrist sensor

Both of these methods were found to work, sometimes the least square harmonic analysis would work better than the autocorrelation, other times it would be the other way around. Extreme Endeavors then began searching for a method of calculation to combine both results and include the calculations of a confidence level in the data. The goal of this would be to allow for several different calculations and selecting the one with the highest confidence level, then providing the confidence level with the heart rate signal.

Further testing was done and it was found that the FFT of the autocorrelation revealed the harmonic content used to calculate the extended least squares harmonic analysis. This discovery permitted the combination of both the harmonic analysis and autocorrelation methods thus producing a quick and robust algorithm that does not need a high power processor to realize the solution. The theory behind this algorithm is to use the Autocorrelation and search for a peak within a specific range and then to take the FFT of the Autocorrelation and do a peak search for the harmonics created from the sounds created from the heart rate. If the heart rate calculated from the autocorrelation does not have harmonics in the second calculation, that value is eliminated as a solution and the calculation is performed once again. The Extended Least Square Harmonic calculation took over 10 seconds to perform, through using the Autocorrelations and FFT; we were able to reduce the calculation time to less than a second.

In Addition, our research has uncovered a correlation between the FFT of the data and the interbeat interval (IBI). If an FFT of the data is taken, the average heart rate can be seen in a single pulse and can be picked out from others since it has harmonics (this is the reason the least squares harmonic analysis works). If we look around that peak we will see two other peaks, one representing the shortest IBI and one representing the fastest IBI. Neither of these peaks have harmonics associated with them. There has only been a limited amount of testing with this at this time, and further work is needed to confirm the reliability.

3 – Transmitter/Receiver:

Simulation

A simulation was performed using MATLAB™ software. The simulation transmitted a random number by selecting a waveform based on a dibit of data. This was performed four times to make a byte of information. The receiving section of the software consisted of a component for down sampling to simulate the analog to digital converter and then utilizing different algorithms for calculating the area under the waveforms. From the area under the waveform, at select times, we were able to determine the phase of the signal.

Noise was then inserted into the transmitted signal, where it was increased in magnitude until at least 50% of the transmitted bytes were not recognizable by the receiver. Optimization was then performed to find the best algorithm for this process.

Hardware

A prototype Software Defined Radio was constructed that performed frequency shift keying; one of the benefits to using the direct digital synthesizer by Analog Devices is the ability to switch from FSK Modulation to QPSK modulation through software. A block diagram of the hardware assembled is shown in Figure 8

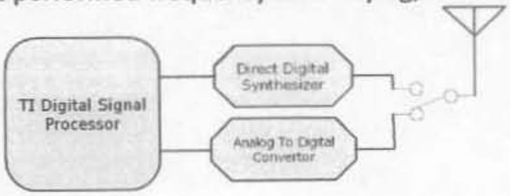


Figure 8: Block Diagram of Software Defined Radio

Code was written for the Digital Signal Processor to perform the data transmission and detection. In an automated testing scenario, it was found that approximately one out of every 50 Bytes was missed in the transmission of data. Processing utilized a frame based approach, where data is collected for approximately 4 ms. After collection, the data is processed while the next frame of data is being collected. The problem of the missing byte was theorized to be when the byte started at a specific point on the edge of a frame. Troubleshooting in the digital signal processors environment quickly became difficult and we changed to utilizing MATLAB simulation to troubleshoot further.

Elimination of the error, at the cost of increased bandwidth, was accomplished through the use of error checking and remembering the state between frames. While this solution worked in the short term, more research is needed in finding the optimal solution.

While the TMS320C6713B-225 is a proven, reliable processor, it consumes a substantial amount of power for battery applications. The next stage in the design of the software defined radio will be to change to a lower power processor such as the TMS320VC5509A.

Antenna

Tests have shown that the operation of the antenna, in particular the impedance and the radiation pattern (or antenna "coverage"), is altered by the proximity of a person's body. The impedance of an antenna is similar to the resistance of an electronic component. How much power is radiated or received by the antenna depends on the impedance, similar to how much current flowing through an electric circuit depends on the resistance. For an antenna, the impedance varies with the frequency.

The antenna is "matched" or "resonant" at a certain frequency. The reflection coefficient or return loss is a measure of how well matched the antenna is. The reflection coefficient is a ratio between the reflected power and the transmitted power. The return loss is the same quantity expressed in decibels. Our goal, which was achieved by this antenna design, was to meet a maximum return loss of –10 dB over the operating range. This amount of return loss equates to a VSWR of approximately 2:1, which results in a system power loss of about 0.5 dB.

Generally speaking, the resonant frequency was reduced when the antenna was brought near the body. Therefore, the design approach consisted of making an antenna that would resonate in free space at a higher frequency than the specified operating range. This fact works to our advantage since it means that the antenna on the body is a smaller size than an equivalent antenna in free space. Size reduction is an important consideration because we are trying to fit the antenna conveniently within the turnout coat.

The decision to place all of the system components on the upper torso, excluding the head, was to satisfy the design goal of "self-containment." We wanted to avoid interconnections between different parts of the PPE, such as the helmet, bunker pants, boots, gloves, hood, etc. Although conceptually possible, using a wireless network to connect the electronics to the sensors and communication device was less desirable than maintaining everything in one location, i.e., within the turnout coat.

Two types of antennas were investigated, a "bowtie" and a "folded dipole." In fact, both are variations of perhaps the simplest antenna of all, the common dipole. A basic dipole consists of two wires, each usually one-quarter wavelength, fed at the middle by a transmission line. The dipole is known for its "doughnut" shaped radiation pattern, which is essentially uniform in one plane. The coverage drops along the axis of the antenna (which is where the holes would be in the doughnut). As long as the antenna is worn in the up-and-down position, these nulls would point at the floor and the ceiling, and the main radiation would be to the sides, which is exactly what is desired for this application.

Prototypes of each antenna type were fabricated from thin sheets of copper or brass, and were initially taped, and subsequently attached with Velcro to the coat liner. The bowtie antenna was small enough to fit on either portion of the sleeve, upper or lower. At first the lower, or forearm position, seemed preferable since its interaction with the body might conceivably be less. However, the bending of the elbow and related wrinkling of the material farther down the arm in addition to the effects of wrist motion led to the selection of the upper arm. The final location of the dipole antenna was the side of the upper arm, just about where an arm patch would be sewn.

The folded dipole antenna tends to be larger than its bowtie counterpart. The larger size is an advantage in that this antenna has somewhat more gain; however, the size also dictated another choice of location. The chosen site for this antenna was the front of the coat slightly nearer the bottom hem to remove it from the area of the SCBA shoulder straps, and just in front of where the arm would naturally hang at your side.

Radiation patterns for both antenna types fall off about 20 dB on the opposite side of the body. However, again because of its location, the pattern from the folded dipole falls of much more rapidly. The coverage of the bowtie antenna located on the sleeve remains relatively constant over an angular region ± 90° from the centerline and falls to –10 dB to –20 dB on the opposite side. In contrast, the radiation level of the folded dipole is down –10 dB at ± 90° and goes from –20 dB to -∞ on the far side. (The 0° reference or "centerline" is the position of the standing person when the antenna is directly facing the base station receiver.)

Ultimately, the bowtie antenna geometry is simpler to fabricate and install than the folded dipole. Also, the sleeve location is preferable to the jacket front. Therefore, the bowtie antenna on the upper sleeve was the final design choice. A bowtie antenna with the same dimensions was made from a fabric material surfaced with a conductive coating. Test results indicated there was no change from the thin metal prototype.

4 – Fire Ground Display:

The development of the software for the PC to display the results was implemented and is shown in Figure 9. This Software reads the RS232 port from a PC and parses information based on a code system configured in the microprocessor. Under the setup window, the user has the ability to select temperature alarms for the yellow zone and the red zone. When these temperature extremes are violated the appropriate LED's will light up on both the individual display and the company display. The company display, shown in Figure 10 summarizes the overall health and monitoring of the

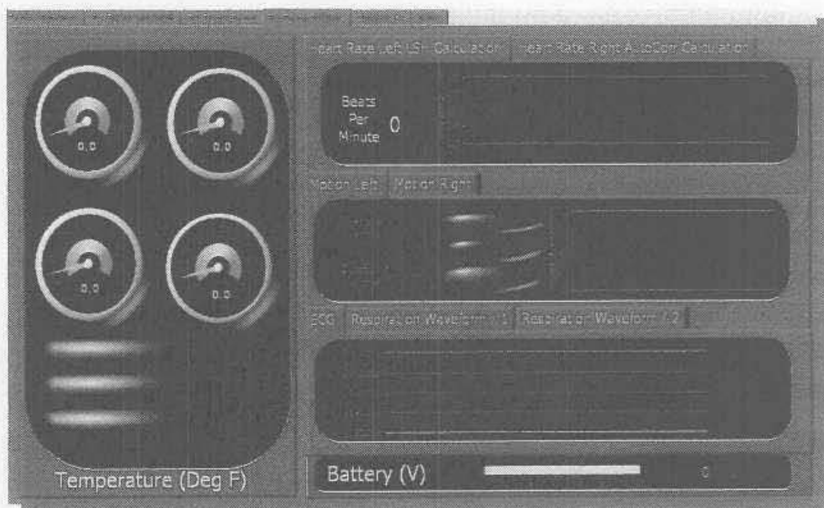


Figure 9: Fire Ground Display for an individual fire fighter intended for viewing the details about the fire fighter's health

company, allowing a safety officer to quickly scan an entire company during a hectic scene.

5 – Testing:

Extreme Endeavors approached the testing within three phases

1- In lab testing
2- Severe duty testing
3- Testing from fire departments

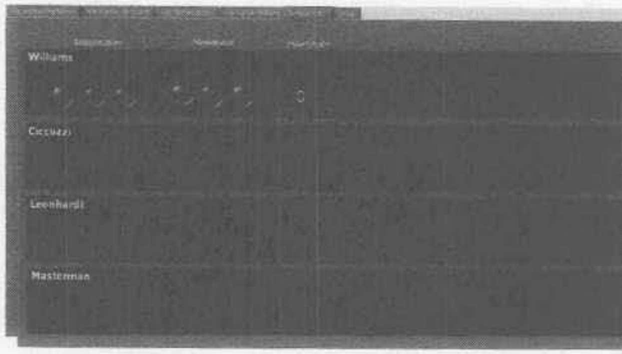


Figure Error! Bookmark not defined.: **Sample of the company display for fire ground operations**

It was our goal not to proceed to the next phase until all issues were addressed. This concept was adapted to insure that the fire fighters were not handed something that marginally works. In many industries you can develop a product, pass it along to industry, receive feedback and make improvements. The fire industry is tight knit group of individuals, if the product receives great reviews during testing then the commercialization process becomes much simpler. Hence, when the physiological monitor and software defined radio is handed to the various fire departments, we want it to work flawlessly and have the fighters respond with information about how our product can be used, and not that it broke half way through the burning building.

During this project Extreme Endeavors made it to Phase 2 of the testing. The high precision analog to digital converters were found to become damaged during severe duty testing. For the PMB board testing showed we had to place a protective resistor on the input to one of the digital I/O pins. The software defined radio we found that the suggested operating conditions of the analog to digital converters relied on time delays from various gates/buffers. The time delays changed drastically with the operating temperatures, thus creating failure in receiving the data. An additional Analog to Digital converter was selected but the project timeline did not allow for integration of this new element.

Conclusions

Extreme Endeavors has developed a physiological and environmental monitoring system for firefighters that is miniaturized and non-invasive such that the fire fighter will not know it is embedded in their coat. This system uses no adhesives or electrical connection to the skin. Designed to be embedded in a coat, a partnership with Lion Apparel was evolved to assist in commercializing this technology.

Through the use of acoustic sensors using a gel pad to listen to the sounds within the human platform we are able to calculate a significant amount of information, two such examples are heart rate and motion level. What has truly made this a robust system is the ingenuity and capabilities of the noise reduction system being used to process data with a signal to noise ratio of -20 dB.

This project has produced a prototype monitoring system that embeds a printed circuit board into the fire fighters coat to measure their heart rate, motion level and environmental parameters surrounding the fire fighter.

The software defined radio was proven to be valid; although additional developments are required, we have a fully integrated solution at this point.

Extreme Endeavors is currently exploring options for Phase III of this project. Current discussions were entered with the West Virginia National Guard about inclusion of this technology in their first responder organizations and industry partnership with Lion Apparel. We will continue to look for different opportunities to take this technology to market, including venture capital.

Publications

Proceedings

Advanced Personal Protective Equipment: Challenges in Protecting First Responders, October 16-18, 2005 Virginia Tech, *NIOSH-NPPTL*, Design of a Wearable Electronics Package for Firefighter Monitoring Michael F. Masterman, Todd D. Leonhardt, Alton G. Dunn, Extreme Endeavors and Consulting, Philippi, West Virginia 26416, USA

Materials available for other investigators

Extreme Endeavors is willing to form partnerships with other investigators to utilize our technology in physiological monitoring and health research topics. Please contact the PI for further information.