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Ultrasound Dispersive Technology for Non-invasive Diagnosis of Brain Injuries and a Non-interfering Ultra Wideband Wireless Communication System

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Introduction on DRDC's Ultrasound Dispersive Technology for Non-invasive Diagnosis of Brain Injuries

Increasing incidents of Improvised Explosive Device (IED) explosions in recent conflicts may have resulted in a fair number of undiagnosed trauma to the brain. DRDC has developed a non-imaging, ultrasound based technology to assess and monitor potential intracranial abnormalities and injuries. We believe that an early diagnosis of non-penetrating Traumatic Brain Injury (TBI) should facilitate a better management of undiagnosed trauma to the head in military operational scenarios in the field.

Research results[2,3] have shown that intracranial density monitoring can be achieved by probing the brain with ultrasonic pulses or with tomography imaging. The propagation speed of the pulses varies with the brain density, and density changes are assessed through the continuous monitoring of the time delay between transmitted and reflected pulses. However, all these techniques provide time delay estimation (or monitoring of density fluctuations) by probing the brain with ultrasound pulses at a specific frequency region. In doing so, they ignore the dependency of the density fluctuations on a wide range of frequencies, and so disregard information essential to accurately account for the dispersive properties of the human brain that may allow for classification of brain injuries and their non-invasive diagnosis.

DRDC's proprietary ultrasound technology[4] is unique with respect to other R&D investigations in the same field in that the innovation exploits the dispersive properties of the brain medium and offers a wide range of degrees of freedom to differentiate the system response for various diagnostic cases.

Reference:

1. Mayer SA, Dennis LL, "Management of Increased Intracranial Pressure", The Neurologist 4: 2-12, 1998.
2. Ragauskas, et al., "Method and Apparatus for Determining the Pressure Inside the Brain", US Patent, 5,951,477, September 14, 1999.
3. Ragauskas, et al., "Method and Apparatus for Non-Invasively Deriving and Indicating of Dynamic Characteristics of the Human and Animal Intracranial Media", US. Patent, 5,388,583, February 14, 1995.
4. Stergiopoulos S. and Wrobel M. "Non-Invasive Diagnostic Ultrasound System Monitoring Brain Abnormalities", US Patent Application: 10/898,208, December, 2001.
5. Andreas Freibert, Miroslaw Wrobel and Matthias Pawlak, Ethics Committee Protocol #621-2531.01-47/00 of the State of Bavaria of the Federal Republic of Germany, final report for DRDC Toronto, Contract W7711-007672/001/TOR, June, 2001.

Principle of Operation

For biological structures, such as the brain, that are heterogeneous the important parameters affecting the velocity of sound are the elastic constant, the bulk modulus (i.e., $B(f)$), which is frequency dependent and slightly temperature dependent. As a result, the propagation speed, c, of ultrasonic waves varies with brain density, and therefore monitoring of density variations, ρ, can be achieved by monitoring changes in the velocity of ultrasound for a sequence of ultrasonic pulses radiated in the brain through a small area of the skull near the human ear (the "temporal bone") that permits ultrasound penetration into the skull[1], as depicted in *Figure 1*.

For accurate diagnosis, however, monitoring of the density fluctuations and their correlation with various conditions of the brain requires estimates of density fluctuations for a wide range of frequencies, to account for dispersive properties, as expressed by $c(f)=(\gamma B(f)/\rho)^{1/2}$. This type of the brain's dispersive properties is in fact what differentiates the present innovation[4] from other non-invasive techniques that have been announced recently[2,3].

Figure 1

A system concept for monitoring intracranial density fluctuations that are based on a time delay estimation, which is the traveling time $\Delta\tau = D/c(f)$, of an ultrasound wave propagating in a confined medium, such as the cranium with fixed dimensions, D, requires very accurate time delay estimation of the order of micro-seconds in order to account for small variations of the intracranial density. Our innovation accounts for the change in D, (i.e., the dimension of the skull) by using a set of monochromatic frequencies to estimate the potential changes in D, (e.g., changes in the dimensions of the cranium due to thermal or other effects) while time estimation processing would account only for variation in c. The observed fluctuations in traveling time τ between the transmitted and reflected acoustic pulse are therefore directly related to fluctuations in the density of the brain because sound velocity c is directly related to density ρ.

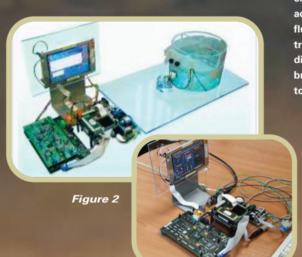


Figure 2

Thus, one of the basic steps of DRDC's dispersive ultrasound methodology is the monitoring of the brain density fluctuations by using a phase estimation approach between a transmitted and reflected monochromatic ultrasound wave. The details about the proposed phase estimation are included in[4] and the accuracy of this phase estimation approach has been demonstrated with the experimental system depicted in *Figure 2*.

Preliminary Test Results from Animal Experiments

Testing of the experimental prototype, shown in *Figure 2*, has been carried out with phantoms in order to confirm the claims of the innovation[4]. The current prototype it uses a number of transmit frequencies in the frequency regime of (0.5 – 4.0) MHz and a pair of transducers.

The experimental set-up used water inside a cylindrical Plexiglas container that was approximately 10 cm in width, as shown in *Figure 2*. The pair of transducers was placed on both sides of the container and the coupling between the container and transducers was maximized using standard ultrasonic probes. To demonstrate the system's sensitivity in $\Delta\varphi$ estimates that correspond to changes in density, the temperature of the water was slowly changed. In this case, hot water was gradually allowed to cool, increasing the density of the water. *Figure 3* shows estimates of $\Delta\varphi$ that correspond to the linear decrease in water temperature. For constant water temperature, estimates of $\Delta\varphi$ were nearly constant as a function of time, as expected.

The diagnostic information of the experimental system in *Figure 1*, has been tested also with animal experimentation and the results are presented in *Figures 4* and *5*. All experiments were approved by the University Animal Care and Use committee and adhered to International Association for the Study of Pain guidelines (Zimmermann, 1983) and are reported in[5].

DRDC's current efforts have been focused on the re-design of the experimental prototype, shown in *Figure 2*, and this is the most important phase of this development to define a complete intracranial ultrasound system that would be ready for clinical trials. This necessitates an extensive signal processing development, testing with phantoms and assessment of the system's capabilities through animal experimentation and clinical trials.

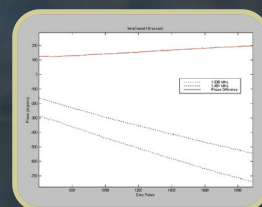


Figure 3

Animal Experimentation

System Response Correlated with Induced Stroke

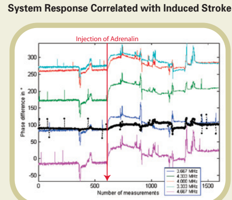


Figure 4. After an intra-arterial injection of adrenalin, the volume of blood in the brain significantly increased due to the rising blood pressure (Case of Stroke). The maximum system response is at 4.0 MHz. Changes of the blood-tissue-ratio caused an alteration in the brain density.

Animal Experimentation

System Response Correlated with Pain

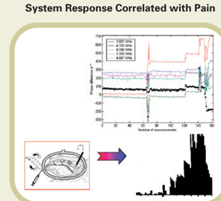


Figure 5. Results of Alteration of the bulk modulus. Detection of Pain. Clear correlation between derived neural pulses (*bottom*) and DRDC's Intracranial System (*top*) during the external stimulation applied onto the animal's knee. The maximum system response is at 4.7 MHz.

Potential First Responder / Combat Casualty Care Applications

Since DRDC's dispersive ultrasound technology can be easily packaged in a portable lightweight ruggedized and battery powered configuration, such a system will be highly relevant in fields of operations for the early non-invasive diagnosis of brain injuries, trauma and for instances where there are no outwardly visible signs of brain trauma or injuries due to a blast and or an IED (Improvised Explosive Devices) attack.

Moreover, the proposed system may be exploited to determine the native and possible location of the injury (e.g., whether in the central brain core or the fluid surrounding it), and it will enable first responders or combat medics to take ameliorative action at an early stage in the field of operations to release the increased pressure (ICP) in the brain, that will be caused by brain herniation.

Conclusion

A full validation of DRDC's ultrasound dispersive technology for the non-invasive diagnosis of traumatic brain injuries in humans remains to be established.

Introduction on DRDC's Non-interfering Wireless Ultra Wideband (UWB) Technology with capabilities for very high bandwidth of data transfer rate of the order of 1.5Gbps

Effective wireless transmission of physiological and medical sensor/monitor information in fields with intense electromagnetic interference (EMI) remains a challenge.

The processing for removing Narrow Band Interference (NBI), and Multiple Access Interference (MAI) is crucial for the commercial exploitation of Ultra Wideband (UWB) wireless communications technologies. Classical digital communication systems are designed for narrow band communications. When applied in wideband communications, the existing techniques leave the large degree of wideband freedom unexploited.

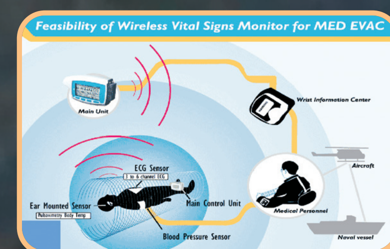
To address this problem, DRDC has developed a non-interfering wireless system technology of adaptive time-frequency-space interference cancellation for UWB wireless systems, which find an elegant balance between performance and implementation complexity. The technical core of the DRDC system resides in: (a) a cognitive UWB pulse shaper to cancel the mutual interference with coexisting narrow band systems; and (b) a cognitive UWB antenna array to reduce the mutual interference with coexisting wide band transmissions. Limited field testing and evaluations of an experimental version of a WVSM (Wireless Vital Sign Monitor) based on DRDC's wireless UWB technology was carried out at the US Army Aeromedical Research Laboratory (USAARL) at Fort Rucker, Alabama. These field tests demonstrated that the UWB wireless prototype is a reliable system component for wireless vital-sign-signal communications, in the EMI field of an operating helicopter for MED-EVAC.

REQUIREMENT: Military MED-EVAC and Civilian Hospital Environments require wireless communications with minimum interference effects, and Compatibility with the military EMC standard MIL-STD-461E.

Existing Wireless Technologies and Products:

- Bluetooth (IEEE 802.15.1) — does not meet requirements
- Zigbee (IEEE 802.15.4) — does not meet requirements
- UWB (IEEE 802.15.3) — meets requirements

Reference: Liang Song, Dimitris Hatzinakos and Stergios Stergiopoulos, "Method and Apparatus of Adaptive Tim-Frequency-Space Interference Cancellation for UWB Communications", US Prov. Patent Application, 60/801,072, Filed 18 May, 2006.



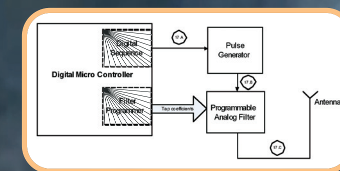


Figure 6. UWB Transmitter Architecture (Single Antenna).

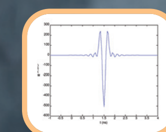


Figure 7. UWB Wave at the Output of PAF (time response).

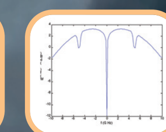


Figure 8. UWB Wave at the Output of PAF (frequency response).

Technical Description

The design concept of the proposed UWB radio platform resides on a wideband cognitive radio operating in the unlicensed UWB range. The definition of cognitive radio is that the radio coefficients can be adaptively reconfigured and programmable in accordance with the current operating electromagnetic environments.

The schematic diagram in *Figure 6*, is straightforward and provides a brief overview of the main components for the transmitter. *Figures 7* and *8* show the adaptively defined wave pulse that would include adaptive notch filters to eliminate potential narrowband interferences.

DRDC's UWB receiver architecture is shown in *Figure 9*. In this figure, Signal 22.A is acquired from the antenna, which is fed into a Pulse Matched Filter (PMF). The system response of the PMF matches the predefined pulse generator in the transmitter. In *Figure 9*, the output of PMF, 22.B, is fed into the PAF at the receiver, which usually matches the PAF at the transmitter. They can however be different, due to the fact that the narrow band system perceptions at the transmitter and the receiver can be different.

The output of PAF, 22.C, is fed into two blocks, which are the A/D Converter (ADC) and the Acquisition Threshold Circuits (ATC), respectively. The ADC, when triggered by the ATC, samples the analog signal 22.C and sends the result (22.D) to the DMC. The ATC, when enabled by the DMC, triggers the ADC whenever the energy level of 22.C exceeds a threshold. This threshold, known as acquisition threshold, is also defined and controlled by the DMC.

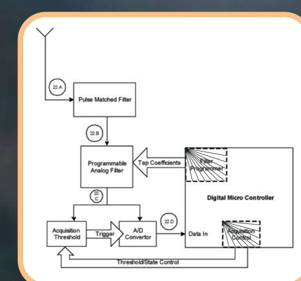


Figure 9. UWB Receiver Architecture (Single Antenna).

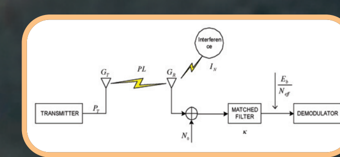


Figure 10. Schematic Representation of the experimental testing of DRDC's wireless UWB non-interfering capabilities.

Experimental Testing

Field testing of DRDC's wireless vital signs monitoring project was carried out at the Electromagnetic (EM) Chamber of UofT. The aim of this testing procedure was to simulate with hardware the helicopter's EM interference environment, as shown in *Figure 10*. In the tests, the UWB emission power was kept below MIL-STD-461E radiated emission constraints, and NETEX experimental results. Further final testing was carried out on board a Black Hawk Helicopter at the U.S. Army Aeromedical Research Lab (August 2006).

The test results in *Figure 11* are for an interference source antenna placed 1 meter away from DRDC's UWB receiver. The interference source was radiating at various levels and frequencies in the range of 3-GHz to 7-GHz and at power levels in the range of -5 to 30dBm.

The impact of the interference was assessed by estimating the Bit-Error Rate of the received source signal by DRDC's UWB receiver, as defined in *Figure 9*. An acceptable level of Bit-Error Rate had to be in the range of 1.0×10^{-2} or 85% to allow for successful transmission of signal of interest in the presence of an interfering signal. As an example, for the frequency of 4.8GHZ, the received signal power by DRDC's UWB receiver was -35dBm, while the power of the illuminated interference on DRDC's UWB receiver was approximately 10dBm, thus producing a Signal to Interference Noise Ratio (SINR) of -42dBm. More specifically, the average received signal power by DRDC's UWB receiver was -73dBm.

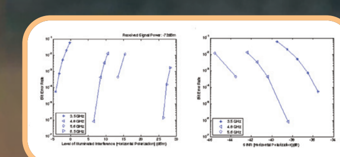


Figure 11. Test results at the EMI chamber of the University of Toronto.

Field Test Results for DRDC's Experimental Wireless UWB VSM at the US Army Aeromedical Research Lab

A limited field testing and evaluation of an experimental WVSM (Wireless Vital Sign Monitor) was carried out at the US Army Aeromedical Research Laboratory (USAARL) at Fort Rucker, Alabama on the 10th and 11th of August 2006. The testing included three phases.

Phase I: On the 2nd of August 2006, USAARL measured the electromagnetic interference (EMI) emissions of the WVSM system using Method RE102 of MIL-STD-461E. The components of the WVSM system assessed during this phase included the NIBP Piesometer Mk-1, the transmitter antenna of the wireless UWB sub-system and a portable PC that provided integration for all the WVSM subsystems. All systems were battery powered. The results showed that the EMI levels of the integrated WVSM system to be acceptable but will require further review by the approving military agencies.

Phase II: On the 10th of August 2006, the noise tolerant blood pressure system, the Piesometer MK-1 with its wireless UWB prototype were tested at the Noise Chamber facility of the USAARL. The noise levels during the testing were measured with a Bruel & Kjaer Sound Analyser type 2260. The results of this test indicate that the Piesometer Mk-1 can provide reliable blood pressure estimates in acoustically very noisy environments with average noise levels up to 110 dB ref 20mPa.

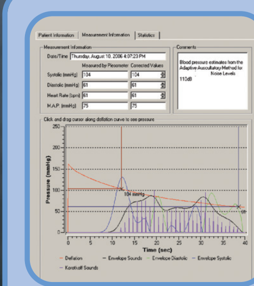
Phase III: On the 11th of August 2006, field testing of the experimental WVSM system took place:

a. on board an operating helicopter and
b. next to an operating helicopter, which in both cases was a Black Hawk JUH-60A type.

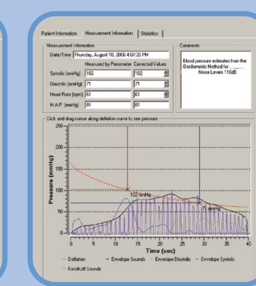
The first objective of this field test was to demonstrate that the NIBP sensor for the WVSM project can provide reliable BP monitoring during MEDEVAC helicopter operations.

The second objective of this field test was to verify and demonstrate that the UWB wireless prototype is a reliable wireless system component of the wireless vital sign signal communications, in the EMI field of an operating helicopter. During the tests, the helicopter was operating while on ground. The noise levels during the testing were measured by Dr. Adrian Houtsma, with a Bruel & Kjaer Sound Analyser type 2260. The recorded average noise levels:

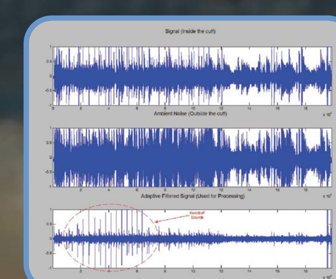
a. 7-m outside the helicopter were in the range of (108 – 110) dB ref 20mPa, and
b. on board the helicopter were (110 – 112) dB.



Blood Pressure Estimate from the adaptive Auscultatory output of the NIBP Piesometer MK-1 at 110dB noisy environment.



Blood Pressure Estimate from the oscillometric output of the NIBP Piesometer Mk-1 for the same blood pressre record at 110dB noisy environment.



NIBP Piesometer Mk-1: Acoustic Signal Outputs in the Noisy Intense Environment of a Black Hawk Helicopter show that the adaptive noise cancellation process is effective in removing strong acoustic interferences.

Conclusion

Field test results of Phases II and III were successful. The non-interfering ultra-wide band wireless communication system has been demonstrated to be effective in an intensive electromagnetic interference MED-EVAC environment (e.g., Black Hawk helicopters).

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