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A Review of the Role of Acoustic Sensors in the Modern Battlefield+

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Acoustic sensors have been used for battlefield applications since World War I. Acoustic sensors provide several advantages and are increasingly employed in the modern high-tech battlefield. The twenty-first century battlefield calls for cutting-edge technology for military superiority and deployment of state-of-the-art acoustic sensor systems that employ advanced acoustic signal processing. Thus acoustic sensing technology is becoming increasingly important to accomplish this superiority. The utilization of several acoustic sensor systems dating from the early 1900s to the present is reviewed. The role of acoustic sensor technology in military exercises for ground-based, aerial, and naval combat is discussed. A detailed review of acoustic signal processing and the different stages involved—sound rejection, detection, localization, classification and cancellation—is presented. The advantages and disadvantages of using acoustic technology for potential battlefield applications are presented, and the potential role to be played by acoustics in future warfare is also discussed.

I. Introduction

THIS paper outlines the use of acoustic sensor technology for battlefield purposes from the early 1900s to the present. The acoustic signatures of vehicles such as battle tanks, aircraft, helicopters, and submarines can easily be detected through the use of acoustic sensing technology. Acoustic sensor systems can ascertain the exact target location, speed, direction of motion, and classification. Acoustic sensor systems provide high precision battlefield awareness and surveillance over a broad range of frequencies and angles, while operating at minimum expense and power consumption. These qualities along with the fact that the acoustic systems are easily deployed and disguised in all types of terrain and the ease of portability of the sensors make the use of acoustic sensor technology both intelligent and efficient in the modern battlefield. However, due to range restrictions, the susceptibility to background noise, and the dependency on atmospheric effects (refraction due to temperature gradients, sound absorption by atmospheric humidity, etc.) and wind conditions (turbulent scattering), acoustic sensing technology has its limitations.

Acoustic sensor systems deployed in the battlefield for target acquisition and surveillance purposes (such as the identification of enemy battle tanks, aircraft, helicopters, and submarines) utilize the acoustic signatures associated

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with enemy combatants to characterize the nature, location, speed, and direction of the enemy combatant motion. The passive sensors detect the acoustic signatures and relay the signal to a computer, which in turn processes the data for sufficient action. These passive acoustic sensors can be established to detect hostile tanks, artillery, incoming missiles, aircraft, UAVs, and helicopters.

Onboard (mobile) and stationary acoustic sensor systems are utilized to guide outgoing attack missiles to reach their appropriate target. Naval applications of acoustic sensor systems include both the detection of enemy submarines and torpedoes and the guidance of outgoing attack torpedoes. Acoustic sensors are also used as counter-measures for the active defense of battleships. Whether utilized alone or in conjunction with other sensing media such as electromagnetic (radar/radio) and electro-optic (EO) sensors, acoustic sensors have great potential for the high-tech battlefield in the twenty-first century.

II. Battlefield Acoustic Sensing Technology

A. Early Battlefield Acoustic Technology

The use of acoustic sensing for battlefield purposes dates back to the early 1900s. During World War I, flash and sound ranging equipment was used to find the exact direction of enemy artillery[1]. The Italian-developed passive acoustic location system (PALS), the sound ranging system-6 (SOARS-6) developed in Sweden, and the Russian-inspired SCHZ-6 are a few of the early attempts to use acoustic sensing technology for battlefield applications around the time of World War I. Fig. 1 shows a French-developed acoustic array[2] that was utilized for battlefield applications during World War I. The device, developed by Sergeant Jean Perrin (the person on the right in Fig. 1), was comprised of two clusters of sensors each consisting of six sub-sensors arranged in a hexagonal fashion. Each cluster can be rotated along different directions and the outputs from each of the sub-sensors were summed up. The direction that yielded the maximum total output was thus the direction of the enemy artillery or aircraft.

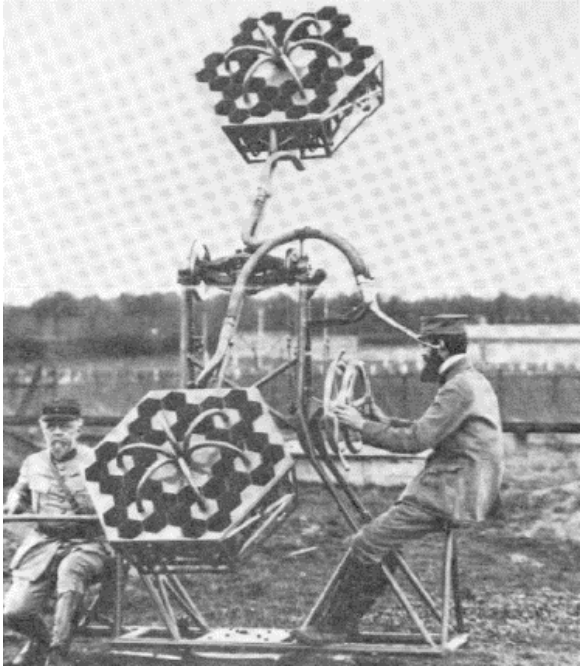

Figure 1. World War I acoustic array[2].

During World War II, air defense was provided by simple airplane-noise detection devices such as giant stethoscopes that were pointed at the sky on both sides of the English Channel to locate, track, and identify aerial combatants and their direction of movement[1]. Acoustic tunnel detectors were used in the Korean War to detect sounds in the tunnels that were dug to penetrate fortifications. The air-deliverable seismic intrusion detection system (ADSIDS) and the remotely monitored battlefield sensor system (REMBASS[1]) were tactically placed to track the movement of troops during the Vietnam War. The sound surveillance system (SOSUS) and the integrated undersea surveillance system (IUSS) were developed during the cold war to provide deep-water, long-range detection of enemy submarines which were posing a great threat.

B. Modern Battlefield Acoustic Technology

Modern acoustic sensing technology is based on robust sensors with high dynamic ranges, imbedded computing and state-of-the-art signal processing and is being used for ground-based, aerial, and naval battlefield applications. Some of the more interesting modern acoustic sensor system applications are discussed in the following sections. Fig. 2 shows an example of a compact acoustic sensor. As mentioned in the website of Signal Systems Corp.[3], this is a revolutionary compact (11 cm) sensor containing a unique chambered design with ultra-low power ASICs (custom application specific integrated circuits) for detecting and localizing vehicles and gun-fire. This is a low power, affordable and versatile acoustic sensor. It can reduce wind noise and is waterproof. This sensor can also be easily mounted onto vehicles, requires a total wake-up power of only 35 mW and a total bearing estimation power of 3.24 mW. This sensor is also covert and has long endurance.

1. Ground-based Battlefield Applications

Considerable amount of research has been carried out to develop and use acoustic sensors in the battlefield. Some of the technical models used for efficient use of acoustic sensors and analysis of the data collected form sensors are discussed here. ESPRIT, a signal processing technique based on eigen-decomposition of a covariance matrix, was used with relatively small baseline acoustic sensor arrays for passive direction-of-arrival estimation and tracking ground vehicles in the battlefield environment[4]. The technique operates at a lower computational rate and is less sensitive to sensor array imperfections. Although the technique possessed these advantages and produced satisfactory results, it required too many sensors when compared with other signal processing techniques like MUSIC.

MUSIC is a signal processing algorithm that detects frequencies in a signal by performing eigen-decomposition on the covariance matrix of a data vector of multiple samples obtained from the received signal. MUSIC assumes that the number of samples and the number of frequencies are known. The efficiency of MUSIC is the ratio of the theoretical smallest variance, given by the Cramer-Rao Lower Bound (CRLB), to the variance of the MUSIC estimator. A detailed description of this algorithm is considered beyond the scope of this paper and can be accessed from numerous papers[2,5,6,7,8].

A modeling approach based on time-varying autoregressive (TVAR) modeling was developed for analyzing the acoustic signatures of moving vehicles[9]. In this approach, the time-varying parameters are expanded as linear combinations of deterministic time functions (e.g., a low-order discrete cosine transform, DCT). The use of high-speed network technologies such as ATM-SONET and Fibre Channel to develop sensors for detecting noise from ships was investigated by Walrod[10].

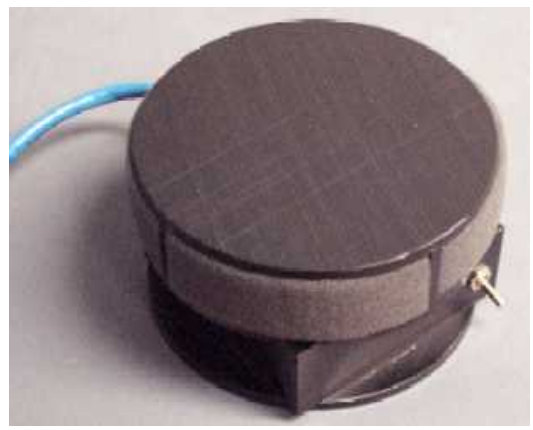

Figure 2. Micro electro-mechanical systems (MEMs) acoustic sensor[3].

The Bochum Verification Project[11] (BVP), undertaken in Germany, analyzed the potential of ground sensors for co-operative verification of ground-based enemy vehicles. Acoustic and seismic sensors with a sensitivity range of 10 – 50 mV/Pa and a frequency range of 2.6 – 20000 Hz were used. The project included the sensing of battle tanks, transport trucks, and armored personnel carriers. Microphones and geophones (seismic sensors which are beyond the scope of this paper) were used appropriately to sense targets. The BVP used 12-bit analog to digital conversion, low-pass filtering and amplification of the signals, and a digital sampling rates of 2.5 – 3 times the filter frequency. The BVP demonstrated the efficient and complete usage of acoustic sensors to detect ground-based enemy vehicles.

The Remotely Monitored Battlefield Sensor System (REMBASS[1]) and the Improved REMBASS (I-REMBASS) were developed during the Vietnam War for battlefield application. They consist of passive sensors that can be left unattended for as long as 30 days. These sensors are normally in an idle mode with very low power dissipation. When a target appears within its detection range, the sensors recognize the change in the ambient energy level and thus get activated. These sensors identify the approaching target and convert the data collected into digital messages and transmit them to a monitoring device. This information that is received by the monitoring device is decoded and displayed indicating the target details.

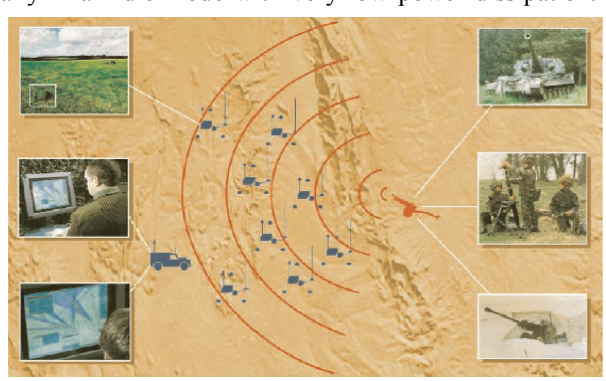

Figure 3. Hostile artillery location system (HALO)[12].

BAE Systems[12] developed the Hostile Artillery Locator (HALO) for the British army during the Balkan War. HALO uses advanced data processing techniques to ascertain the location of artillery and mortars. The system was comprised of distributed acoustic sensor array posts having clusters of highly sensitive microphones that detect the acoustic pressure wave generated by enemy gun or mortar fire (right in Fig. 3) and passes on the data to the HALO Command Post (HCP). The HCP (denoted by the truck in Fig. 3) processes the data and determines the location of the sound source. Each sensor post can scan 360 degrees and can detect enemy gun positions up to a firing rate of 8 rounds per second.

Acoustic technology was recently applied in the design of the anti-armor munitions in the form of brilliant anti-armor (BAT) munitions[1] developed by Northrop Grumman. This development is merely an extension of the traditional military ear for listening to sounds on and around the battlefield. Utilizing high-tech, miniaturized, high-speed, high-capacity, on-board data processing, the BAT acoustics system analyzes sound waves. Using state-of-the-art algorithms and differentiating characteristics, BAT filters all sounds that its wide-open acoustic sensors acquire to focus on and attack selected targets. Acoustic BAT munitions employ capabilities to detect and home-in on engine noise from enemy tanks and eventually destroy enemy tanks[13].

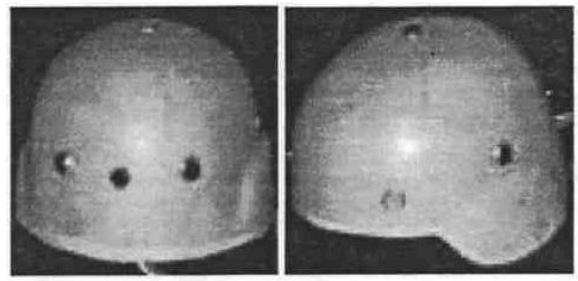

Figure 4. Acoustic helmet system[14].

The recent military operations in Afghanistan have provided an appropriate opportunity for the utilization of modern acoustic sensor technology. Helmet-mounted acoustic sensors (Fig. 4) were used to provide warnings against hostile mortars and artillery[14]. Acoustic sensor systems mounted on robotic vessels (iRobot[14] Packbot, Fig. 5) were also used to hunt for absconded snipers. The robotic platform acoustic sensor systems enhance the capability of the military to undertake reconnaissance, surveillance, and target acquisition missions. The soldier and the robot work in collaboration to provide triangulation information for an algorithm to estimate the exact location of an active enemy acoustic source.

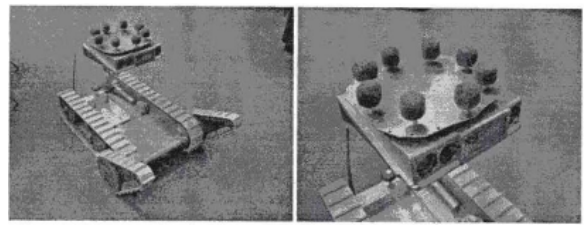

Figure 5. iRobot Packbot with acoustic sensor array[14].

The Vehicle Acoustic Warning and Surveillance System (VAWS) developed by the Signal Systems Corporation[3] is mounted on ground based vehicles like tanks and trucks as shown in Fig. 6. This system can detect land based enemy targets in the range 100-2000m and requires a power under 75 Watts per sensor.

Figure 6. The VAWS system on ground based military vehicles[3].

2. Aerial Battlefield Applications

A common framework for the testing of flight parameter estimation using both narrow and broadband methods was formulated by Ferguson and Lo[15]. A turboprop fixed-wing aircraft and two types of rotary-wing aircraft were made to transit a planar array of passive acoustic sensors several times. While the narrowband method requires a time-frequency analysis of the signal, the broadband method requires an observation of retarded time. Both methods were found to provide reliable estimates of the speed and altitude of the fly-over aircraft, with the narrowband capable of estimating the blade-passage frequency, which is essential for aircraft classification.

The flight of an aircraft undergoing zero acceleration can be detected by the noise received by a differential sensor made up of three or more microphones. Dommermuth and Schiller[16] developed an algorithm, which was found to be reliable, based on real-world data results. Ground-based sensors due to the high sound pressure amplitudes associated with their propulsion systems can detect Low-flying airplanes easily. The acoustic sensor systems can also estimate flight parameters like speed, direction of flight, height above ground, and azimuth and elevation angles, and acoustic sensor systems can also classify the source based on its acoustic signature. This calls for the necessity to have multiple acoustic sensors within the battlefield.

An acoustic sensor for the detection of air vehicles with various acoustic signatures, based on their jet noise, propeller/rotor noise and engine was developed after accounting for the ambient noise by Berman and Zalevsky[17]. The BAT[1] acoustic sensors (discussed earlier) not only detect and identify targets of interest from a static ground platform but they perform target discrimination from an air vehicle moving at high speed. More sophisticated aerial applications, such as acoustic anti-helicopter missiles, use acoustic-based sensors track and destroy a given target for which a missile is programmed.

Unmanned Air Vehicles (UAVs) are a vital platform on which acoustic sensors can be mounted. UAVs can approach enemy targets much closer than airplanes and therefore are widely used in present day battlefields. Thus mounting state-of-the-art acoustic sensors to UAVs can provide a tactical advantage against the enemy. Several acoustic sensors and technologies have been developed specifically for UAVs of which a few are discussed below.

Scientific Applications & Research Associates (SARA) Inc.[18] developed the Low Cost Scout UAV Acoustic System (LOSAS) for application in UAVs. These acoustic sensors are jam resistant, low weight, low cost and have coverage over a wide area. They also feature autonomous search algorithms, which makes operations without a line of sight possible. LOSAS can also detect enemy aircrafts and artilleries fired from the ground. The prototype has been successfully designed, fabricated and tested in powered flight. The company is currently trying to integrate LOSAS with an IR camera for more efficient operation.

According to its website, SARA is also applying its expertise in digital signal processor design and advanced data processing algorithms to develop acoustic unattended ground sensor (UGS) technologies for military and civilian applications[18]. Acoustic UGS can monitor vehicle movements to provide battlefield situational awareness, cueing of intelligent minefields, or monitor environmental noise. The Enhanced Acoustic Algorithms for Ground Vehicle Surveillance (EAAGVS), currently in development at SARA for the US Army, should enable a network of acoustic UGS to operate in a target rich environment that would overwhelm current systems.

Roke Manor Research Limited[19], based in the United Kingdom, has developed technologies for efficient use of acoustic sensors mounted on UAVs. Microphones mounted onto the UAVs fuselage, wings and tail, creating arrays of sensors that facilitate 3D target identification. Roke Manor has performed research on wind noise and engine/propeller noise cancellation, thus making the use of acoustic sensors mounted onto UAVs, a prominent technology for battlefield application. It is also noteworthy to mention that the Hunter and Dragon Eye UAVs also use acoustic sensors for target identification[20].

3. Naval Battlefield Applications

Navies across the globe are engaged in an inexhaustible arms race to make their submarines stealthier and develop better methods of identifying and tracking hostile vessels. There are a multiple of acoustic sensing technology applications that include passive "listening" arrays for submarine detection. A passive, two-dimensional acoustic array positioned on the ocean floor was used to successfully measure ambient sound ranging from 0.01 – 6000 Hz in order to detect passing vessels[21]. A twin-lined, towed acoustic array with the capability of scanning a marine battlefield environment and resolving individual surface ships within hundreds of miles was developed[22].

During the cold war, submarines were designed to launch cruise missiles capable of delivering nuclear warheads. This called for the need to possess state of the art technologies for long-range submarine detection. Thus several acoustic-based sensor systems were developed during the cold war. One of the notable ones among them was the Sound Surveillance System (SOSUS)[1]. It tracked submarines with just a faint acoustic signal. SOSUS consisted of high-gain long fixed arrays in the deep ocean basins.

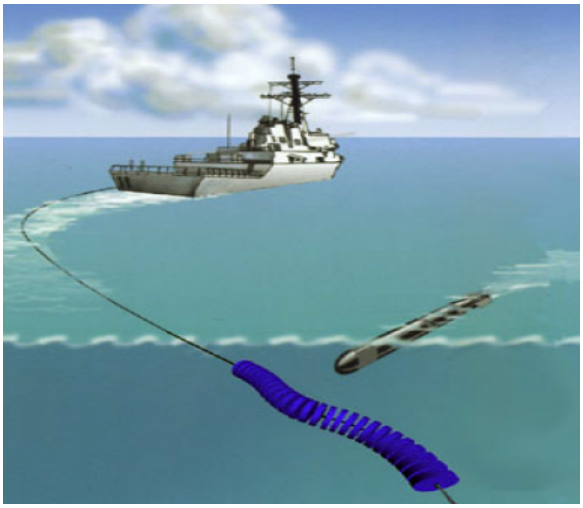

Figure 7. Surface vessel towing acoustic decoy[23].

As illustrated in Fig. 7, naval surface ships tow an acoustic source that serves as a self-defense mechanism against incoming torpedoes that are guided by onboard acoustic sensors[21]. The towed source performs the role of a decoy for the homing torpedo by masking the acoustic signature of the ship. This may however not work for multiple hostile torpedoes fired at a surface ship. Thus, the existing Nixie system[23] is undergoing an upgrade under the WSQ-11 torpedo defense system procurement to allow efficient operation. The towed source will be altered to provide prospects for operation at high acoustic power over a broader frequency range. Lockheed Martin developed

the TB-29 thin-line towed array[24], towed by submarines. Its increased length over earlier arrays allows the TB-29 to offer superior detection, classification, and localization performance.

The Surveillance Towed Array Sensor System Low Frequency Active (SURTASS LFA)[25] is an antisubmarine system and is deployed from a surface ship. This system consists of both active and passive sensors. The passive part (SURTASS) consists of a long array of hydrophones to monitor underwater sounds emanating from enemy submarines. When the enemy submarine has its propellers turned off, it is quiet enough to avoid the SURTASS. In such cases, the LFA is employed. LFA is the passive part, and consists of sound emitting sensors suspended from a long cable beneath the ship as shown in Fig. 8. Thus the sound emitted by the LFA reflects from the enemy submarines and is detected by the SURTASS. The LFA consists of 18 active acoustic sensors emitting sound at a level of 215 dB (underwater). This level of sound may pose a threat to marine animals, and thus the NAVY has certain restrictions in its usage. Submarine launched torpedoes like the MK-46, MK-48 and MK-50 have been developed which are guided by onboard acoustic sensors, both passive and active. These torpedoes attack enemy submarines and can be launched from submarines, warships and aircraft

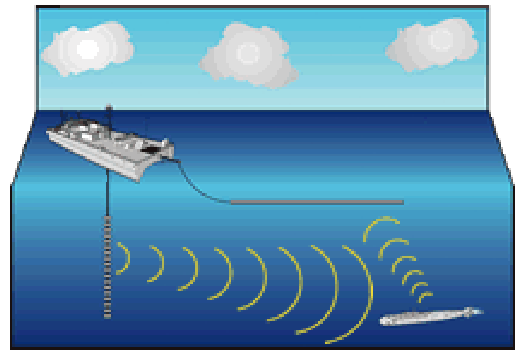

Figure 8. SURTASS system[25].

Investigators at the Swedish Defence Research Agency investigated underwater communication, which has potential battlefield applications. They presented results based on experiments conducted in the Baltic sea[26]. They studied methods for both high and low data rate acoustic transmissions. They achieved a decoding rate of 4000 bits per second over a transmission range of 38 Km. Mobile ranges were used to measure the acoustic signatures of ships and submarines by Silhouette and Tonelli[27]. The authors compared mobile and fixed ranges, presented solutions for mobile ranges and discussed a method to process the measurements obtained from experiments performed in the sea. This is one of the procedures for the estimation of propulsor noise from naval vessels and submarines. The authors developed a procedure to manage the ship signature by calculating the flow on the rotating propeller behind the ship or submarine. These calculations enabled a good assessment of cavitation inception speed.

C. Acoustic Signal Processing

Acoustic signal processing is a branch of signal processing that deals with the extraction of data from signals conveyed by propagating sound waves. This involves five intermediate processes: noise rejection, detection, location, classification, and cancellation. A large number of articles and textbooks have been devoted to the discussion of these processes, especially in relation to radar signals. These processes are applicable to most wave phenomena, including acoustics. As such, only a limited discussion of each process will be provided here.

1. Noise Rejection

Noise induced by wind causes a big problem in acoustic monitoring by aeroacoustic sensors. This is specifically the case for monitoring low-frequency artillery blast noise where the wind noise masks the blast. A real-time system capable of detecting signals and rejecting the unwanted wind noise, based on spectral and correlation methods has been developed by Benson[28]. This system features a 97 percent detection and rejection rate.

Messerschmitt and Gramann[29] examined the dominant mode rejection (DMR) beamformer performance using a bottom-mounted horizontal line array in a shallow-water environment. They processed the data with a fully adaptive beamformer and the DMR beamformer. They showed that the DMR beamformer performed better than the fully adaptive beamformer when using arrays with larger numbers of hydrophones. Thus, they concluded that in highly dynamic noise environments, the DMR beamformer may be a more appropriate implementation to use for

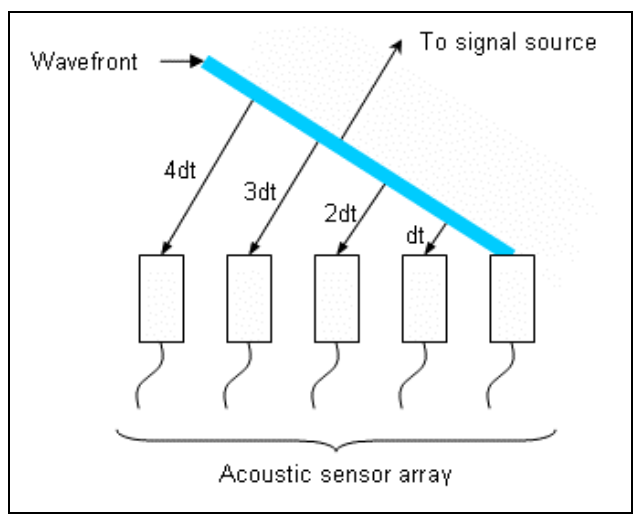

Figure 9. Acoustic sensor array sampling illustration.

passive sonar detection systems. Bodson[30] discussed different methods for the rejection of periodic disturbances which are often encountered in active noise control. He considered two cases: when the frequency of the disturbance is known and when it is unknown.

2. Noise Detection

Detection of sound involves methods of enhancing signal-to-noise ratio. Signal detection techniques based on time-frequency signal analysis with the Wigner-Ville distribution (WVD) and the cross Wigner-Ville distribution (XWVD) were discussed by Boashash for under-water application[31]. These techniques were shown to provide high-resolution signal characterization in a time-frequency space, and good noise rejection performance. This type of detection was applied to estimate the signature, detection, and classification of specific machine sounds like the individual cylinder firings of a marine engine. The ability of a receiver to detect a particular signal depends on the signal-to-noise (S/N) ratio at the input of the receiver. The S/N ratio has to be high for accurate target identification.

Goo[32] detected underwater targets in the presence of background acoustic noise using a resonance detection technique. This has potential applications in naval warfare.

3. Noise Location

Phased array is the most common acoustic signal location system. An array of acoustic sensors is located at distinct spatial locations to measure a propagating wave. As shown in Figs. 9 and 10, an array of acoustic sensors samples the field at the different sensor locations at different instances of time. Beamforming provides an array with directionality, effectively amplifying sound from a preferred region in space while attenuating sound from other regions. The basic principle is illustrated in Fig. 9 with the help of a plane wave sound propagating towards an array of microphones. A linear array of equidistant microphones (mics) collects data about a plane wave propagating toward the array at angle θ. The wave will reach successive adjacent mics with a constant time difference, Δt, given by $\sin\theta = c\ dt/b$, where c is the speed of sound and b is the mic separation distance. The ultimate goal of acoustic array signal processing is to coalesce the output from all the sensors so that: (1) the signal-to-noise ratio is superior to that of a single sensor, (2) the propagating wave is characterized, and (3) the energy sources as they move in space are tracked. Thus, in principle, the exact direction of the incoming sound wave can be determined. Phased array technology (or beamforming) is accurate in estimating the exact direction from which the sound waves originate. The acoustic signals can be processed to extract information about enemy combat vehicles that help in making intelligent decisions and actions.

Figure 10. 16-element cross sensor array with one-foot spacing located on the ground[33].

Thus the exact direction of the incoming sound wave can be determined. By measuring the sound pressure level, and thus calculating the pressure, the distance between the source and the sensor array can be estimated by assuming inverse square law. Finding the angle and distance results in estimation of the exact location of the source with respect to the sensor array. This method was used in the early days. Modern phased arrays consist of acoustic sensors arranged in more complex fashions and thus the estimation of the target location is more complicated but more accurate, although similar in principle to the procedure just discussed. The relative movement of the sound source relative to the arrays causes a Doppler shift. By measuring this shift, the relative velocity of the sound source can be estimated[2]. Thus, the angle, distance and velocity of the target source can be estimated with the use of phased array technology.

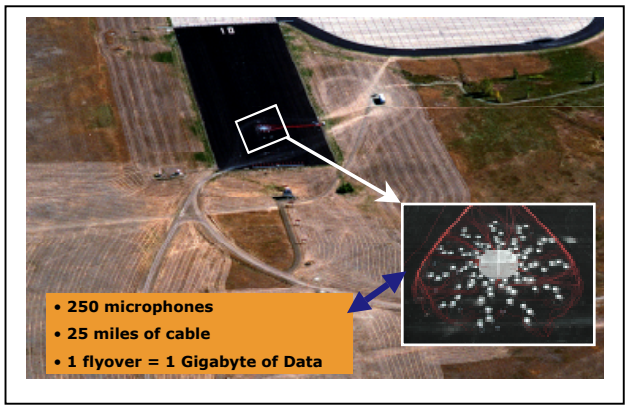

Figure 11. Large microphone array used by Boeing for a locating sources on a flying aircraft[36].

Considerable advances have been made in phased arrays in the recent years by the aeroacoustic community. Such arrays have been used in the laboratories to locate sources of noise on wind tunnel models[34]. More recently, such arrays have been used by aircraft researchers to detect the low frequency sound produced by aircraft wakes. Researchers have employed close to 250 microphones to locate the position of noise sources on a flying aircraft[35]. Clearly, this capability offers significant military advantage to detect air vehicles just from their wake noise. Although not established in the open literature, it is reasonable to assume that an aircraft with a unique wake will have a unique signature. Another effort is worthy of note is the location of sources of noise of different frequencies generated by various protrusion on an aircraft. Such efforts have been motivated by the need to determine what sources are located where on the airframe so that appropriate measures can be taken to control them. It is a major task to acquire such data from a full-scale flying aircraft. Such a task has indeed been carried out by the researchers at Boeing Company using a very large array on the ground. This array taken from Stoker et al[36] is shown in Fig. 11. This array has successfully located the sources of noise in different parts of an aircraft. The signal processing has been improved significantly[37] to provide more accurate results. This experience by the aeroacoustic community should help the military improve its noise location capability of flying vehicles from a distance.

4. Noise Classification

Classification of sound involves two different ways: using neural networks and using tables, of which the former is important. In most warfare, the types of weapons possessed by the enemy are usually known, and thus often their acoustic characteristics. This makes the use of neural networks effective in the classification of the acoustic signatures of the enemy artillery, as the signal has to be classified to be one among a few known signals. Several neural network configurations can be applied and compared with each other to classify the incoming signal (for example, see Luo[38)]. Some of the methods for estimating the direction of arrival of the enemy artillery are: the maximum likelihood (ML) technique, the minimum variance method, the minimum norm method, MUSIC method and the propagator method. Among these, the ML method is known to have the best performance. MUSIC and propagator methods are used when the signal-to-noise ratio and the number of samples are not very small. A novel efficient neural network detector was proposed using an XOR-Tree configuration by Gelenbe and co-workers[39]. The authors performed tests with synthetic and real noise and showed this approach to work. With real (non-white) noise obtained from sonar data, the XOR-Tree network performed successfully.

A neural network based framework for classification of oceanic acoustic signals was proposed by Maccato and Figueiredo[40]. They split the task of acoustic signal processing into two stages. First, a highly structured, hierarchial/symbolic representation of the data was created using scale space algorithms. This calculation overcame moderate noise and warping distortion present in the acoustic recording and at the same time reduced the data to be processed. Second, neural network architectures were applied to the resulting symbolic structures to obtain the desired signal parameters. The advantages of using structured neural networks (SNN) over the classical model-based approach have been discussed in detail by Bruzzone and others[41].

The Mean Separator Neural Network (MSNN) is another efficient use of neural networks in the classification of signals. A simple type of projection pursuit scheme was developed and applied to classification of signals by Fargues and Duzenli[42]. The scheme was used to significantly reduce the number of class features obtained from the wavelet packet decomposition of the signals to be classified. Results showed this scheme to efficiently classify underwater data without significant loss of performance.

The second way of signal classification is by the use of tables, where the acquired signal is compared with existing tabulated values and the characteristics are estimated. Several neural network systems involve the use of tables for comparing the signal characteristics.

5. Noise Cancellation

Acoustic sensors mounted on platforms such as trucks, tanks and missiles often also measure the noise emanating from the platform due to its motion. Acoustic sensors desired to track down a specific enemy target also measure other surrounding noise sources such as birds, wind/flow, mortar explosions, other enemy vehicles, etc. Hence it is always desired to cancel out these sources of background noise. This calls for the need to design and master techniques to cancel background noise so as to obtain a pure noise of a specific target. A number of noise cancellation or active noise control have been developed over the years and published in numerous articles, proceedings and books. The methods need to be invoked to ensure that the on-board sensors are measuring only the signal of interest. This is a major challenge and research continues on innovative ways of extracting signals buried in noise. Of particular note is a multi-microphone method, dubbed as '3/5/7/…' microphone technique, developed by Minami and Ahuja[43].

III. Multi-microphone Method

A new method of signal enhancement based on using an odd-number of acoustic sensors for separating different correlated noise sources contaminated with uncorrelated extraneous noise from far-field measurements has been developed recently. This technique employs spectral and coherence functions to estimate coherent signal sources in the presence of uncorrelated background noise. Three microphones are needed if only one correlated signal is known to exist, five and seven for two and three coherent sources, respectively. For the five microphone method, the underlying assumption is that the five microphones measure the sum of the two separate correlated signals and another signal that is uncorrelated at all microphones at frequencies of interest.

Minami and Ahuja[43] have shown that this technique works for odd-number of acoustic sensors. They show that the five microphone method gives rise to 55 equations and as many unknowns. For the five microphone method, the system of 55 equations is non-linear and hence has to be solved numerically. While the five microphone method can be applied to any case that includes two correlated and one uncorrelated noise sources, the three microphone method can be applied only to one correlated noise source. This methodology has applications in battlefield acoustic sensing due to several advantages: improved signal-to-noise ratio, detecting enemy tanks, helicopters and other military vehicles, detecting missile launches, etc. Although not tested for battlefield application yet, the 3/5/7 microphone method has the potential for its use in the battlefield to differentiate between the noise emanating from an enemy tank or helicopter in the presence of noise from the relatively smaller artillery and background noise. More research on this technique is currently underway at the Georgia Tech. Research Institute by the research team of the third author.

IV. Advantages of Acoustic Technology

The superiority of acoustic sensors for wide range target identification is a result of the technology itself. Unlike their electromagnetic (radio/radar) or electro-optic (EO) counterparts, acoustic sensors are capable of searching all frequencies and angles allowing for a wide-open range capability. The wide-open, simultaneous target acquisition of all incoming signals means acoustic sensors are much more efficient than their counterparts.

Acoustic sensors can provide immediate information on the location of the hostile artillery and characterize weapons based on their acoustic signatures. Heat and electromagnetic radiation seeking sensors can be easily fooled by countermeasures like dispensing flares or jamming the electromagnetic signal, as the case may be. However, current countermeasures cannot be guaranteed success against acoustic homing. In order to escape an acoustic-based weapons system, an enemy must hide its acoustic signature; however, many targets cannot operate without generating a detectable acoustic signature (e.g., a tank cannot move without running acoustically distinctive engines or making acoustically distinctive track noises).

Acoustic sensors have the further advantages of operation in cloudy or overcast battlefield environments, non-determent by smoke blanketing, and high cost-effectiveness. The previous qualities along with the fact that acoustic sensors do not require a direct line-of-sight view for target identification and surveillance make the utilization of acoustic sensor systems more prominent in modern high-tech battlefield applications.

V. Disadvantages of Acoustic Technology

Acoustic sensor systems do not have the enormous long-range capabilities of their radar or electro-optic counterparts. Acoustic sensors are also strongly affected by atmospheric conditions. The presence of mean temperature profiles can cause sound waves to refract, and thereby making the use of acoustic sensors in warfare ineffective. The historic significance of the effect of temperature on battlefield acoustics in fact dates back to the civil war, during the Battle of Gettysburg in 1862. Temperature gradients in the atmosphere caused the sound waves to bend, thus the sounds from the battle of Gettysburg could not be heard even 10 miles away, but were heard 150 miles away in Pittsburgh. Likewise, sound messages transmitted by the troops of General Lee could not reach their desired destination due to temperature gradients in the atmosphere causing the sound waves to bend[46].

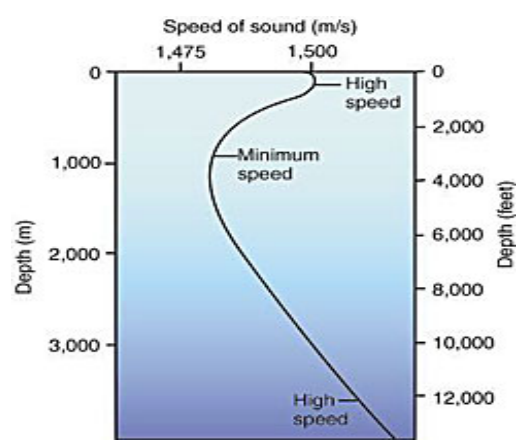

Figure 12. Speed of sound variation along ocean depths[47].

Platform and wind noise reduction techniques are required to obtain useful acoustic sensing data. Sound waves tend to be scattered by wind turbulence, shear and other random atmospheric motions. The acoustic sensors used in underwater applications for submarine and torpedo surveillance are sometimes rendered inactive by deep-sea currents, which can bend the sound waves producing a zone of silence. These sensors can also be affected (to a minor degree) by the differences in salinity along ocean depths. The combined effect of temperature, pressure, ocean currents and salinity in the ocean depths gives rise to a speed of sound profile that can vary significantly along the ocean depths[47] as shown in Fig. 12. This is a problem that has to be accounted for in the design of acoustic sonar and torpedoes deployable from submarines.

Unattended acoustic sensor systems used for battlefield awareness and other wide range area surveillance require state-of-the-art algorithms to address the challenges incurred in detecting, classifying, and tracking battlefield targets. These state-of-art algorithms are not easily generated, and the algorithms require the processing of large amounts of acoustic data over a minimal time frame, thus leading to the need for state-of-art computational mechanisms. Multi-target resolution and identification also create problems while utilizing acoustic sensing technology.

VI. Future Acoustic Battlefield Applications

Emerging technologies with great potential for the high-tech battlefield of future could benefit significantly by employing modern acoustic technology. Coupled with terminal guidance sensors, acoustic-based homing sensors are ideal for wide range area target identification for the mission of finding and destroying enemy targets. Acoustic technologies emerging on the twenty-first century battlefield offer the prospects of a major leap forward from contemporary target acquisition and surveillance systems.

Large vehicles, be they aircraft, helicopters, tanks automobiles, or missiles, produce infrasonic signatures (0 to 20Hz) that can travel long distances without being attenuated much. These signal are not audible to humans but can be heard by sophisticated sensors. Considerable work has been done in this area in the recent years. Typical infrasound spectra for three automobiles measured by Higaki, Ahuja, and Funk[48] is shown in Fig. 13. This figure shows a comparison of spectra acquired for three different vehicles of different sizes by a special infrasound microphone located outside the vehicles during their passby. The analysis was done at $\Delta f = 0.09$ Hz. The frequency and magnitude of the large low frequency hump is dependent on the size and speed of the vehicle. The pickup and UPS truck were moving at approximately the same velocity. The larger size of the truck results in a much higher magnitude signal at low frequency. Typically the magnitude and frequency of the hump increases with increasing velocity. The compact car shows a higher frequency and higher magnitude than the pickup due to its higher speed, but a lower magnitude than the UPS truck due to its smaller size.

The spectrogram during the pass by of one these vehicles is shown in Fig. 14. It clearly indicates that where the vehicle passes by the microphone, the dominant frequencies here in the 0 to 2 Hz range, and frequencies lower than 2 Hz persist for the longest duration. Such signatures, which can be much stronger for larger and faster moving vehicles, can be used very effectively for the military applications.

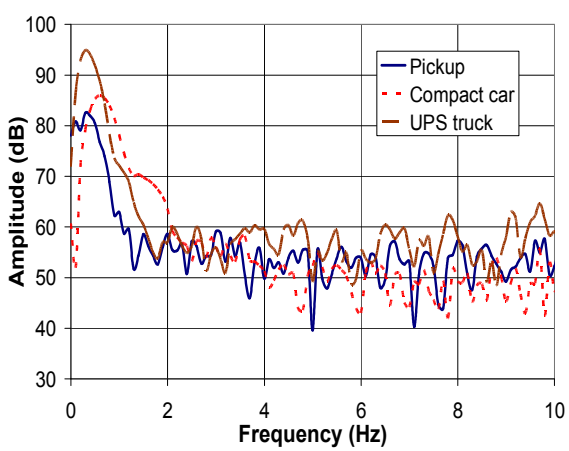

Figure 13. Spectrogram of a UPS truck passby[48].

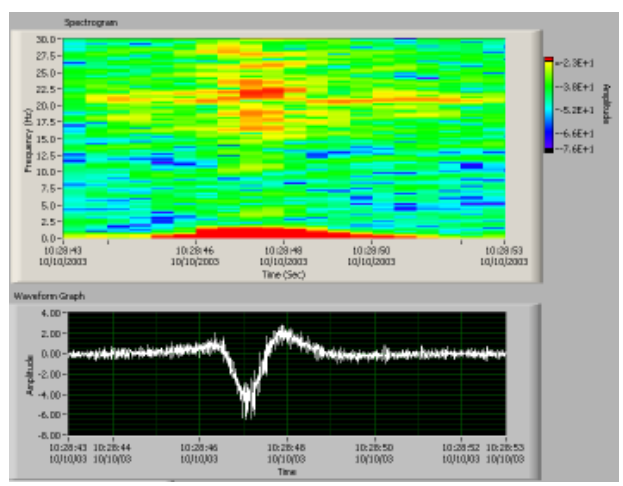

Figure 14. Spectrogram of a UPS truck passby[48].

Higaki et al attribute the cause of this infrasound in the 1 to 2 Hz region to the wake of the vehicle. The infrasound signature of large vehicles can first be used to detect them from a long distance. Signals in the high frequency region can then be used for homing in on them. Jet engines produce enormous amounts of noise; thus, the development and utilization anti-aircraft missiles which home in on the sound waves produced by hostile jet engines are a seemingly achievable weapons system of the future. As previously mentioned, navies across the globe have developed sophisticated sound detection and analysis systems to track submarines. These systems can easily determine the exact type of submarine by their unique engine and propeller sounds (acoustic signature). Therefore, acoustic missiles could be fine-tuned to attack unique jet engines. An anti-aircraft acoustic weapons system would allow acoustic missiles to be fired at suspected hostile aircraft before visual identification is confirmed. The acoustic missile would have the capability to ignore the jet engine noise produced by friendly aircraft, thus minimizing (if not eliminating) the problem of friendly-fire accidents. In fact, the current aeroacoustics understanding can allow for the addition of special spectral features to the friendly aircraft acoustic signatures to ensure elimination of friendly-fire. They would provide fighter aircraft with a new weapon and infantrymen with a simple shoulder-fired surface-to-air missile to complement proven heat-seeking missiles.

As mentioned earlier, acoustic sensors have already been tested for BAT air-to-surface munitions. The utilization of acoustic missiles to target the low rumble of tank or ship engines seems promising. Acoustic missiles can function at night or during poor weather, and jamming would prove very difficult. Acoustic sensing and tracking is very simple and inexpensive technology that is not affected by the "lock-on" problems of infrared, electromagnetic, and electro-optical technology. Acoustic missiles are capable of instantly "hearing" the sound waves left behind by aircraft at very long distances.

The slow travel of sound waves leads to the questioning of the potential of acoustic missile against fighter aircraft, which could maneuver quickly enough to escape acoustic missiles (assuming they see the missiles coming from behind). However, acoustic missiles could prove deadly against slow, high or low-flying aircraft. They could be aimed by radar, large sound detectors, or even by infantryman sight. The acoustic missile need only fly within its "hearing" range of the rear of the aircraft to detect an engine noise, and then pursue the sound. If the missile were tuned to the unique engine sounds of larger aircraft, it would ignore escort fighters diving by to distract the missile. A long-range cruise missile could use acoustic sensors to seek out large aircraft hundreds of miles away. Acoustic missile technology is not complex and could revolutionize warfare.

VII. Conclusion

Acoustic sensing technologies emerging on the modern battlefield provide a glimpse into their future usefulness as part of reconnaissance, surveillance, and target identification systems. A brief review of some of the uses of acoustic sensors both for past and present battlefield applications has been discussed. Ground-based, aerial, and naval battlefield applications have been outlined. A brief summary of the different processes involved in acoustic signal processing like rejection, detection, location, classification and cancellation has also been presented. A brief summary of the multi-microphone method is also discussed. Some of the advantages and disadvantages of acoustic sensors that should be taken into account in the design and fabrication of battlefield-application acoustic sensor systems have also been highlighted. A futuristic role to be played by acoustics on the twenty-first century battlefield has been presented.

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