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MODELING GROUND VEHICLE ACOUSTIC SIGNATURES
FOR
ANALYSIS AND SYNTHESIS

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ABSTRACT

Both security and weapon systems have used the wealth of information contained in acoustic sensor signals to reliably classify and identify moving ground vehicles. Developing robust signal processing algorithms that achieve these tasks is an expensive process, particularly in environments that include high levels of acoustic clutter or countermeasures that can generate false alarms. In this paper, the authors propose a parametric ground vehicle acoustic signature model to aid the system designer in understanding which signature features are important, developing corresponding feature extraction algorithms and generating low-cost, high-fidelity synthetic signatures for testing.

The authors have proposed computer-generated acoustic signatures of certain armored, tracked ground vehicles to deceive acoustic-sensored smart munitions. They have developed quantitative measures of how accurately a synthetic acoustic signature matches those produced by actual vehicles in order to document synthetic signature performance and to evaluate proposed improvements. This paper describes the parameters of the model used to generate these synthetic signatures and suggests methods for extracting these parameters from signatures of valid vehicle encounters. The model incorporates wide-bandwidth and narrow-bandwidth components that are modulated in a pseudo-random fashion to mimic the time dynamics of valid vehicle signatures. Narrow-bandwidth feature extraction techniques estimate frequency, amplitude and phase information contained in a single set of narrow frequency-band harmonics. Wide-bandwidth feature extraction techniques estimate parameters of a

correlated-noise-floor model. Finally, the authors propose a method of modeling the time dynamics of the harmonic amplitudes as a means adding necessary time-varying features to the narrow-bandwidth signal components.

The authors present results of applying this modeling technique to acoustic signatures recorded during encounters with one armored, tracked vehicle. Similar modeling techniques can be applied to security system applications in two areas: 1) understanding acoustic signature components that are important in particular applications and 2) developing low-cost, high fidelity acoustic signals for testing systems that avoid the cost of hiring high-value, ground vehicles for exhaustive testing.

INTRODUCTION

ACOUSTIC SENSORS ON THE BATTLEFIELD

There was a time when acoustic signal processing was used only on large submarines in the middle of vast oceans where the targets were few and their characteristic sounds were well understood. But technology marches on and ground-based acoustic systems are now beginning to achieve high performance in atmospheric media. These sensor systems are performing long-range target detection, non-cooperative identification friend or foe, target bearing tracking and range estimation, and fire control decisions. The processed acoustic information must be reliable and accurate enough to allow autonomous weapons to engage and attack enemy ground vehicles. The enemy, of course, is trying to do the same thing as their own acoustic sensor systems listen and wait for our

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vehicles to rumble along. Then, the cycle comes back to us. We employ active and passive noise control to quiet our vehicles and evade the enemy sensors. To perplex the enemy further, we deploy acoustic decoys that mimic the real force and draw down enemy resources. This creates an even more challenging environment in which our acoustic sensor systems must reliably recognize enemy vehicles, friendly vehicles, and friendly acoustic countermeasures.

ACOUSTIC SENSORS IN PHYSICAL SECURITY

An analogous situation may develop between a physical security force and its adversaries. Acoustic sensor systems can be used to detect intruders approaching in ground vehicles and other unauthorized vehicular activity. For success, these systems must detect the adversary with high probability while producing an acceptably low false alarm rate. The adversary wants to avoid detection until it is too late. To that end, he is likely to be as quiet as possible and may attempt to blend into the acoustic clutter of normal activities. He may create a diversion to drown out the sounds of his intended activity. Friendly security forces may even contribute to this acoustic clutter. The acoustic sensor system must be able to detect the intruder's activity in the presence of acoustic clutter and to discriminate it from friendly activity.

Fielding an acoustic sensor system that performs either the physical security or the military role requires realistic and thorough testing. Tests must provide high-fidelity acoustic

signatures that closely match real targets in real environments - so close that processing algorithms are unable to tell "is it real or is it Memorex?" Researchers must also understand acoustic phenomenology well enough to pose realistic acoustic countermeasures that sufficiently test their discriminatory capabilities. Synthetic acoustic signatures may help performing both these tasks, but these signatures must be free of extraneous features that reduce electronic sensor performance and in many cases must sound realistic to a human listener. A methodology for identifying, extracting, and generating the instantaneous and long term features of the acoustic signatures of real vehicles is a major step towards insuring that our security and military acoustic sensors are not deceived.

A MODEL FOR GROUND VEHICLE ACOUSTIC SIGNATURES

In order to use acoustic sensor information to detect, classify, or identify any source, the acoustic signature of that source must have a set of characteristics that is unique in the expected environment. The following discussion describes the chief characteristics of ground vehicle acoustic signatures at frequencies below 500 Hz. The features are divided into two classes: narrow-bandwidth and wide-bandwidth, referring to the range of frequency content attributed to the features.

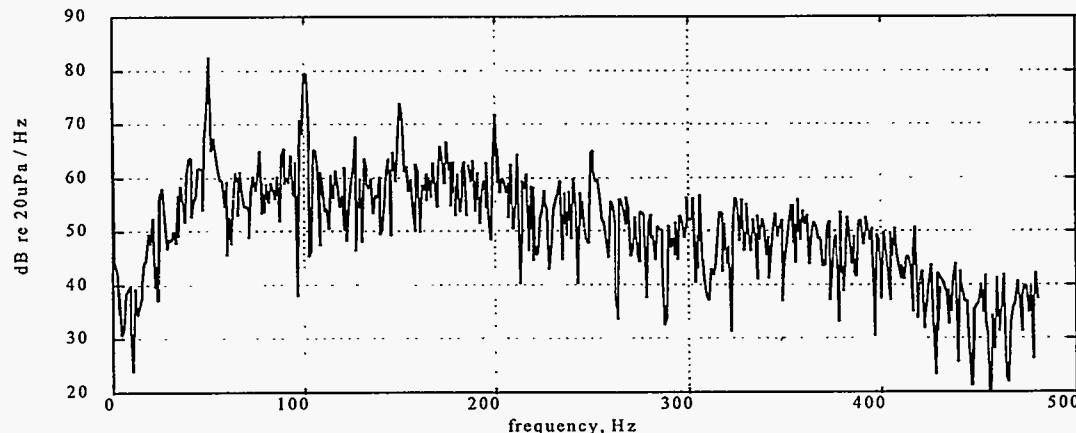


FIGURE 1. SPECTRUM OF TYPICAL GROUND VEHICLE ACOUSTIC SIGNATURE

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NARROW-BANDWIDTH FEATURES

Figure 1 shows the power spectral density of a typical ground vehicle acoustic signature measured by a microphone approximately one-half meter off the ground. Note the amplitude peaks at multiples of a fundamental frequency of approximately 50 Hz. Most ground vehicle signatures contain one or two sets of these *quasi-periodic* signal components. Each of these sets contain energy concentrated at frequencies that are multiples of a single fundamental frequency. Common sources for these harmonic sets in armored military vehicles are engine firing and exhaust and drive train or track noise. The term *quasi-periodic* refers to the fact that the fundamental is continually changing. The amplitude of each harmonic relative to another within the set as well as the phase of each harmonic with respect to each other form two classes of narrow-bandwidth features.

The phase of each harmonic is typically very difficult to track without a precise fundamental frequency reference, so, practically speaking, this class of information is not available to systems that do not have this reference. However, if a synthetic acoustic signature has a fundamental frequency that is constant over several seconds, signal processing algorithms can "lock-on" to this fundamental and reveal that the relative phases among harmonics are also static, and hence, not typical of a real vehicle. So, the authors recommend either a pseudo-randomly varying fundamental or one that varies with platform speed in real-time.

On the other hand, the set of amplitudes of each harmonic relative to each of the others provides the most reliable features for vehicle identification. These harmonic amplitudes typically exhibit dynamic behavior and often change as the aspect from vehicle to sensor changes. It is important that a signature model include some mechanism for introducing dynamics to the amplitudes because one cannot

rely on atmospheric propagation and ground reflections to produce these in the field.

WIDE-BANDWIDTH FEATURES

Note in figure 1 that a noise floor exists between the harmonic peaks with an amplitude that varies from 0 to 25 dB below that of the nearest harmonic peak. The spectral shape of this wide-bandwidth energy over several hundred Hz and the separation of each harmonic peak above the noise floor are features that may be useful either to classify or to identify a vehicle signature. Often, the shape of this noise floor changes as the harmonic peaks move in frequency, so the authors have used an adaptive filter to shape white noise in a dynamic fashion.

ACOUSTIC SIGNATURE MODEL

Figure 2 summarizes the above discussion of salient features contained in ground vehicle acoustic signatures in functional block diagram form. Note that the narrow-bandwidth and wide-bandwidth features are generated separately and then summed. The narrow-bandwidth components are sinusoidal components whose relative phases are fixed, but whose amplitudes are each modulated by an independent, filtered, zero-mean noise source summed with a desired mean. The decoy platform speed is used to update both the fundamental frequency of the harmonic set and the noise floor spectral shaping. Note that the figure only shows the amplitude modulation for a single harmonic oscillator, but that all oscillators are modulated prior to summing at the output node.

Figure 3 illustrates the results of applying the model to the signature in Figure 1. It is the power spectral density measured by the same microphone but of a synthetic signature projected from a decoy platform. Note that the amplitude of the second harmonic (two times the fundamental) is lacking, but that overall, agreement is quite good.

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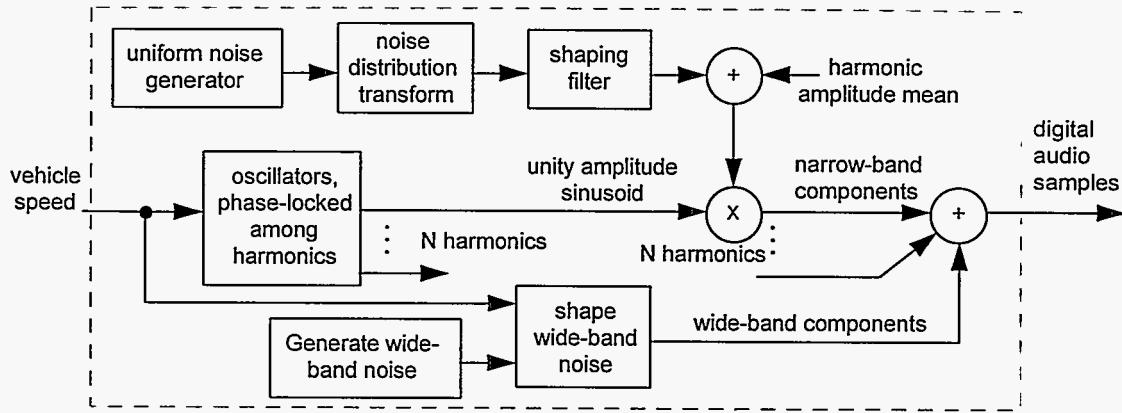


FIGURE 2. BLOCK DIAGRAM OF SIGNATURE MODEL

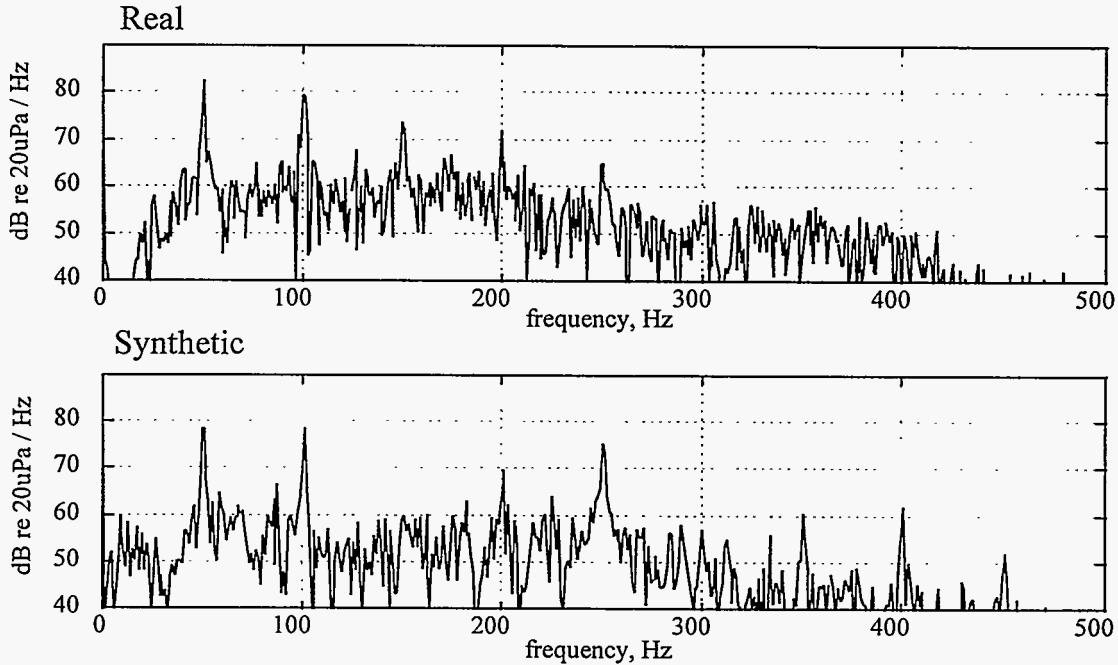


FIGURE 3. COMPARISON OF SYNTHETIC TO REAL

HARDWARE IMPLEMENTATION OF THE SIGNATURE MODEL

Producing a propagating acoustic disturbance in the atmosphere from the mathematical model requires three steps. First, a digital computer must be programmed to produce the desired waveforms in digital form. Second, the digital signal is converted to an electronic analog signal. Finally, the analog electronic signal is amplified and used to drive a transducer that produces the acoustic disturbance.

One may employ any of a variety of hardware platforms to perform the first two steps. Only two components are necessary: 1) A microprocessor to generate samples of the desired waveform and 2) hardware to convert the digital signal to analog. The authors began their work using a two-channel sound card hosted in a personal computer (PC) and have recently moved to a standalone card with a TMS320C31 digital signal processor (DSP) and four analog channels. The PC system excels at playing back digital microphone recordings and computer-generated synthetic signatures stored on the hard disk. The

DSP system is designed for generating signatures in real-time that match the platform speed in real-time.

The authors use high-power audio amplifiers driving an array of eight loudspeaker enclosures to achieve the desired sound pressure levels. The entire acoustic system is mounted on a standard rack to allow easy interchange among host vehicles. Figure 4 illustrates one version of their platform.

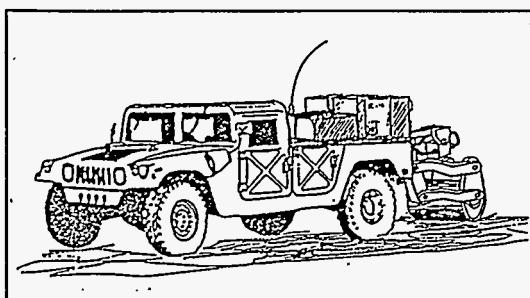


FIGURE 4. ACOUSTIC DECOY

INTEGRATING ACOUSTIC SIGNAL PROCESSING IN PHYSICAL PROTECTION

In a smart weapon, acoustic signal processing may perform some or all of the following processes: vehicle detection, bearing tracking, classification or identification, warhead cueing. At the beginning of an encounter, the

weapon performs rather crude, low-energy signal processing on received acoustic and seismic signals until it detects the presence of a vehicle. Then, using processing that requires much higher power, the weapon tracks the bearing and estimates the range of the approaching vehicle. It may also estimate the vehicle class (e.g. heavy vs. light) or even the vehicle type (e.g. main battle tank vs. armored personnel carrier). Finally, if the weapon has identified the vehicle as a valid target both by class and by predicted route (that it will enter the range of the weapon's warhead), the warhead delivery system is activated in the proper way.

These same four processes can be integrated into a physical security system in which detecting vehicles with unique acoustic signatures is important. For portable sensor stations, the same low-power detection processing greatly extends the battery life. As the target bearing and range become apparent, the system would alarm for both assessment and response in systems without other assessment sensors. Vehicle classification or identification could perform some level of automated assessment to reduce the false alarm rate. Finally, if the security system uses other assessment equipment (e.g. video cameras), the acoustic sensors would cue the assessment equipment in fashion similar to activating the warhead delivery system. Figure 5 illustrates these concepts as functional blocks.

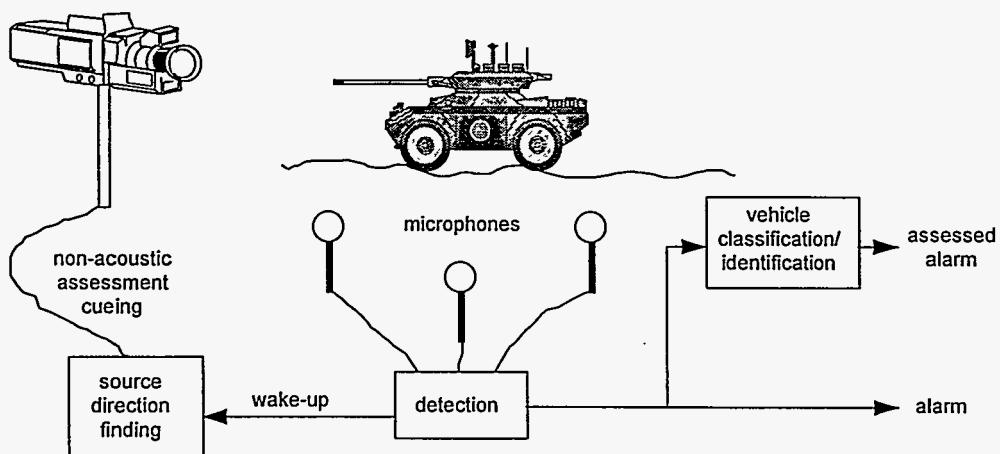


FIGURE 5. INTEGRATING VEHICLE ACOUSTICS IN PHYSICAL PROTECTION

ACOUSTICS IN PHYSICAL SECURITY: A VIGNETTE

The high fidelity synthetic acoustic signature model is a cornerstone in the development of robust acoustic sensor systems. The model aids understanding which acoustic signatures components are most important to particular sensor applications and can provide cost effective ways to test these sensor applications with challenging signatures.

In a particular application, an acoustic sensor system is faced with dynamic acoustic clutter created by the entrance and exit of friendly vehicles through a controlled area and the possibility of disguised hostile intrusion. For example, consider a perimeter security system on a high value industrial site. The site is not a typical military site, so it has many paved access roads and a limited security force to assess and respond to alarms around a long perimeter. An acoustic sensor system has been deployed to enhance this response force. This system must constantly evaluate the acoustic environment and decide whether any noises warrant an alarm. Only sounds associated with adversarial activity to a high degree of confidence should create alarms. False alarms can not be tolerated as they present an additional burden to an already stressed security system. The acoustic sensor system must know the sounds of normal activity. Regular traffic patterns, the sounds of common vehicles, and normal background noise should not cause alarms. However, unusual or unknown vehicles, those associated with aggressive activity, and even common vehicles close to the perimeter should be assessed. The sensor system must have knowledge of these acoustic features and trends to perform its mission. A tolerance is imposed on variations of non-hostile paths to account for wind, atmospheric refraction, and variations in benign vehicle motion. When a substantial difference in bearing and range is found and the trend of this track is consistent with an unauthorized approach, more scrutiny is needed. Frequency content of the acoustic signature of a potential intruder might identify it as friendly. If a detailed examination of the acoustic signature reveals that the approaching vehicle is not from any friendly vehicles typically found in the area, the acoustic sensor system should alarm. The sensor system has used a detailed understanding of the acoustic

environment and of features of local sound sources to reduce the false alarm rate to an acceptably low level.

Testing scenarios like this one could be time consuming and expensive. For example, consider a remote site that is threatened by a variety of vehicles. Heavy construction equipment or even farm equipment might be used to defeat physical barriers. The possible variations of vehicles, approaches, and background activity might be too numerous to test with actual vehicles. These types of events could be simulated with acoustic decoys: programmable systems capable of reproducing the real sounds, but without the overhead acquiring the variety of possible vehicles for testing. The features of the local acoustic environment have been identified and extracted in the course of developing the sensor system. The models include signature qualities important to identification. The final step is then taken to reproduce these sounds from high fidelity mobile acoustic sources. If these decoys have transducer hardware able to produce the amplitude and frequency band of the real noises, they will prove indistinguishable from the real vehicles - at least to the limits of the acoustic sensor processing.

The synthetic acoustic signature model has performed a function like the one described above for a defense program. A detailed analysis of real vehicle sounds has revealed the critical features of the acoustic signature. The features are used in a acoustic decoy system to perform a deception mission against a surrogate threat. The same feature extraction methodology has been successfully used to identify differences between the real signature and that of the decoy. Application of the feature extraction methodology has not only improved the signature performance of the decoy, but also will contribute to the robustness of the threat acoustic sensor system.

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