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Cueing of the Surrogate Remote Sentry Using an Acoustic Detection System

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The Surrogate Remote Sentry (SRS) system is an Advanced Technology Demonstration (ATD) for the Rapid Force Projection Initiative (RFPI). The device consists of a remotely controlled surveillance system used to monitor approaching enemy vehicles on the battlefield for perimeter defense applications. The surveillance system is made up of a compact integrated multisensor system capable of being implanted behind enemy lines to provide day or night unmanned surveillance and targeting information.

The Acoustic Detection System (ADS), designed at the Army Research Laboratory (ARL), has been integrated with the SRS. The ADS is a wide-field-of-view (WFOV) sensor system that uses an array of microphones and a simple processor to detect, track, and classify targets in the battlefield. When a target is detected, the ADS generates lines of bearing (LOBs) to the target relative to the position of the microphone array. When the ADS is integrated with the SRS, the LOBs can cue the narrow-field-of-view (NFOV) SRS sensors toward approaching targets as they come within the detection range of the acoustic sensor. The ADS integrated with the SRS has been successfully demonstrated at the Early Version Demo (EVD) in September 1994.

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1. Introduction

The Surrogate Remote Sentry (SRS) system being developed by the Night Vision and Electronic Sensors Directorate (NVESD) of the Communications–Electronics Command (CECOM) is an Advanced Technology Demonstration (ATD) for the Rapid Force Projection Initiative (RFPI). The system is a remotely controlled surveillance system, designed to be implanted behind enemy lines. The SRS is used to monitor and provide targeting information on approaching enemy vehicles on the battlefield for perimeter defense applications. It consists of integrated, compact, electro-optic sensor modules, including one day camera, one night camera, and a laser rangefinder, all mounted on a remotely controlled pan and tilt motor. Using the SRS, a remote operator can track and determine the range of targets as they approach the sensor. Because of the narrow field of view (NFOV) of both cameras on the SRS, monitoring a large area for approaching targets becomes a difficult task. An omnidirectional sensor is therefore required to cue the SRS to the direction of approaching targets in the battlefield.

At the request of NVESD, the Army Research Laboratory (ARL) integrated the Acoustic Detection System (ADS) with the SRS. The ADS is an omnidirectional acoustic sensor system that uses a circular array of microphones and a simple processor to detect, track, and classify targets in the battlefield. When targets are detected, the ADS determines lines of bearing (LOBs) to the targets relative to the position of the microphone array. When integrated with the SRS, the ADS can cue the SRS to approaching targets as they come within the detection range of the acoustic sensor.

2. ADS Description

Acoustic technology has attracted considerable interest in recent years because of its many advantages. Acoustic sensors are passive, have non-line-of-sight (NLOS) detection capability, and can localize and identify targets at long ranges.

The ADS was developed at ARL for the long-range detection of ground and air vehicles in a typical battlefield environment. The ADS consists of an array of microphones connected to a signal processing box that determines the LOB's frequency, signal-to-noise ratio, and classification of detected targets. The sensor array consists of several sensors positioned in a specific geometric configuration to maximize beamforming capabilities.

2.1 Acoustic Array Microphone Geometry and Hardware

The acoustic array is composed of eight ceramic microphones connected to an electronic box that contains signal conditioning amplifiers. A gain of 40 or 60 dB is provided to boost the signal levels so as to produce maximum voltage at a sound pressure level (SPL) of 120 dB.

The array is configured with seven microphones, six arranged in an 8-ft-diameter circle, and one in the center. The microphones are provided with 6-in.-diameter windscreens to reduce the effects of wind noise and are mounted on aluminum spikes that hold them vertically to the ground. The acoustic array can be configured in a variety of ways, depending on the mission. The beamformer (BF) software that resides in the processor unit can be reprogrammed to process LOB information based on a chosen array geometry. The acoustic system estimates target bearing using a frequency-domain BF to provide a degree of directional noise rejection and allow high-resolution estimation of the direction of arrival of the various signals.

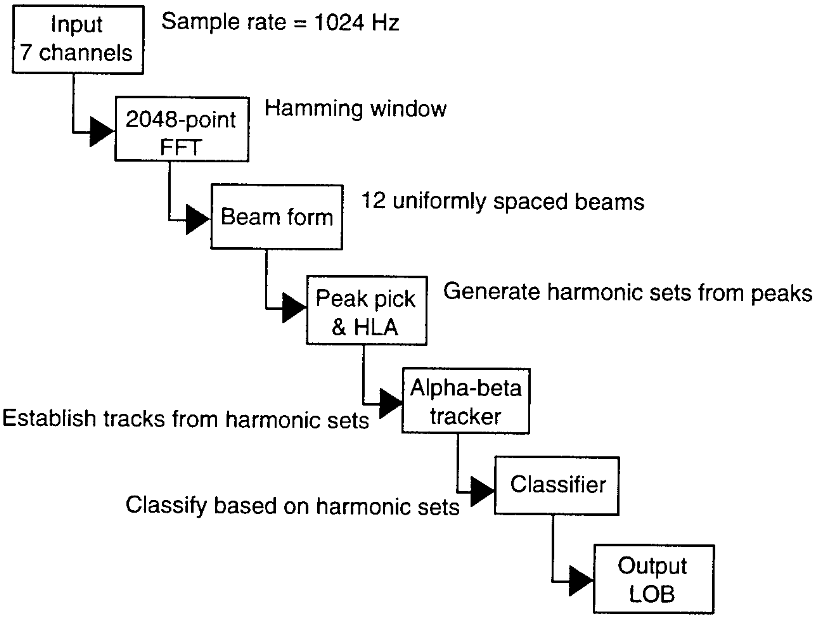
2.2 Array Processor Box Architecture

The ADS is designed to detect, localize, and identify both air and ground combat vehicles. Narrow-band spectral analysis exploits the periodic nature of vehicular noise sources available in a typical battlefield environment (fig. 1). Subsequent operations process the spectral information to detect the sources of noise. A tracking function exploits the time continuity of the process to refine localization estimates and derive direction of travel and speed. Target bearing information is then used to cue the optical system. The following is a step-by-step explanation of how acoustic signals are processed.

2.2.1 *Data Input, Signal Conditioning, and Digitization*

The analog outputs from the microphones are filtered with a four-pole Butterworth low-pass filter with a cutoff of 300 Hz. This provides the anti-aliasing protection that needs to be carried out before digitization. The analog signals are converted to 16-bit digital words at a rate of 1024 samples per second. All seven channels are sampled simultaneously. The processor consists mainly of a hardened personal computer. The signal

Figure 1. Remote sensor algorithm overview.



processing operations are carried out on an MM96 Ariel board, which consists of two digital signal processing (DSP) units, each with a potential processing capacity of 50 megaflops. Processed data are in turn sent out through an RS232 interface to the stepper motor.

2.2.2 *Spectral Analysis*

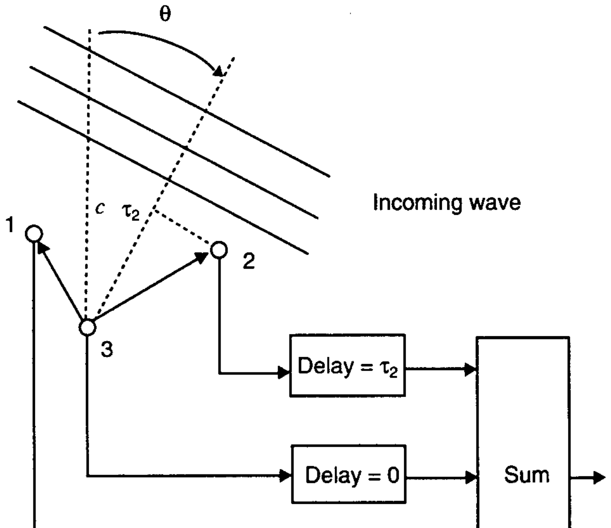
Each channel of digital data is converted to the frequency domain by the application of a fast Fourier transform (FFT) that uses a 2048-point data frame (2 s) and a Hamming window. These frames are overlapped by 50 percent, so that the effective output rate of spectral data is 1 Hz. Although processing resources are available to compute longer FFTs, improved spectral resolution does not result in improved target detection because the targets are not stationary.

2.2.3 *Beamformer*

The acoustic system estimates target bearing using a frequency-domain beamforming algorithm to provide a degree of directional noise rejection and allow high-resolution estimation of the direction of arrival of the various signals. Twelve beams are formed simultaneously. Data from the microphones are processed through a delay-sum BF. The delay-sum BF (fig. 2) is a method where each signal is delayed by an amount that will bring the signals from all channels into coincidence.

The beamforming implementation assumes that the microphones were placed in the desired array geometry and that all microphones have identical gain and phase characteristics. When these conditions are not achieved, errors occur in the pointing direction of the beam, which in turn result in bearing estimation errors. Three types of errors can occur: array misalignment, microphone displacements, and variations in microphone gain and phase characteristics.

Figure 2. Conventional delay sum beamforming.



Array misalignments can be minimized if the array is carefully laid out in a presurveyed position where true north has been clearly determined. In situations where true north cannot be accurately surveyed, the array is pointed to magnetic north, which may be subject to large deviations. The effect of a misalignment error can be corrected for by the addition of the number of degree deviations to the measured bearing.

Misplacement errors occur when the microphone positions do not correspond to the intended locations. This type of error can be minimized by the use of a rigid microphone array template. An error of 1° can arise from the misplacement of one of the microphone arrays by 6 in.

Microphone errors can also cause deviations. The beamforming equation assumes that all microphones have identical phase and gain characteristics. The inexpensive microphones used in the ADS are subject to variations in phase and gain that are pronounced below 100 Hz, precisely in the band of frequencies where most of the targets of interest are. Phase errors can be serious for small arrays. In an actual array, each microphone will have random phase and gain errors. Phase calibration is then performed to minimize bearing errors.

2.2.4 *Peak Picking and Harmonic Line Association*

The output of the BF is directed to a peak picking function that identifies the presence of narrow-band spectral lines in each of the BF channels. The algorithm carries out the peak picking operation by finding local maxima in the spectra and comparing those maxima to the median level of the spectral lines in a symmetric band around them. If the potential peak exceeds the local noise level by a threshold value, the peak is detected.

The detected peaks and their frequencies are sorted by the harmonic line association (HLA) function into families of harmonically related narrowband lines, which form a harmonic set. The presence of a harmonic set indicates the presence of a target, since most propulsion systems emit periodic sounds.

For each detected peak, a fine-resolution bearing is computed. Each spectral peak will have a maximum level in a certain main beam, with lower levels in the adjacent beams. These peaks are input to a quadratic interpolator that computes the bearing at which the peak amplitude occurs. Although the spatial resolution of each beam is limited by the available signal-to-noise ratio (SNR) at the output of the BF, the algorithm provides fairly good results for most targets of interest.

2.2.5 *Tracking and Data Association*

Target reports containing bearing information are produced every second by the sensor algorithm. The data are partitioned into sets of observations or tracks produced by the same source. An observation is referred to a measured quantity like position (bearing), velocity, and time estimate, included in an output detection of a sensor array. Once tracks are formed (so that background and false reports are reduced), target information can be estimated, such as velocity and future predicted bearing. Filtering and prediction methods are used to estimate present and future target kinematic quantities, such as position and velocity. An alpha-beta tracking filter is implemented to reduce the number of false reports and provide an association of incoming data with existing tracks. The alpha-beta filter is a fading memory type that uses fixed tracking coefficients. Data received from previous scans are included in the present estimate. These data tracks are associated to determine the target direction and bearing rate of change. Report association takes into consideration many points of data (from multiple targets), with their inherent measurement errors and ambiguities.

The alpha-beta filter has an advantage over other adaptive filters because of its simple implementation. The smoothed (filtered) position at scan k is defined by

$$x_s(k) = x_p(k) + \alpha\left[x_0(k) - x_p(k)\right] \ , \tag{1}$$

where $x_0(k)$ is the observation received at scan k, and α and β are the fixed coefficient filter parameters. The velocity, which equals the rate of change of position at scan k, is defined as

$$v_s(k) = \dot{x}_s(k) = v_s(k-1) + \frac{\beta}{qT}\left[x_0(k) - x_p(k)\right] \ , \tag{2}$$

where T is equal to the sampling interval. The quantity q is normally defined to be unity, but when no observations are present, its value defaults to the number of scans since the last measurement. The future predicted position is defined as

$$x_p(k+1) = x_s(k) + Tv_s(k) \ . \tag{3}$$

The initialization process is defined as

$$x_s(1) = x_p(2) = x_0(1) \ , \tag{4}$$

$$v_s(1) = 0 \ , \tag{5}$$

$$v_s(2) = \frac{x_0(2) - x_0(1)}{T} \ . \tag{6}$$

Equation (1) is used directly when an observation is received at scan k. When the probability of detection is low, the observation does not report a line of bearing. Then the smoothed position is set equal to the prediction, $x_s(k) = x_p(k)$, and $v_s(k)$ is unchanged. This amounts to setting $x_0(k) = x_p(k)$. The prediction $x_p(k+1)$ is computed next.

Several criteria have been used in estimating the filter fixed coefficients. The ADS algorithm uses a value of 0.9 for α and a value of 0.25 for β. Although there are other strategies for picking the values for α and β, the ones used in the ADS are based on experience from trials performed in previous field experiments.

2.2.6 *Target Identification*

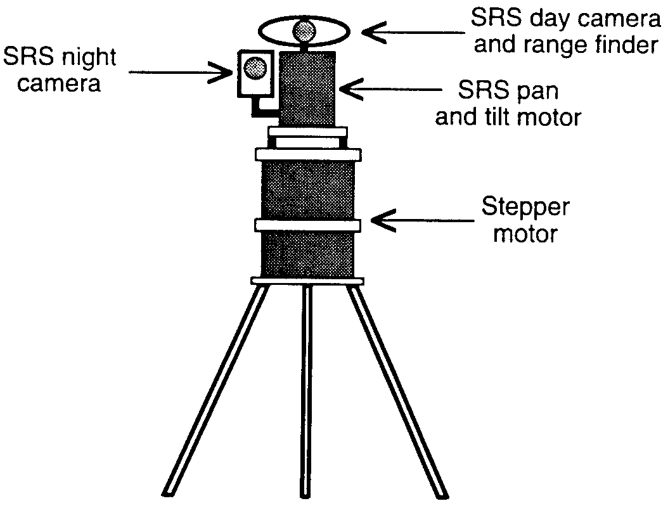
The selection of appropriate target-signature features is critically important in the effectiveness of target ID algorithms. For robust target identification, invariant features and interfeature correlations must be determined. The training data set selected must have a large enough feature set so that different targets can be uniquely separated in feature space, both from other targets and from the multitude of background conditions and noise. Detection of ground targets and identification from their acoustic emissions are particularly difficult, since normal operating conditions provide many features that are anything but invariant. Normal but time-varying features of ground vehicles are due to variations in driver operation, terrain topology, and ground composition. All contribute to the nonstationary nature of the acoustic power spectrum of the target. Target aspect, signal propagation, and multipath effects are additional factors, which may or may not be time dependent, but which can contribute to power spectrum variability. Two techniques are currently used to identify targets: maximum likelihood classifier and neural network processing. The latter approach currently provides more robust performance, together with higher probability of correct identification.

3. System Operation

In the fully integrated system, the ADS cues the SRS to the direction of approaching targets through a stepper motor. The pan and tilt platform of the SRS is mounted on top of the stepper motor, which is controlled by the ADS (fig. 3).

During operation, the SRS operator monitors images received through the two cameras. The ADS continuously monitors the surrounding environment for harmonically related sounds in the "window of interest" (an adjustable scan area that will be monitored for approaching enemy targets; the ADS is thus prevented from tracking in areas where friendly targets are positioned). When the ADS detects a potential target, it cues the SRS to

Figure 3. SRS mounted on step motor.



point the cameras in the direction of the detected target. The SRS operator then verifies it as a valid target through the camera images and assumes control of the target tracking with the pan and tilt motor of the SRS. The pan and tilt motor allows the operator to optically track the target and find its range with the laser rangefinder. The operator then re-engages the ADS control of the stepper motor to track other targets.

In a multiple-target situation, the ADS is designed to track and cue the SRS to the strongest acoustic signal within the window of interest.

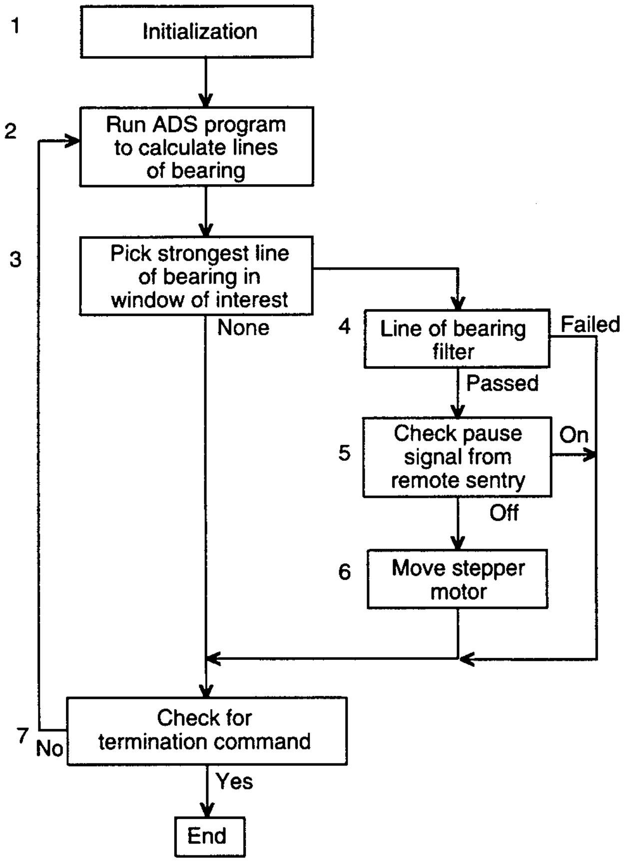
3.1 Software Integration

The integration of the ADS with the SRS required additions to the current ADS software for control of the stepper motor and communications with the SRS. Figure 4 diagrams the software flow of the modified ADS software.

A detailed description of the ADS software follows:

1. The ADS and stepper motor software algorithms are initialized.
2. The ADS program is executed until the LOBs are calculated. A minimum of zero and a maximum of eight LOBs are calculated, with the lines numbered from 0 to 7 according to signal strength (0 for the LOB with the strongest signal strength).

Figure 4. SRS software flow diagram.



3. The strongest LOB in the window of interest is picked out. In some instances, there may be no LOBs in the window of interest, in which case the ADS program will bypass all modifications and continue to step 7.
4. The program passes the chosen LOB through a filter to eliminate false reports and provide a smooth continuous track. The filter compares the current LOB with the previous 10. If three of the previous 10 are within ±10° of the current LOB, the current LOB becomes the new position to cue the stepper motor. All the filter constants can be changed before the start of the program. For this configuration, the filter length is 10, the match number is 3, and the filter error is 15. If the current LOB does not meet the filter requirements, the program will again bypass the remaining modifications and continue to acquire new targets.
5. If the LOB passes the filter requirements, the control line to enable the motor is checked next. The control line is a simple high or low signal coming from the SRS and fed into a data line on the parallel port of the ADS computer. If the line is high, the ADS program will again bypass the remaining modifications and continue to step 7.
6. If the motor enable control line is low, the ADS will move the stepper motor to the new LOB and transmit the LOB in ASCII through the serial port of the ADS computer. The SRS reads the LOB information from the serial port and transmits it back to the remote operator controlling the SRS.
7. The ADS checks for program termination resulting from operator command or program error. If no termination is required, the ADS program continues back at step 2 to acquire new LOBs.

The communications routines that are used to transmit the LOB over the serial port and read the motor enable control line over the parallel port are simple port interrupt and port polling routines, respectively, and have no effect on the system performance of the ADS. The motor control routine, on the other hand, directly affects system performance by changing the LOB update rate. The modified ADS will not update the LOB until the stepper motor has come to a complete stop after being cued. The maximum amount of time required for updating the LOB therefore becomes the time needed for the stepper motor to move a full 180°.

3.2 Hardware Integration

The only hardware connections needed between the SRS and the ADS are the lines used to enable the motor and transmit the LOB information between the two. The enable signal is transmitted from a simple plug connection from the SRS to the parallel port on the ADS computer. The LOB information is transmitted from the RS232 serial port on the ADS computer to an RS232 serial port on the SRS. The serial information is transmitted with a format of 9600 baud, 8 data bits, 1 stop bit, and no parity.

4. Conclusion

A recent field experiment tested the cueing of the SRS with the ADS to identify and correct problems. In September 1994, the system was included in the Early Version Demonstration (EVD) for RFPI. The ADS detected a single tank and, in following runs, a column of tanks, and properly cued the SRS to the correct bearing of the detected targets. The EVD was one month long, and the ADS was operated throughout by some Army scouts. The complete SRS was termed successful. This exercise provided the SRS with the capability for autonomous, remote, wide-area surveillance and target acquisition. The complete system will increase the scout's survivability through the battlefield, extend his range and area of surveillance, and provide the capability to remotely and optically monitor detected targets based on the performance of the acoustic sensors.

5. Recommendations

During the progress of this project, a few improvements were identified that will greatly enhance the performance of the SRS:

1. Improve LOB accuracy by the use of a more sophisticated beamforming algorithm.
2. Cue the SRS based on the identification provided by the acoustic sensor system and not on the strongest spectral peaks. In a multitarget environment, some detected vehicles are more lethal than others. A ranked list of identified targets will enhance the capability of the system and help cue the SRS to the more lethal target.
3. Use a more sophisticated filter scheme to eliminate false alarms. A Kalman filter would greatly enhance the reduction of false LOBs.
4. Use a network of acoustic sensors to enhance the area of surveillance and to allow the target's location to be determined by triangulation of multiple LOBs.

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