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# Comparative Analysis of LMS, NLMS, and RLS Adaptive Filters in Vehicle Automation Systems Under Mixed Noise Conditions

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## A B S T R A C T

In modern vehicle automatic systems, noise interference presents a significant obstacle to the precision and dependability of sensor-based control and communication. This study offers a comparative performance evaluation of three adaptive filtering algorithms Least Mean Squares (LMS), Normalized LMS (NLMS), and Recursive Least Squares (RLS), to utilized for adaptive noise cancellation (ANC) under mixed noise conditions. A MATLAB-based graphical user interface (GUI) simulation was created to estimate and illustrate the performance of each method across three noise types: Gaussian, Impulsive and Mixed. The results informed that RLS attained the greatest signal to noise ratio (SNR) enhancement (15.6 dB) and with the minimal mean square error (MSE), whereas the NLMS offered a proficient equilibrium between velocity and computing complexity. This research evaluation that appropriateness of NLMS in real time vehicular control applications and RLS requiring high accuracy.

## 1. Introduction

Modern automation systems depend on processing to guarantee safety and precise signal capture, In fact, enhancement in applications like autonomous driving, engine management, and adaptive cruise control all these systems have complex situations where as sensor signals are often expected by noise who is come from electromagnetic interference environmental disturbances, and mechanical vibrations. This deterioration negatively impacts the accuracy of vehicle automation systems control and decision-making processes. Consequently, effective noise reduction measures are important for efficiency of vehicle automation systems. Adaptive Noise Cancellation (ANC) is known to be reducing undesirable noise by modifying filter settings according to the input signal's characteristics by an efficient method . In contrast to fixed digital filters, adaptive filters adjust their coefficients in real time system to decrease the bit error rate between a reference signal via desired signal. The frequent algorithms are used the Least Mean Squares (LMS), Normalized LMS (NLMS), and Recursive Least Squares (RLS) for ANC each one of these are presenting unique performance regarding convergence rate and computational complexity. The noncoherent, narrowband for Direction of Arrival is moving objects in Gaussian noise is estimated by using the the Estimation of Signal Parameters via Rotational Invariant Techniques (ESPRIT) algorithm method in this study [1], and the accuracy of Direction of Arrival tracking is purposing by using the LMS, NLMS, and RLS algorithms In [2], the effectiveness of these algorithms as LMS, NLMS, RLS, QR decomposition based recursive least squares algorithm (QRD-RLS), and inverse QR decomposition based recursive least squares algorithm (IQRD-RLS) adaptive filters for noise cancellation in public radio transmissions is examined. IN [3] proposed historical and research on adaptive filter algorithms, including all main three type of Adaptive Noise Cancellation which is LMS and RLS, which effect on efficiency of noise cancellation and enhancements of algorithmic for expedited convergence and reduced computing complexity. This paper compares RLS, LMS,and NLMS, adaptive algorithms for the elimination of power line interference from ,he electro encephalo graphy (EEG) signal confirm that RLS offers best noise cancellation and enhanced signal dependability for Brain Computer Interface applications [4]. In [5], they worked in multichannel acoustic for acoustic echo suppression (AES) and acoustic echo cancellation (AEC), which that Fast Affine Projection in adaptive filters offer a good exchange between convergence, tracking ability, and calculation of cost compared to time domain and frequency-domain for all three types of ANC like LMS, NLMS, and RLS filters. In [6] define and compare among LMS, NLMS, and RLS adaptive algorithms for noise decreasing in wireless communication, proposed that RLS attains faster convergence than LMS and NLMS using Verilog simulations and MATLAB . In [7] they researched a comparative analysis of main type of ANC as LMS, NLMS, RLS, and SMI adaptive beamforming algorithms, including hybrid filter combinations, evaluating their convergence speed, maximum side-lobe stage, and null depth for linear antenna arrays of equal sizes. In [8], LMS, NLMS, NLMF, and RLS adaptive filters are proposed for system identification and noise cancellation, however, their result based on main square error (MSE) ,Peak Signal to Noise Ratio (PSNR), complexity of the system , and accuracy. In paper [9], the effectivity of ANC in three type as LMS, NLMS, and RLS adaptive filters isproposed for the attenuation of different ambient noise in speech signals, illustrating the improvement of the SNR ratio by ANC in noisy paradigm. Introduces a low power, action area and power reduction for efficient very large scale integrated (VLSI) signal processing applications, in [10]. proposed that enhanced of four adaptive filters for reduction of speech noise from electric and non-electric vehicles, apply in Lab-view-based experiments and finding the performance through enhancements in global SNR ratio which called (GSNR)[11].

System identification [12] of definition system is connected by applying all three type LMS, NLMS, and RLS adaptive filters, which repetitive adjust their weights to reduced of error and synchronize the output with the signal, with first LMS start using the least complicated, NLMS normalized, and RLS which is best efficient. the researcher was analyzed and studied to calculate the efficacy of conventional by using median filters against advanced weighted median filters and the requirement for increased noise reduction algorithm in high noise environment [13].

Prior paper on medical image in [14] denoising underscored the necessary of decreasing radiation exposure using efficient noise reduction method, and hybrid filtering methodological analysis studied to keep diagnostic integrity while decrease image distortion.

Not with standing significant advancements, the main of this paper is paradigm on individual noise categories, like Gaussian noise or impulsive noise interference. actually, type of noise considers as a combination of many components of noise such as Gaussian, impulsive, sinusoidal, and burst noise explanation this noise more complex. In fact, A significant investigate need continue in evaluated adaptive algorithms in mixed noise situations, especially with in automotive systems.

This study establishes a MATLAB-based simulation framework with a graphical user interface to conduct a comparative performance analysis of the LMS, NLMS, and RLS adaptive algorithms for vehicle automation systems. The system facilitates testing in six distinct noise environments Gaussian, Uniform, Impulsive, Sinusoidal, Burst, and Mixed and assesses algorithmic performance using three principal metrics: SNR enhancement, MSE. This comparative analysis seeks to determine the optimal adaptive filtering technique for improving signal clarity and reliability in contemporary car automation systems.

## 2. Methodology

The adaptive noise cancellation (ANC) framework was developed to compare the Efficiency of the Least Mean Squares , Normalized Least Mean Squares , and Recursive Least Squares algorithms against three noise categories which refer to Gaussian, Impulsive, and Mixed noise. The system model of the proposed research , depicted in Fig. 1, comprises by a primary input with a desired signal while add by different noise, an adaptive filter and that Iterative proces using to evaluate mean sqaure error with filter factor to decrease noise interference.

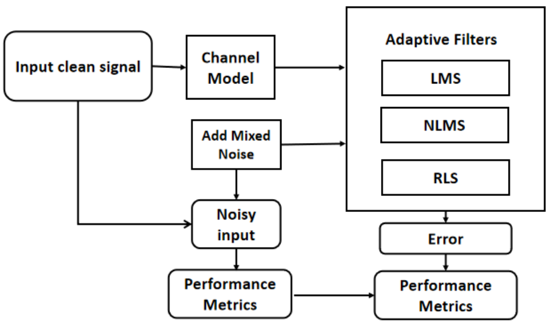



**Fig. 1.** System model of the proposed adaptive noise cancellation framework.

A pristine reference signal s(n) was synthetically produced as a composite of two sinusoidal components with frequencies of 50 Hz and 120 Hz, described in Eq. (1), depicted in Fig. 2.

$$s(n) = \sin(2\pi f_1 n T_s) + 0.5 \sin(2\pi f_2 n T_s) \quad (1)$$

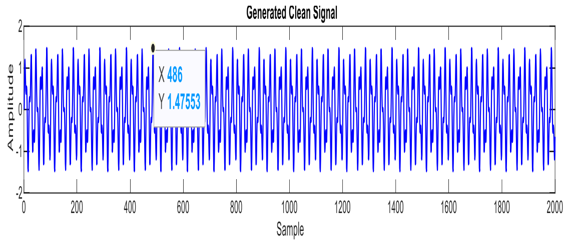



**Fig. 2.** The waveform of the original clean signal.

Where sampling period denotes by clean signal s(n) the samples of N= is equal to 2000 were used in each simulation. The input noisy signal $x(n)$ in channel was generated by superimposing a chosen noise type onto the clean signal represented in Eq. (2)

$$x(n) = s(n) + v(n) \quad (2)$$

In this context, v(n) denotes the supplementary noise component, whereas the input SNR was consistently maintained at 5 dB across all scenarios. Gaussian noise was characterized as zero-mean, regularly distributed random noise; impulsive noise was defined as intermittent high-amplitude spikes; and mixed noise was represented as a synthesis of Gaussian and impulsive interference to simulate intricate real-world scenarios, particularly those seen in vehicle situations. The adaptive filtering phase sought to reduce the instantaneous discrepancy between the desired signal $s(n)$ and the predicted output $y(n)$. The error signal e(n), which is used for weight adaptation represented Eq (3).

$$e(n) = s(n) - y(n) \quad (3)$$

The LMS algorithm utilized a constant step size μ to adjust weights according to the Eq. (4). in fact, the filter weights were adjusted alliterative depending on the chosen adaptation algorithm. $w(n)$ represent the filter coefficient at iteration $n$ and $\mu$ is step size.

$$w(n+1) = w(n) + \mu\, e(n) x(n) \quad (4)$$

The entrancement in NLMS method occurrence stability by normalizing the step size based on the input signal power, expressed in Eq. (5).

$$w(n+1) = w(n) + \frac{\mu}{\|x(n)\|^2 + \epsilon} e(n) x(n) \quad (5)$$

where $\epsilon$ is the prevents division by zero.
The enhanced accuracy by iteratively reducing the exponentially weighted least squares error done by RLS method denoted by Eqs. (6), (7) and (8).

$$w(n) = w(n-1) + k(n) e(n) \quad (6)$$

$$k(n) = \frac{P(n\text{-}1)x(n)}{\lambda + x^T(n)P(n\text{-}1)x(n)} \quad (7)$$

$$P(n) = \frac{1}{\lambda}[P(n\text{-}1)\text{-}k(n)x^T(n)P(n\text{-}1)] \quad (8)$$

where λ refer to the forgetting factor and this indicate the inverse-correlation matrix. However, all algorithms employed a filter order equal to 16 or grantee the uniform circumstances for performance evaluation. The system's performance was evaluated with two quantitative metrics which is the improvement of the SNR Ratio and the Mean Squared Error. The S/N ratio enhancement is evaluating by the Eq. (9). The MSE was computed using the Eq. (10).

$$SNR_{out} = 10\ log_{10}\left(\frac{var(s(n))}{var(e(n))}\right) \quad (9)$$

$$MSE = \frac{1}{N}\sum_{n=1}^{N} e^2(n) \quad (10)$$

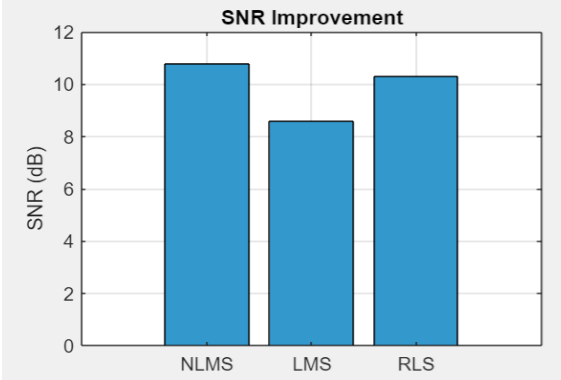
Collectively, these measures assess each algorithm's efficacy in noise reduction and the precision of signal estimation. All simulations were conducted utilizing MATLAB R2023a in a 64 − bit Windows 10 environment,

## 3. Results and Discussion

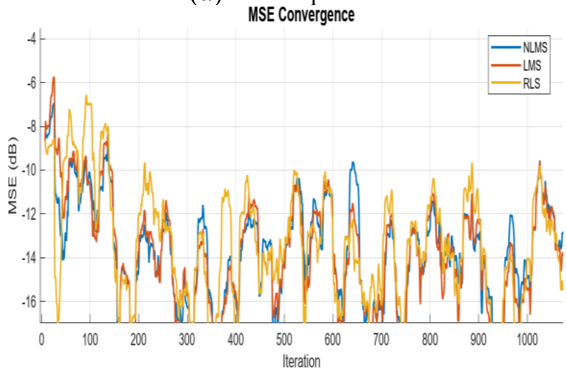
The adaptive noise cancellation algorithms was evaluated to saw the comparative efficiency of the LMS, NLMS, and RLS algorithms due to three distinct Gaussian noise and mixed noise environments.whereas all simulation used N is equal to 2000 samples and the filter order is 16, ,an input SNR of 5 dB, step sizes (μ = 0.01 for LMS, μ = 0.5 for NLMS) and forgetting factor (λ = 0.99 for RLS). Performance of the system was consider to measure both SNR enhancement and MSE metrics.

### A. Gaussian noise

In Gaussian noise, both LMS and NLMS algorithms possess effective on attenuation of noise . however , NLMS demonstrated superior reduced mean square error owing and SNR enhancement to its normalized and modulation, facilitating expedited convergence and improved stability.in fact, The RLS algorithm earned the biggest signal gain and the lowest MSE error among the three approaches algorithms represented in Fig. 3, under stationary noise conditions, a validating its higher convergence rate and accurate adaptation and Despite its computational simplicity, LMS algorithms represented slower convergence and retained a little higher level of residual noise as show in Fig.3.




(a) SNR improvement

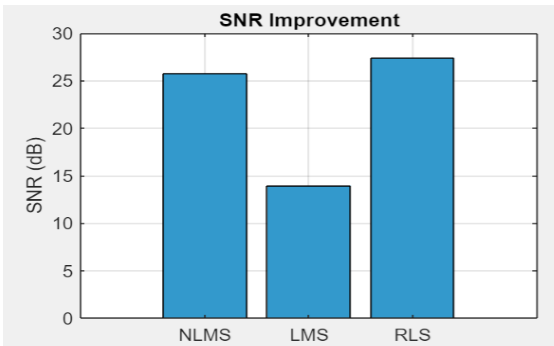



(b) MSE convergence

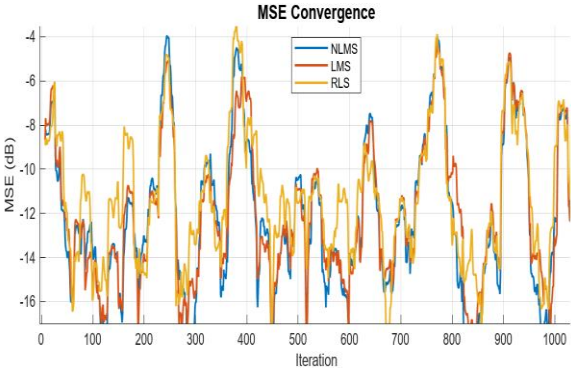
**Fig. 3.** Comparison between SNR and MSE for LMS, NLMS, and RLS algorithms under Gaussian Noise environment.

### B. Impulsive noise

The performance of the LMS defined as markedly when the signal was damaged by impulsive noise, which is demonstrated by abrupt, high-amplitude spikes, due to its susceptibility to substantial error values. NLMS realized superior resilience by dynamically modifying its learning rate, there by guaranteed to improved stability. RLS actually, achieved optimal results by effectively adjusting to abrupt amplitude turn and mitigating high energy outliers, in fact, to achieved the lowest mean square error seen in Fig. 4.




(a) SNR improvement




(b) MSE convergence

**Fig. 4.** Comparison of SNR and MSE convergence for LMS, NLMS, and RLS algorithms under impulse noise circumstances.

The tradeoff for this enhanced performance was its accrued to increased computing complexity.

### C. Mixed noise

The mixed noise environment, was defined as Gaussian and impulsive elements together, and the most formidable situation. RLS algorithms consistently demonstrated all noise cancellation, preserving elevated SNR levels with some little error variation. NLMS determined an equitable tradeoff between computational efficiency and accuracy, operating near RLS while demonstrating reduced the processing of costs, as seen in Fig. 5. The LMS showing worse performance due to convergence and elevated steady-state error, rendering it less appropriates for mixed or nonstationary noise environments.

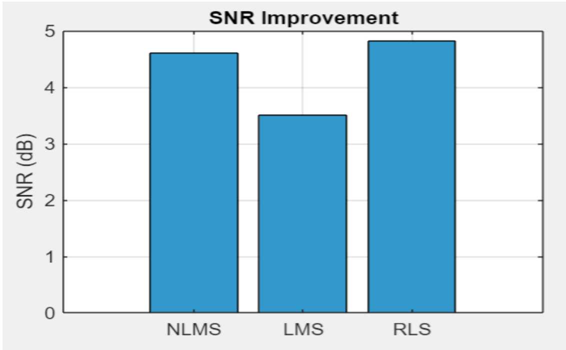
The entire performance trend regarding SNR enhancement and MSE reduction across all noise settings may be stated as Eq (11).

$$RLS > NLMS > LMS \qquad (11)$$

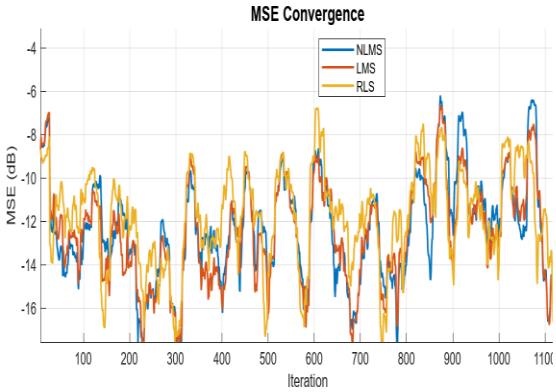
The connection is inversely proportional regarding computing efficiency represented in Eq. (12).

$$LMS < NLMS < RLS \qquad (12)$$

Consequently, the RLS method offers optimal signal reconstruction and is particularly effective in intricate or dynamic noise settings, such as in vehicular autonomous systems, where exact adaptive performance is essential. The NLMS method provides the optimal balance between performance and real-time computing efficiency, whereas the LMS algorithm is suitable for cost-effective applications where simplicity is prioritized above accuracy.




(a) SNR improvement




(b) MSE convergence

**Fig. 5.** Comparison of SNR and MSE convergence for LMS, NLMS, and RLS algorithms under mixed noise circumstances.

## 4. Conclusion

This paper conducted a comparative assessment of LMS, NLMS, and RLS adaptive filtering algorithms for the attenuation of noise in signals affected by Gaussian, Impulsive, and Mixed noise. Simulation results indicated that RLS consistently attained the highest output SNR and the lowest mean squared error, validating its superior convergence rate and noise suppression efficiency. In fact, NLMS offering a beneficial balance between computational complexity and performance, whereas the LMS- algorithms, despite its straight forwardness and elevated residual noise. These evaluated and indicate in RLS algorithms which is optimal for dynamic and all noise environments, in fact, this improvement comes at the cost of higher computational complexity. However, those dedicated in vehicular systems, while NLMS proposed an efficient solution for real- time applications system that involve moderate computational resources with less accurate.

Future endeavors may expand the framework to include nonlinear adaptive filtering techniques for multi-channel active noise control structures to address extremely wide band noise and non-stationary.

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