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# Design and implementation of a realtime co-processor for denoising Fiber Optic Gyroscope signal

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ABSTRACT

The amount of noise present in the Fiber Optic Gyroscope (FOG) signal limits its applications and has a negative impact on navigation system. Existing algorithms such as Discrete Wavelet Transform (DWT), Kalman Filter (KF) denoise the FOG signal under static environment, however denoising fails in dynamic environment. Therefore in this paper an Adaptive Moving Average Dual Mode Kalman Filter (AMADMKF) is developed for denoising the FOG signal under both the static and dynamic environments. Performance of the proposed algorithm is compared with DWT and KF techniques. Further, a hardware Intellectual Property (IP) of the algorithm is developed for System on Chip (SoC) implementation using Xilinx Virtex-5 Field Programmable Gate Array (Virtex-5FX70T-1136). The developed IP is interfaced as a Co-processor/ Auxiliary Processing Unit (APU) with the PowerPC (PPC440) embedded processor of the FPGA. It is proved that the proposed system is an efficient solution for denoising the FOG signal in real-time environment. Hardware acceleration of developed Co-processor is 65× with respect to its equivalent software implementation of AMADMKF algorithm in the PPC440 embedded processor.



## 1. Introduction

Fiber Optic Gyroscope (FOG) is a proven technology for measuring the angular velocity of an object. The accuracy of FOG is limited by different kinds of noise due to internal device operation and environmental disturbances while measuring the rotation rate [1,2]. FOG is one of the important components of Inertial Measurement Unit (IMU) used in the navigation processor to compute position, velocity and altitude of the moving object [3]. It consists of three accelerometers and three gyroscopes. The navigation state, i.e., position and altitude are derived from the measured signals of these accelerometers and gyroscopes. The estimated navigation states (i.e., position, velocity and altitude) drift with time due to integration of sensor errors (such as biases, scale factors, and noise) over a period of time. Therefore, it is essential to develop an efficient signal processing algorithm to denoise/suppress these errors.

To improve the accuracy and performance of FOG, both manufacturers and users are keen to know about sources of noise and the quantity of noise present in the signal. Complementary to this, user can also improve the navigation solution by using the different denoising algorithms. Different signal processing techniques like Discrete Wavelet Transform (DWT) [4–6], Kalman Filter (KF) [7–9], adaptive Kalman filter [10,11] and hybrid Kalman filter [12,13] have been used to denoise the FOG signal. Recently the present authors have demonstrated a variant of Kalman filter to denoise the single and three axis FOG signals in both static and dynamic environment [14,15]. The performance of denoising algorithm is characterized by quantifying random noise in the signal using Allan Variance analysis, bias drift and Signal to Noise Ratio (SNR). Different random errors like Quantization error (Q), Angle random walk error (N), Bias instability error (B), Rate random walk error (K) and Drift rate ramp (R) are quantified before and after denoising the signal [16].

There are several choices to select the hardware platform, i.e., micro-Controllers ($\mu$C), Digital Signal Processors (DSP), Field Programmable Gate Arrays (FPGA) and Application Specific Integrated Circuits (ASIC) for developing an embedded system. The selection of platform depends on factors such as performance, power consumption, cost per chip, ease of tools accompanied by a specific platform to assist the developers in producing the system within the constraints of system cost and project time [3]. The platforms such as micro-Controllers ($\mu$C) and Digital Signal Processors (DSP) make use of embedded software oriented methodologies to develop the system. However, the designers who use FPGAs as their development platform, have the flexibility to use either the processor-based approach, developing their system partly

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in firmware and partly in hardware, or developing their system entirely in the hardware. Recently FPGA based Real-Time Embedded System is developed for vehicular navigation system, consisting of a gyroscope and an odometer or wheel encoders, along with a GPS receiver and Kalman filter [3].

In order to have on-board denoising of the FOG signal, the denoising algorithm needs to be implemented in the hardware and integrate it to the FOG sensor board. Recently the authors have demonstrated a variant of AMADMKF algorithm that uses sliding window technique for estimating the threshold [14,15], whereas in the present work the threshold is calculated as 95% upper tail of the exponential distribution with expected value as mean of sample variances of the current frame [22]. Due to this the hardware resource utilization is minimized. Moreover the algorithm was implemented in the FPGA to process the off-line data. In [15], FOG signals were stored and processed from the memory. However in real-time environment there is a need to develop SoC for on-line processing of FOG noisy signals.

Thus, this work aims to develop an embedded platform (SoC) solution for real-time denoising the FOG signal. The proposed SoC solution for FOG signal denoising system consists of an embedded processor (PPC440), peripherals such as UART (RS232), Flash memory, DDR2-SDRAM, custom Auxiliary Processor Unit (APU). The main objective of this work is to narrow the idea-to-implementation gap that follows the algorithm development and its realization in real time embedded platform. Thus the present work has mixed contributions on both algorithm and as well as the development of embedded platform for its implementation.

The rest of the paper is organized as follows: Section 2 presents the basics of Kalman filter and adjusting KF parameters, Section 3 presents the proposed algorithm. Section 4 describes the experimental setup followed by the hardware of the proposed algorithm in Section 5. Section 6 presents detail about system on a chip implementation of the proposed AMADMKF algorithm. Section 7 presents the algorithmic simulation and results, Section 8 presents the system on chip implementation results followed by conclusions and future work in Section 9.

## 2. Kalman Filter (KF)

Kalman filter is commonly used in Inertial Navigation Systems for signal estimation and filtering. In this approach, the bottleneck is the proper estimation of KF parameters. Process noise covariance matrix $Q_k$ and measurement noise covariance matrix $R_k$ are the main parameters that effects the performance of KF. In case of basic KF, the process noise and measurement noise characteristics are assumed to be statistically known and thus fixed values of $Q_k$ and $R_k$ are considered to filter the signal. The denoising process has two stages

1. First stage predicts the current state and the error covariance based on previous state estimate.
2. The second stage correct the previous predicted values using the present measured value.

These stages can be represented by the following equations

$$\hat{x}_k^- = A\hat{x}_{k-1} + Bu_k \tag{1}$$

$$P_k^- = AP_{k-1}A^T + Q_k \tag{2}$$

$$K_k = P_k^- H^T \left(HP_k^- H^T + R_k\right)^{-1} \tag{3}$$

$$\hat{x}_k = \hat{x}_k^- + K_k\left(z_k - H\hat{x}_k^-\right) \tag{4}$$

$$P_k = (I - K_k H)P_k^- \tag{5}$$

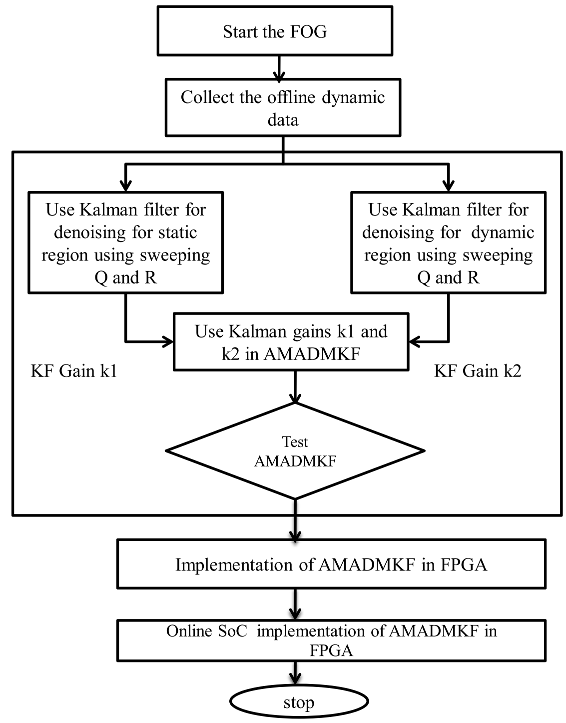


**Fig. 1.** Adjusting KF parameters in off-line mode of the AMADMKF.

where

| | |
|---|---|
| $x_k$ | is the state vector at time $k$, |
| $u_k$ | is the optional control input at time $k$, |
| $Q_k$ | is the process noise at time $k$, |
| $R_k$ | is the measurement noise at time $k$, |
| $z_k$ | is the measurement taken at time $k$, |
| $P_k$ | represents error covariance matrix at time $k$, |
| $A$, $B$ and $H$ | are state space representation matrices, |
| $Q_k$ and $R_k$ | are discrete white noises having Gaussian distribution with zero mean and covariances respectively. |

The Kalman filter output can be written as Eq. (6), where KF gain ($K_k$) is a dominant parameter that effects the KF performance.

$$\hat{x}_k = \hat{x}_k^- + K_k\left(z_k - \hat{x}_k^-\right) \tag{6}$$

### 2.1. Adjusting KF parameters

The Kalman gain ($K_k$) depends on the measurement noise covariance ($R_k$), process noise covariance ($Q_k$) and error covariance ($P_k$) matrices of the filter. The estimation of these parameters for real time filtering is still unsolved [7]. The values of these parameters depend on the FOG dynamics which are not explicitly known a priori. The effective denoising can be achieved by appropriate initialization of $R_k$, $Q_k$ and $P_k$ [17,18]. For denoising the dynamic signal, there is a trade-off between the quality of denoising and following trend of the signal, and it depends on the value of $Q_k/R_k$. For the dual mode KF, $Q_k/R_k$ is selected such that KF has a choice to choose the optimum value of $Q_k/R_k$ for effective denoising and following the trend of the signal independently. Since the application has two variables ($R_k$, $Q_k$) and was evaluated in off-line mode as explained in Fig. 1.

In static condition, KF gain $k1$ was calculated for the obtained values of $Q_k$ and $R_k$ using the sweep plot. It is observed that output of KF is stabilizing after processing certain number of samples. This sample delay did not effect much in static condition, whereas in dynamic condition this delay is not tolerable. The KF parameters are not only impact on the noise level of output signal, but also on the settling time of KF. It is observed that the settling time